
by

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Graduate Department of Electrical and Computer Engineering
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Abstract


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Advancements in digital circuitry, wireless transceivers and microelectro- mechanical systems have paved the way for the development of integrated sensor systems operating inside the unlicensed spread spectrum. Inch scale sensors can work unattended for long periods of time while energy harvesting techniques can extend their lifetime. A main challenge in these networks is energy efficiency. This thesis presents the design, implementation and evaluation of two routing protocols for a variety of applications with the main focus on energy efficiency.

After reviewing the theory of opportunistic routing and opportunistic spectrum access, a scalable solution that combines the advantages of these approaches is presented. The CNOR protocol explores the spectrum availability while it uses opportunistic routing to take advantage of the broadcast nature of wireless communications. CNOR is designed for WSNs with limited power resources.

Next, ECUR protocol for Self-powered WSNs is introduced. ECUR uses a novel prioritization metric for the neighbour nodes. ECUR protocol balances the residual energy level in a node with the packet advancement. Also, it takes into consideration the limited memory and processing capacity of the nodes.

Lastly, the system implementation of the protocols is presented. Both protocols are examined through a novel Self-Powered Wireless Sensor Network testbed that was developed.
Dedication

To my parents,
Kleomeni and Eleftheria
and to my lovely sister Dimitra,
who have always been by my side
and supported me.

Στους γονείς μου,
Κλεομένη και Ελευθερία
και στην αγαπημένη μου αδερφή Δήμητρα,
που είναι πάντα δίπλα μου
και με στηρίζουν.
Acknowledgements

“Wishing to be friends is quick work, but friendship is a slow ripening fruit.”

Aristotle

As you set out for Ithaca, hope the voyage is a long one, full of adventure, full of discovery1/.../.

At the beginning of my graduate studies, I had the unique opportunity to meet and have as my Ph.D. advisor, Professor Dimitrios Hatzinakos. I am forever indebted to Dimitris for his constant guidance and mentorship in my research. He was always there to support my academic work. Without his generous help, this research would not have been possible. I have benefited tremendously from him, and I truly appreciate his countless dedications to my intellectual and personal growth. I would like to thank him for everything he has done for me, both professionally and personally. I would also like to thank him for generously financing my many trips to conferences worldwide, which has proven to be an educational and cultural experience.

Besides my advisor, I am thankful to the rest of my Ph.D thesis committee: Professor Deepa Kundur, Professor Alberto Leon-Garcia and Professor Ben Liang for taking time to provide useful insight on this dissertation. Professor Ioannis Lambadaris served as my external examiner, and I would like to thank him for all his comments and generous feedback.

I feel obliged to acknowledge my advisor of my undergraduate studies, Professor Stavros Christodoulakis for giving me the opportunity to come to the University of Toronto. His support and advice made this academic journey feasible.

[...]Hope the voyage is a long one. May there be many a summer morning when, with what pleasure, what joy, you come into harbors seen for the first time[...].

I would like to express special thanks to Dr. Liang Song for his excellent collaboration over the past years and for helping me to improve my technical skills. I would like to extend my sincere appreciation to all my co-authors for our collaboration. Thanks are due to several people I met in conferences, devoted time to talk with me, comment on my work and often encouraged me to continue. I am especially thankful to Professor Dimitris Toumpakaris and Angelos Marnerides for the excellent collaboration and for

1Constantine P. Cavafy – Ithaca

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the fun and adventurous times we had at different places worldwide when attending conferences. Vladimiro Cirillo and Mary Stathopoulos, our graduate secretaries, made dealing with departmental paperwork a joyful experience.

.../Keep Ithaca always in your mind. Arriving there is what you are destined for.../

I would like to thank all my fellow researchers and friends here at the University of Toronto: Ioannis Sarkas, Anastasios Zouzias, Apostolos Dimitromanolakis, Christina Christodoulaki and others. They played a big role in my studies and kept me sane over the years. They all made this long journey towards my PhD more pleasurable.

Many thanks to my uncle Michalis, my cousin Jim Syrbos and their restaurant “Square Boy”, for all the great food they provided which kept me full while conducting research.

.../Ithaca gave you the marvelous journey. Without her you would not have set out.../

The multimedia communications group has been a highly enriching environment for me, as I have met so many incredible individuals during my study here. I would like to thank all my colleagues and especially my lab mates in BA 4154 over the past four years for their inspiring interaction and support in my Ph.D. studies. With the danger of forgetting someone (so I apologize in advance) I would like to thank Dr. Francis Bui, Dr. Hoda Mohammadzade, Jiexin (Alice) Gao, Sahar Javaher Haghighi, Gagan Goel and Peter Sam Raj.

My friends in Greece provided emotional support since I left. I would like to thank them, especially Dimitris and Tasos, for staying the way they were, despite the passage of time.

.../And if you find her poor, Ithaca won’t have fooled you. Wise as you will have become, so full of experience, you will have understood by then what these Ithacas mean.

Special thanks to my Neda. She supported me through the “crazy” days towards this Ph.D. and has been by my side throughout important stages of my life. Also, with her corrections, she helped me make this thesis understandable for non-Greeks.

Last but not least, my thanks must be paid to my family, my sister Dimitra and my parents Eleftheria and Kleomenis. Their love has been the source of my energy all these 0110 years and without them none of this would have been possible. They are my Ithaca.
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\( A \) \hspace{1em} \text{constant decided by the antenna gain}
\( c_{i,j} \) \hspace{1em} \text{cost of delivery between the node } i \text{ and the node } j
\( Ch_N \) \hspace{1em} \text{number of channels}
\( C_{1CNOR} \) \hspace{1em} \text{constant related with the number of the neighbour nodes for CNOR protocol}
\( C_{2CNOR} \) \hspace{1em} \text{constant related with the transmission range and the number of the neighbour nodes for CNOR protocol}
\( C_{1EAOR} \) \hspace{1em} \text{constant related with the transmission range of EAOR protocol}
\( C_{2EAOR} \) \hspace{1em} \text{constant related with the energy at the node of EAOR protocol}
\( C_{1ECOR} \) \hspace{1em} \text{constant related with the energy at the node of ECOR protocol}
\( C_{1ECUR} \) \hspace{1em} \text{constant related with the initial energy at the node of ECUR protocol}
\( C_{2ECUR} \) \hspace{1em} \text{constant related with the transmission range of ECUR protocol}
\( C_{GEOR} \) \hspace{1em} \text{constant related with the transmission range of GEOR protocol}
\( C_{1GeoProb} \) \hspace{1em} \text{constant related with the transmission range of Geo-probabilistic protocol}
\( C_{2GeoProb} \) \hspace{1em} \text{constant related with the randomness of Geo-probabilistic protocol}
\( cnd \) \hspace{1em} \text{candidate node}
\( C_{1SEAOR} \) \hspace{1em} \text{constant related with the capacity of the battery in SEA-OR protocol}
\( C_{2SEAOR} \) \hspace{1em} \text{constant related with RSSI value in 1m distance in SEA-OR protocol}
\( d_{prop} \) \hspace{1em} \text{propagation delay}
\( d_{trans} \) \hspace{1em} \text{transmission delay}
\( d_f \) \hspace{1em} \text{delivery rate on the link from the sender to the destination}
\( d_r \) \hspace{1em} \text{delivery rate on the link from the destination to the sender}
\( d_{i,j} \) \hspace{1em} \text{packet advancement from node } i \text{ to node } j
\( dist(i,j) \) \hspace{1em} \text{Euclidean distance between the node } i \text{ and the node } j
\( \hat{D}_{i,j} \) \hspace{1em} \text{estimated distance between the node } i \text{ and the node } j
\( dst \) \hspace{1em} \text{destination node of the network}
\( E_{init} \) \hspace{1em} \text{initial energy in a node}
\( E_{cons}(t) \) \hspace{1em} \text{energy consumption at time } t
$E_{lv}$ an approximation of the energy level - the percentage of the remaining energy at a node

$E_{res}$ the percentage of the residual energy in the node

$E_t$ total energy consumption

$E_{tx}$ packet transmission energy consumption

$E_{rh}$ threshold below which the node stops transmitting

$E_{rx}$ packet reception energy consumption

$K_i$ set of candidate nodes for node $i$

$F_d$ length of the data packet in bit

$L_{ACK}$ length of ACK packet

$L_{DATA}$ length of DATA packet

$L_f$ length of frame

$L_{RTS}$ length of RTS packet

$L_{CTS}$ length of CTS packet

$T$ the mean of the explicitly applied PRLS

$L_k$ the packet relevance level

$n$ wireless channel path loss component

$N_i$ set of neighbour nodes for node $i$

$P_{i,j}$ delivery probability between the node $i$ and the node $j$

$P_{scan}$ power consumption on scanning different channels

$P_t$ power consumption in transmitting mode

$P_{r/i}$ power consumption in receiving/idle mode

$P_s$ power consumption in sleep mode

$P_{(A,B)}$ delivery probability from node $A$ to node $B$

$Q_x$ cumulative distribution function of $x$

$\text{rand}(0,1)$ pseudorandom number generator between 0 and 1

$R$ transmission rate

$\text{Range}$ communication range of a node

$S$ set of all the nodes in the network

$src$ source node of the network
\( T_{\text{ACK}} \) timeout period for receiving an ACK
\( T_{\text{bCNOR}} \) backoff time for CNOR protocol
\( T_{\text{bCROR}} \) backoff time for CROR protocol
\( T_{\text{bEAOR}} \) backoff time for EAOR protocol
\( T_{\text{bECOR}} \) backoff time for ECOR protocol
\( T_{\text{bECUR}} \) backoff time for ECUR protocol
\( T_{\text{bGEOR}} \) backoff time for GEOR protocol
\( T_{\text{bGeoProb}} \) backoff time for Geo-probabilistic protocol
\( T_{\text{bSEAOR}} \) backoff time for SEA-OR protocol
\( T_{\text{CTS}} \) timeout period for receiving a CTS
\( T_{\text{RTS}} \) timeout period for receiving a RTS
\( T_{\text{trans}} \) total transmission time
\( Th_{\text{PER}} \) threshold for PER
\( Th_{\text{PRR}} \) threshold for PRR
\( \mathbf{v}_{AB} \) vector connecting a node A and a node B
\( \alpha \) path-loss exponent
\( \gamma(d) \) Signal to Noise Ratio in distance d
\( \theta \) angle between 0 and 90 degrees
\( \rho \) encoding ratio
\( \sigma \) log-normal shadowing variance
\( \sigma^2 \) noise power
\( \phi \) inclination angle between the source node and a neighbour node
## List of Abbreviations

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<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>ADRS</td>
<td>Ange-based Dynamic Routing Scheme</td>
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<tr>
<td>ALC</td>
<td>Anycast Link Cost</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic Repeat Request</td>
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<tr>
<td>ASR</td>
<td>Adaptive Spectrum Radio</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase-Shift Keying</td>
</tr>
<tr>
<td>CA</td>
<td>Collision Avoidance</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal–oxide–semiconductor</td>
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<td>CNOR</td>
<td>Cognitive Networking with Opportunistic Routing</td>
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<tr>
<td>CORE</td>
<td>Coding-Aware Opportunistic Routing Mechanism</td>
</tr>
<tr>
<td>CORMAN</td>
<td>Cooperative Opportunistic Routing Scheme in Mobile Ad Hoc Networks</td>
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<tr>
<td>CR</td>
<td>Cognitive Radio</td>
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<td>CRN</td>
<td>Cognitive Radio Network</td>
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<td>CROR</td>
<td>Content Relevance Opportunistic Routing</td>
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<td>CRSN</td>
<td>Cognitive Radio Sensor Network</td>
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<tr>
<td>CSN</td>
<td>Cognitive Sensor Network</td>
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<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<tr>
<td>CTS</td>
<td>Clear To Send</td>
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<td>CW</td>
<td>Continuous Wave</td>
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<td>DBM</td>
<td>Digital Building Model</td>
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<td>Dynamic Spectrum Access</td>
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<td>EAX</td>
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<td>ECUROUR</td>
<td>Efficient Cognitive Unicast Routing</td>
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<tr>
<td>EPA</td>
<td>Expected Packet Advancement</td>
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</table>
ETA    Estimated Time of Arrival
ETX    Expected Transmission Count
ExOR   Extremely Opportunistic Routing
GeOppe Geographical Opportunistic
GEOR   GEographic Opportunistic Routing
GeRaF  Geographic Random Forwarding
GOR    Geographic Opportunistic Routing
GUI    Graphical User Interphase
HARBINGER Hybrid ARQ-Based Intercluster Geographic Relaying
IAQ    Indoor Air Quality
LCOR   Least-Cost Opportunistic Routing
LOS    Line-of-sight
MAC    Media Access Control
METD   Minimum Estimated Time of Delivery
MORE   MAC-Independent Opportunistic Routing and Encoding
MOS    Metal–oxide–semiconductor
MSAOR  Multi-channel Spectrum Aware Opportunistic Routing
NADV   Normalized Advance
NLOS   Non-line-of-sight
OAPF   Opportunistic Any-Path Forwarding
OLT    Opportunistic Link Transmission
OFDM   Orthogonal Frequency Division Multiplexing
OPM    Opportunistic Mesh
OPRAH  Opportunistic Routing in Dynamic Ad Hoc Networks
OR     Opportunistic Routing
OSA    Opportunistic Spectrum Access
OSI    Open System Interconnection
PRLS   Packet Relevance Level Scheme
PER    Packet Error Rate
PRR    Packet Reception Rate
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>ROMER</td>
<td>Resilient and Opportunistic Routing Solution For Mesh Networks</td>
</tr>
<tr>
<td>RPC</td>
<td>Remaining Path Cost</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indicator</td>
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<td>RTS</td>
<td>Request To Send</td>
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<td>SAOR</td>
<td>Spectrum Aware Opportunistic Routing</td>
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<td>SAMER</td>
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<td>SEA-OR</td>
<td>Spectrum and Energy Aware Opportunistic Routing</td>
</tr>
<tr>
<td>SIFS</td>
<td>Short Interframe Space</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>SOAR</td>
<td>Simple Opportunistic Adaptive Routing</td>
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<tr>
<td>s-OSA</td>
<td>Simple Opportunistic Spectrum Access</td>
</tr>
<tr>
<td>SPSN</td>
<td>Self-Powered Sensor Network</td>
</tr>
<tr>
<td>UTD</td>
<td>Uniform Theory of Diffraction</td>
</tr>
<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver/ Transmitter</td>
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<tr>
<td>VOCs</td>
<td>Volatile organic compounds</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<td>WMSN</td>
<td>Wireless Multimedia Sensor Network</td>
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<td>WSN</td>
<td>Wireless Sensor Network</td>
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Modern Wireless Sensor Network (WSN) platforms, which are characterized as one of the key technologies contributing to the so-called “digital evolution”, are endowed with the ability to create networked artifacts (human and non-human) to sense their environment, and accordingly adapt their behaviour in beneficial manners. The potential applications are numerous, including effective monitoring and sustainable governance in structural health, disaster relief, transportation, law enforcement, and public safety and security.

A major rationale for these WSN technologies is that they can enable the users to make decisions in a “smarter”, more “aware” and “responsive” manner [1]. Indeed, a distributed monitoring capacity gives us a “novel” visualization of our environment that allows more effective planning: the ability to respond in a more timely fashion, and to develop more effective actions to resolve environmental problems. The social and economic implications can be enormous, for not only public, but also private organizations. Evidently, this technological innovation impacts many aspects of human life: health and safety, information and communications, energy and environment, as well as security, to name a few.

While there are irrefutable advantages to be reaped with the WSN infrastructures, these strategic values are not without caveats. On the one hand, the larger a sensor network becomes, the smarter and more responsive we become, as our visualization becomes more global and informative. On the other hand, as the size of the network increases, so does the associated complexity and management [2]. To facilitate deployment and acceptance of such networks, the network sensors must be inexpensive, non-intrusive, and communicate effectively. Together, these conditions imply two fundamental requirements that influence the operation of the network: scalability and sustainability. Without these
two requirements, the operation and impact of the WSN would be questionably limited, if not short-lived.

An appealing solution for unattended surveillance and monitoring application is Self-Powered Wireless Sensor Networks (WSNs). One of the main reasons is that energy harvesting can be used to significantly extend the network lifetime and the network can work unattended for long periods. However, these networks are characterized by multi-hop lossy links and resource constrained nodes while they have to face the coexistence problem with other applications.

An example of a Self-Powered WSN can be seen in Figure 1.1. A number of sensor nodes work unattended in the field. The nodes should transmit the data to a control centre. The nodes availability can change over time while there are other wireless infrastructure in the area that use the same transmission band.

The purpose of this thesis is to present new ideas at the routing and system level for Self-Powered WSN platforms.

1.1 Motivation

The wide advancements in the field of WSNs, made them an appealing solution for broad applications [3–5]. They have an easy deployment at low cost without relying on existing infrastructure. This progressive research in WSNs explored various new applications enabled by larger scale networks of sensor nodes capable of sensing information from the
environment, processing the sensed data and transmitting it to the remote location [6].

However, some applications require the sensor nodes to have a long lifetime [7]. Energy efficiency has been considered as an important issue in the design of network architecture. WSNs are composed of small energy-limited autonomous units. The lifetime of such a network is seriously dependent on the initial energy stored in the nodes as well as the energy efficiency of network protocols.

Inch scale sensor nodes can operate unattended for long periods if they have sufficient energy sources [8]. Energy harvesting (also known as power scavenging) can be an appealing solution. This process helps provide unlimited energy for electronic devices. Consequently, it increases the network lifetime.

Although energy harvesting can address the problem, it still poses important challenges. The network should operate continuously. The nodes should always provide information about the monitoring area. In addition, the network connectivity is of high importance. Therefore, the limited energy resources of those networks should be carefully used.

Another challenge is the network scalability and the coexistence with other infrastructures. Usually, these monitoring applications are deployed close to other already deployed infrastructures. Hence, the network should have limited interference and collision with other transmissions while it should retain network connectivity and real-time data forwarding.

Traditional routing protocols [9–11] for multi-hop wireless networks follows the concept of routing in wired networks. They abstract the wireless links as wired links, and find the shortest, least costly, or highest throughput path(s) between a source and destination. However, this abstraction ignores the unique broadcast nature and spacial diversity of the wireless medium. More important, it does not cope with common dynamic changes on the link availability.

1.2 State of the Art

Opportunistic routing (OR) was introduced [12] to take advantage of the broadcast nature of wireless communications. OR integrates the network and MAC layers [12–19]. In contrast with traditional routing which has a predefine node to forward the packet to, OR has a set of nodes that can serve as relay node. The selection of the relay node follows the instantaneous wireless channel condition and node availability at the time of
transmission. OR is an efficient mechanism to combat time-varying links and use the benefits of the spacial diversity of wireless communication. OR improves the network throughput [12,17,20,21] and energy efficiency [14,16,21]. Performance of OR depends on several factors. The forwarder set selection, the prioritization of the set and the duplicate avoidance mechanisms, have great impact on the protocol performance [22].

Although opportunistic routing has shown its effectiveness in achieving better energy efficiency [14,16] and higher throughput [12] than traditional routing, there are still many important issues in OR which have remained unanswered or ambiguous.

First, the existing works are not designed for the limited computational requirements of WSNs. Advance and optimized routing schemes with routing tables are not applicable on inch scale sensor nodes with limited memory and processing capacity. Second, there is a lack of theoretical analysis on the throughput bounds achievable by OR. Third, one of the current trends in wireless communication is to enable devices to operate using multiple transmission rates.

At the same time, the WSN scalability and coexistence problem can be alleviated through efficient spectrum usage [23]. Spectrum sensing has gained new aspects with cognitive radio and Opportunistic Spectrum Access (OSA) concepts [24]. OSA allows unlicensed users to share the spectrum in space and time with no or little interference with primary users [25]. However, it also brings new research challenges in MAC and protocol design.

First, the sensor nodes should have the necessary equipment to perform channel sensing. The energy cost of the sensing should not increase the total energy consumption in the network. Second, the design of the spectrum access mechanism should have the least impact with the environment. Even if collision occurs or the spectrum is crowded, the nodes should find a slot to transmit the data. Third, the device should sense and identify spectrum opportunities, coordinate and use them.

In this dissertation, a combination of OR with OSA for Self-Powered Wireless Sensor Networks is proposed. The main goal is energy efficiency along with acceptable packet latency by means of a novel routing protocol that will be proposed.

1.3 System Model and Assumptions

In this section, a brief description of the network model along with some of the main assumptions are presented. The system model and the assumption applied to all the
protocols presented in this thesis. If there are any additional assumptions, they are included in the description of each protocol.

A multi-hop wireless sensor network with \( S \) nodes arbitrarily located on a plane is considered. The network may have multiple sources, but there is only one destination. Every node in the network knows the address of the destination node through an initialization phase. Nodes can join or leave the network at any time.

Each sensor node \( s_i \) \((1 \leq i \leq S)\) has a neighbour node set \( N_i \). The neighbour node set consists of all the sensor nodes in the transmission range of the sensor node \( s_i \). There is also a candidate node set \( K_i \) which is a sub-set of \( N_i \). The candidate node set consists of the nodes that are located closer to the destination than \( s_i \).

Every node in the network knows its relative location. In general, the node location information can be obtained by prior configuration, by the Global Positioning System (GPS) receiver as in [26], or through some sensor self-configuring localization mechanisms as in [27]. Due to the hardware limitations, in this work the relative location is acquired with the use of the RSSI value [28]. For some theoretical analysis, the packet advancement \( d_{ij} \) is used. This is the Euclidean distance between the transmitter sensor \( i \) and the destination node \( dst \) subtracting the Euclidean distance between the neighbour node \( j \) and the destination node. The packet advancement can be defined as:

\[
d_{ij} = \text{dist}(i, dst) - \text{dist}(j, dst) \tag{1.1}
\]

Each node can transmit a packet at the same rate \( R \). Every packet transmission is subjected to a Packet Error Rate (PER). An opportunistic link is used only if the PER of the link is lower than a non-negligible positive threshold \( T_{\text{PER}} \). In some of the protocols the Packet Reception Rate (PRR) is also used as link quality indicator. There are several link quality mechanisms [29–32] to obtain the PRR on each link. In this dissertation, it is assumed there is no power control scheme and the PRR on each link is independent.

### 1.4 Organization of the Dissertation

The remainder of this thesis consists of six chapters. Chapter 2 briefly describes opportunistic routing and reviews the opportunistic routing protocols. A categorization of the different schemes is presented. Four different approaches on the relay node prioritization are evaluated and compared in terms of network performance. Chapter 3 reviews the op-
portunistic spectrum access principles. Two approaches of opportunistic spectrum access are designed and evaluated. Chapter 4 presents the design, implementation and performance evaluation of Cognitive Networking with Opportunistic Routing protocol. An accurate channel model is built to examine the performance of the protocol in a complex indoor environment. Chapter 5 presents the design, implementation and performance evaluation of two energy efficient routing protocols for Self-Powered WSNs. The two protocols are compared in terms of network lifetime. Chapter 6 presents an overview of the applications that the proposed routing protocols can be applied in. Two implementations of the protocols are proposed. The protocols are examined under prototypes and the testbed that was developed. Finally, Chapter 7 concludes this thesis and discusses potential future research.

1.5 Research Contributions

A number of protocols are presented and discussed in this dissertation. The key contributions of this thesis are summarized below:

- A Cognitive Networking with Opportunistic Routing (CNOR) protocol for WSNs is proposed [33]. The protocol is simulated and also implemented in hardware. One fundamental challenge in WSNs is energy efficiency. Sometimes the battery replacement is infeasible or impossible. The network connectivity is based on the usage of the limited power sources. If a node runs out of energy, there is no connection between the node and the destination. CNOR efficiently uses the limited energy of the nodes and extends the network lifetime. CNOR combines the advantages of opportunistic spectrum access with opportunistic routing. The protocol was simulated and evaluated with prototypes.

- An Efficient Cognitive Unicast Routing (ECUR) protocol for Self-Powered WSNs is developed [34]. The protocol is implemented in self-powered wireless sensor node prototypes. An outdoor monitoring application which makes use of the protocol is developed. ECUR is designed specifically for Self-Powered nodes and evaluated through simulations and prototyping. ECUR uses the residual energy of the nodes to prioritize the neighbour nodes and extends their operation time.

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1Please refer to Chapter 7 - Section 7.1 for a detailed table with the different schemes.
• A novel prioritization metric for opportunistic routing protocols is introduced [35]. The metric is used in a number of applications that have been developed. The metric balances the packet advancement, the residual energy level of the node and the link reliability. Existing advance metrics optimize the performance of the different metrics, but increase the complexity of the implementation on a sensor. The proposed metric is designed for Self-Powered wireless sensor nodes with limited capabilities.

• A testbed is developed to examine the performance of the different protocols [36]. The testbed consists of 50 prototypes [37–39]. An accurate channel model was designed to simulate the performance of the protocols in large-scale networks.

This doctoral work has resulted in more than 20 research publications including 3 journal papers, 1 book chapter, and 19 conference and workshop papers in premier forums on wireless networking. ²

²Please refer to Chapter 7 - Section 7.5 for a complete publication list.
Chapter 2

Opportunistic Routing Protocols

This chapter describes the main principles of Opportunistic Routing (OR) protocols and how they can be applied in WSNs. First, the routing mechanism of OR is illustrated and compared with traditional single hop routing protocol. The OR protocols are classified according to common design approaches. They are further categorized based on their forwarder set selection and the prioritization of the forwarder set. Then, a survey on the OR protocols is provided and some protocols are briefly described.

Moreover, in this chapter a description of a simple GEographical Opportunistic Routing (GEOR) protocol is provided. The protocol performance under different network scalabilities is examined. GEOR is simulated and later in this thesis is implemented in hardware. Also, an extension of GEOR that can prolong the network lifetime is examined. The Angle-based Dynamic Routing Scheme (ADRS) uses inclination angles. A detailed theoretical analysis of ADRS is provided and the performance of ADRS is compared with theoretical results as well as single hop traditional routing. Last, since this chapter provides a classification of the different OR protocols, four protocols of different approaches are examined and simulated. The main focus is on the impact of the next node selection criteria on the network performance. Their performances are evaluated and compared in terms of energy consumption, delivery ratio and packet latency. Then, the challenges in the implementation of each approach in a WSN are discussed and the potential application for each one.
Chapter 2. Opportunistic Routing Protocols

2.1 Opportunistic Routing Principles in WSNs

In recent years, a lot of effort has been devoted to improve the performance of wireless ad hoc networks, in terms of power consumption and packet latency. One promising approach is to allow the relay nodes to cooperate, thus using the spatial diversity to increase the capacity of the system. However, one of the main drawbacks of this approach is that it requires information exchange between the nodes. This introduces overhead and increases the complexity of the receivers.

A simpler way of exploiting the spatial diversity is Opportunistic Routing (OR), also called opportunistic forwarding [12]. OR tries to benefit from the spacial diversity of the wireless medium. In contrast with traditional routing which involves only one relay candidate, OR involves a set of forwarding candidates. OR tries to overcome the drawback of unreliable wireless links by taking advantage of the broadcast nature of the wireless medium. One transmission can be overheard by multiple nodes. As a consequence, a cluster of nodes can serve as relay candidate set. From the candidate set, only one node will become the next relay node and forward the packet. In this way, OR improves the reliability and efficiency of packets relay. In OR, intermediate nodes collaborate to packet forwarding in order to achieve high throughput in the face of lossy communication links. As it can be inferred, the task of routing in an opportunistic forwarding protocol is crucial for the network performance [40], and it can be divided into a number of steps.

2.1.1 Traditional Routing Principles

The task of routing includes the relay node selection process and the route selection process towards the destination. Traditional routing protocols usually perform best relay and best path routing. In this approach, the transmitter forwards all the packets to the neighbour node over the most reliable link. This link is usually towards a node that is close to the transmitter and hence, the Packet Error Rate (PER) is small. In many implementations, a link is reliable if the PER is below a predefined threshold $Th_{PER}$. When a path between the transmitter and the destination is found, this path remains the same for every the packet transmission. The same nodes are always selected for all the consequent packet transitions. The best path between the source and the destination is chosen before the transmission starts and remains fixed.

However, the highly dynamic and lossy nature of wireless medium causes frequent
transmission failure. This leads to retransmissions and as a result, waste of network resources, or even system breakdown. To overcome these problems, OR tries to discover multiple paths towards the destination and to forward the packets over different paths, according to network conditions. In contrast with traditional routing, OR is a dynamic approach that selects the communication paths according to the network conditions during the transmission time.

2.1.2 An Illustration of Opportunistic Routing

Opportunistic routing is a dynamic multi-hop routing protocol which tends to select the best available routing path according to the network conditions, during a packet transmission. The idea of OR was introduced in [12]. The relay node and the route selection process are different from traditional routing. These two important aspects of OR are illustrated through the following examples:

**Relay node selection.** An illustrative example of the relay node selection in OR is depicted in Figure 2.1, where a directed graph represents a wireless network. There is one link between the source node \textit{src}, and each intermediate node \(A, B, C\) and \(D\), with delivery probability of 25%. There is also a link between each intermediate node and the destination node \textit{dst}, with delivery probability of 100%.

Traditional routing will achieve 25% end-to-end delivery probability through any possible intermediate node. An OR approach called relay-based opportunistic forwarding could use all the intermediate nodes as relay nodes and achieve a delivery probability of:
Chapter 2. Opportunistic Routing Protocols

Figure 2.2: Path-based opportunistic example.

\[ P_{(src,dst)} = (1 - (1 - P_{(src,A)}) \times (1 - P_{(src,B)}) \times (1 - P_{(src,C)}) \times (1 - P_{(src,D)})) \]
\[ = (1 - (1 - 0.25)^4)) \approx 68\% \]

where \( P_{(A,B)} \) is the delivery probability from node \( A \) to node \( B \).

The relay node selection is crucial and has great effect on the network performance. In some OR schemes, the relay node selection can be optimized if sufficient information is proved. Usually this information regards the location of the nodes.

**Route selection.** An illustrative example of the route selection and the different paths towards the destination that an OR can provide is depicted in Figure 2.2. The links with the dots represent opportunistic links. A delivery probability \( P_{(i,j)} \) from node \( i \) to node \( j \), for each link has been assigned.

Traditional best path routing will always choose the most reliable links. This results in the path:

\[ src \rightarrow A \rightarrow B \rightarrow C \rightarrow D \rightarrow dst \]
which has end-to-end delivery probability \( (0.9)^5 \approx 59\% \), after 5 hops.

An OR scheme with the restriction of 3 hops has the following paths:

- **Path(1)**: \( src \rightarrow A \rightarrow C \rightarrow dst \)
- **Path(2)**: \( src \rightarrow B \rightarrow D \rightarrow dst \)
- **Path(3)**: \( src \rightarrow B \rightarrow C \rightarrow dst \)

The first path has probability of successful delivery:

\[ Path(1) = P_{(src,A)} \times (1 - (1 - P_{(A,C)} \times P_{(C,dst)})) \]
\[ = 0.9 \times (1 - (1 - 0.6 \times 0.6)) \]
\[ = 32.4\% \]
The other two paths have probability of successful delivery:

\[
Path(2,3) = P_{(src,B)} \times (1 - (1 - P_{(B,D)} \times P_{(D,dst)})) \times (1 - P_{(B,C)} \times P_{(C,dst)})
\]

\[
= 0.6 \times (1 - (1 - 0.54) \times (1 - 0.36)) \approx 42.3\%
\]

The overall probability of successful delivery of the above paths is:

\[
P_{(src,dst)} = 1 - ((1 - 0.324) \times (1 - 0.423)) \approx 60.9\%.
\]

From the previous two examples, it can be inferred that an efficient node selection and route selection through an OR scheme can improve the performance of a network in end-to-end packet delivery.

### 2.2 Classification of Opportunistic Protocols

In the design of any OR scheme the fundamental issues are [41]:

- the forwarder set selection,
- the prioritization of the forward set and
- the avoidance of duplicate transmissions.

![Figure 2.3: Classification of opportunistic routing and the different strategies.](image-url)
Especially the construction and ordering of the forwarder set has high impact on the network performance and is of crucial importance for the design of the scheme. The duplicate avoidance can either be part of these two strategies or a separate strategy. In this work, it is considered part of the prioritization step. By taking these three factors as different design strategies, in the following the current major OR schemes are further categorized. This classification is shown in Figure 2.3.

2.2.1 Forwarder Set Selection

The selection of the forwarder set is the first process in every OR scheme. This set includes the candidate nodes that compete to get the packet and become the next relay node. The forwarder set is a subset of the neighbour node set of each node. The forward set can change dynamically or remain the same during the network operation. Moreover, when the forwarder set has been selected, there are approaches that prioritize the nodes based on different metrics. However, there are approaches which follow a probabilistic model. In this section, these different approaches are discussed.

2.2.1.1 Updates of forwarder set

The forwarder set can be determined once and for all the packet transmissions, also referred as end-to-end selection [12, 42–45], or defined for every transmission on the fly on a per packet basis, known as hop-by-hop selection [13, 14, 16, 46–48].

The first approach can optimize the forwarder selection. However, this approach does not adapt to dynamic network changes, such as link quality or node availability. Moreover, it might lead to duplicate packet transmissions since non-neighbouring forwarders can make inconsistent decisions on packet forwarding.

On the other hand, the second approach is easy to be implemented and it scales well. Each packet holder determines independently its own forwarder set during the packet transmission. However, in a larger scale network this might introduce extra packet delay.

2.2.1.2 Forwarder candidate selection

Once a candidate node has received a packet, whether or not this node will become next relay node can be decided in a deterministic or a probabilistic way.

In a deterministic approach, the schemes can assign priority to every node [14, 43, 48]. In this case, the next relay node is based on the prioritization metrics, which is covered
in the following section.

In a probabilistic approach, the nodes independently decide the probability which they should act as the next relay node [44, 45]. This approach does not have any cooordination between the nodes. Hence, it is more resilient to highly lossy and uncertain wireless environments. However, the number of duplicates can increase dramatically, if the probability is not carefully selected.

### 2.2.2 Prioritization of the Forward Set

After the forwarder set has been selected, the nodes that belong to the set should be prioritized. There is a number of different metrics that can be used for prioritization. Moreover, the network information that each metric requires varies. In this section, some of the most commonly used metrics are covered. Also, the way some OR schemes make use of location information as part of the prioritization procedure is described. This section is concluded with a brief description on the coordination of the forwarder set.

#### 2.2.2.1 Metrics

The node priority assignment is performed according to their goodness to act as the next forwarding node. Over the years, a number of metrics have been used for this purpose. The routing performance is greatly affected on how these metrics integrated into the protocol design. Moreover, the accuracy of most of these metrics depends on the proper measurement and has high impact on the final forward set prioritization. The most commonly used metrics can be classified as follows:

- **Geo-distance.** It is also knows as packet advancement. It measures how close to the destination node $dst$, the packet will be if received by a candidate node $cnd$ [13,14]. It compares the distance from the source node $src$, to the destination node $dst$, and the distance from the candidate node $cnd$ to the destination node $dst$. It can be defined as:

$$d_{src,cnd} = dist(src,dst) - dist(cnd,dst)$$ \hspace{1cm} (2.5)

where $dist(i,j)$ represents the Euclidean distance between node $i$ and node $j$.

This metric requires the location information of nodes. The more accurate the location the better the performance of the metric. However, in networks with high
density and without advanced location estimation technologies, this metric might not be easily used.

- **Link cost.** It is based on the link reliability and properties. There are several link quality measurement mechanisms [29–32]. Some examples are the Packet Error Rate (PER), the Packet Reception Rate (PRR) and the delivery rate of a link. These values can be either estimated or self monitored from the network [49].

- **Hop-count.** It is the number of hops between the source and the destination [45, 47]. Some routing protocols in ad hoc networks focus on optimizing the number of hops between the source and the destination so the hop count is minimum. However, this approach might increase the physical distance between the nodes hence, it increases the PER. Moreover, the utilization of this metric requires an initialization phase to gather the necessary information.

- **Expected Packet Advancement (EPA).** It is an estimation of the packet progress towards the destination over different number of forwarding candidates [50, 51]. A generalized definition of EPA and its upper bound was examined in [21].

- **Expected Transmission Count (ETX).** It estimates the number of tries needed to successfully transmit a packet over a link [12, 42]. Following its definition in [52], if the sender node is src and the destination is dst, the ETX is defined as:

\[
ETX(src, dst) = \frac{1}{d_f \times d_r}
\]

where \(d_f\) is the delivery rate on the link from the sender to the destination and \(d_r\) is the reverse delivery ratio - the probability that the ACK packet is successfully received. Similar to hop-count, this metric also requires an initialization phase.

- **Expected Any path Transmissions (EAX).** This metric captures the expected number of transmissions following an opportunistic forwarding scheme. It was introduced in [53] and requires an initialization phase.

- **Normalized Advance (NADV).** This is a more general framework [49]. NADV normalizes various types of link cost such as transmission time, delay and power consumption. However, NADV did not consider simultaneous packet receptions from
one node neighbours and their ability for opportunistic forwarding. Hence, it applies to geographical routing which involves a single forwarding candidate. As a consequence, it cannot be directly used for geographical opportunistic routing.

- **Bit-meter advancement per second.** This metric is based on the transmission rate of the different available links. It is specially indicated when the network is supported with a wide variety of radio technologies. This metric was introduced in [54].

As it can be inferred, there is a wide range of metrics that can be used for prioritization. One of the most commonly used especially for WSNs, is the geo-distance. For this metric, the geographical location of the nodes is important. In general, the geographical location of the nodes can be used for different purposes during the design of the OR scheme. In the following, the OR schemes in those which make use of location information and those which they do not require any location information are separated.

### 2.2.2.2 Location information

The forwarder set selection and more important the prioritization process of a scheme may require location information regarding the nodes. Although most of those schemes make use of the geo-distance as described above, the accuracy and the size of the information has great impact on the final design.

There are schemes in which the prioritization is determined based on little or no global topology-based network state information. These OR schemes are known as location-based prioritization [13, 14, 16]. These schemes have better scalability for large-scale wireless networks and are easy to be implemented.

In contrast, the topology-based prioritization requires exact location information to enable opportunistic routing [12, 42, 48]. These schemes can optimize the network performance and perform better than the other approach. However, this approach is more complicated to implement and requires advanced capabilities of the nodes. Moreover, the required location information can increase the cost of the network, if advanced equipment is used.

### 2.2.2.3 Coordination of the forwarder set

The different OR schemes have different mechanisms on the way they perform the prioritization. The decision on the prioritization of the forwarder set can be made locally or
globally.

In the former mechanism the nodes need to cooperate on the prioritization. The nodes compete for the packet hence, these schemes tend to select the best node to become the next relay node [12, 43]. This prioritization mechanism gives the opportunity to each packet transmission to explore and find the best available relay node. However, it can introduce extra packet delivery latency.

In other mechanisms the cooperation is globally decided. A common approach is the Request to Send / Clear to Send (RTS / CTS) handshake [14, 47]. The candidate node that replies first with a CTS becomes the next relay node. This mechanism can avoid duplicates. Another mechanism is through the Acknowledges (ACKs). On the reception of the packet the nodes reply with an ACK in a predetermined order. The node which replies first becomes the next relay node and the other resign. However, this mechanism requires the candidate nodes to be neighbours in order to overhear the ACK transmission, otherwise there will be duplicates. Finally, there are mechanisms that do not require any coordination [42, 44, 45]. In these approaches the data packets are broadcasted which can largely ease the design of the MAC. It will however, increase the duplicate transmissions at the destination node.

2.3 Survey on Opportunistic Routing Protocols

This section is a brief description of the most well known and used opportunistic routing protocols.

During the last decade, a number of opportunistic protocols have been developed. The first opportunistic routing has been introduced in [12]. Extremely Opportunistic Routing (ExOR) selects the next relay node by a slotted ACK mechanism. Having successfully received a data packet, the node calculates a priority level, which is inversely proportionate to the Expected Transmission count metric (ETX) [55], which is based on the distance between the node and the destination. The shorter the distance, the higher the priority. The node with the highest priority will then be selected as the next relay node. The main drawback of ExOR is that it prevents spatial reuse because it needs global coordination among the candidate nodes. Candidate nodes transmit in order, only one node is allowed to transmit at any given time while all the other candidate nodes try to overhear the transmission in order to learn which node will be the next relay node. Moreover, the simple priority criteria that it uses (ETX distance), may lead
packets toward the destination through low-quality routes. To overcome this problem, Opportunistic Any-Path Forwarding (OAPF) [46] introduces an expected any-path count (EAX) metric. This can calculate the near-optimal candidate set at each potential relay node to reach the destination. However, it needs more state information about the network and it has high computational complexity.

ExOR ties the MAC with routing, imposing a strict schedule on routers access to the medium. The scheduler goes in rounds. MAC-Independent Opportunistic Routing and Encoding Protocol (MORE) [42] tries to enhance ExOR. MORE uses the concept of innovative packets in order to avoid duplicate packets which might occur in ExOR.

In [14, 16] a Geographic Random Forwarding (GeRaF) technique was proposed. In GeRaF each packet carries the location of the sender and the destination and the prioritization of the candidates nodes is based on location information. This technique is simple to be implemented, but it requires location information for all the nodes in the network. Hybrid ARQ-Based Intercluster Geographic Relaying (HARBINGER) [13] is a combination of GeRaF with hybrid automatic repeat request (ARQ). In GeRaF, when there is no forwarder within the range of the sender node, everything must start over again while in HARBINGER hybrid ARQ is used for a receiver to combine the information accumulated over multiple transmission from the same sender.

Geographical Opportunistic Routing (GeOpps) [56], for vehicular networks tries to exploit the available information in modern vehicles along with an opportunistic routing in order to select the next carrier efficiently. In [57], Simple Opportunistic Adaptive Routing (SOAR) was introduced. SOAR incorporates an adaptive forwarding path selection along with a priority timer-based forwarding, local loss recovery and adaptive rate control to achieve high throughput to the current network conditions. GeOpps introduces the use of Minimum Estimated Time of Delivery for the packet (METD) which is based on the Estimated Time of Arrival (ETA) and the geo-distance of the vehicles.

Least-Cost Opportunistic Routing (LCOR) [58], tends to compute the optimal choices of candidate relays. It also defines the Anycast Link Cost (ALC) metric which generalizes the ETX and also the Remaining Path Cost (RPC) to prioritize the routes. However, it needs to enumerate all the neighbouring node combinations to get the least cost OR paths.

A number of other opportunistic routing protocols have been proposed [43–45, 47, 48, 59]. A cooperative opportunistic routing scheme was introduced in [59]. In Cooperative Opportunistic Routing Scheme in Mobile Ad Hoc Networks (CORMAN), the nodes
in the network use a lightweight proactive source routing protocol to determine a list of intermediate nodes that the data packets should follow en route to the destination. Coding-Aware Opportunistic Routing Mechanism (CORE) \cite{48, 60} is an integration of localized interflow network coding and opportunistic routing. By integrating localized network coding and opportunistic forwarding, CORE enables a packet holder to forward a packet to the next hop that leads to the most coding changes among its forwarder set. Opportunistic Routing in Dynamic Ad Hoc Networks (OPRAH) \cite{43} builds a braid multi-path set between source and destination via on-demand routing to support opportunistic forwarding. For this purpose, OPRAH allows intermediate nodes to record more subpaths back to the source and also those subpaths downstream to the destination via received Route Request and Route Replies. Resilient and Opportunistic Routing Solution For Mesh Networks (ROMER) \cite{44} builds a forwarding mesh on the fly and on a per packet basis.

### 2.3.1 Opportunistic Routing Classification Table

Table 2.1 has the classification of the opportunistic routing protocols as described above.

### 2.4 GEographical Opportunistic Routing

Geographic forwarding, prioritizes the candidate nodes according to their geographical location. Nodes that are closer to the destination have higher probability of becoming the next relay node. In this section, a Geographical Opportunistic Routing (GEOR) approach is introduced. The idea behind GEOR is similar to many other approaches such as in \cite{14, 16, 61}. The difference is on the prioritization process. In order to prioritize the nodes, GEOR uses a backoff time $T_{b_{GEOR}}$ as in \cite{62}. This time is inversely proportional to the distance between the source node $src$, and the candidate node $cnd$, as follows:

$$T_{b_{GEOR}} = \frac{C_{GEOR}}{d_{src,cnd}} + SIFS, \quad \hat{D}_{src,cnd} \leq \text{Range}$$

(2.7)

where $C_{GEOR}$ is a constant related with the transmission range of each node, Short Interframe Space (SIFS) is the small time interval between the DATA and its ACK, and $d_{src,cnd}$ is the packet advancement as in Eq.1.1. $\hat{D}_{i,j}$ is the estimated distance between node $i$ and node $j$ and is defined as:
Table 2.1: Classification of opportunistic routing protocols.

\[
\hat{D}_{src,cnd} = 1 + |dist(src, cnd) - dist(cnd, dst)|, \quad src \neq cnd
\]  

It is important that the \( cnd \) node belongs in the candidate node set \( K_{src} \) of the source node. For instance, in Figure 2.4 nodes \( B \) and \( C \) are at the same absolute distance from the source node \( src \). Hence, Eq.(2.7) should apply only to candidate nodes. To cope with
Chapter 2. Opportunistic Routing Protocols

Figure 2.4: Example of estimated distance calculation to form the candidate set. Links show the approximate distance between the source node src, and the neighbour nodes while links with dots represents the approximate distance of each node from the destination node dst.

To address this problem, during the initialization phase, the source node src defines and prioritizes its candidate set according to the estimated distance as in Eq. (2.8).

As it can be illustrated in Figure 2.4, with the use of Eq. (2.8) the transmitter node can find the node that is in greatest distance in the transmission range of the source, but is also located toward the destination, hence it belongs to its candidate set. In this example, candidate node B and node C are in the same distance from the source node src. The use of the absolute distance between the transmitter and the candidate node will not be helpful. However, following Eq. (2.8):

\[
\hat{D}_{src,A} = 1 + |10 - 5| = 6
\]

\[
\hat{D}_{src,B} = 1 + |10 - 30| = 21
\]

\[
\hat{D}_{src,C} = 1 + |10 - 10| = 1
\]

As a consequence, nodes A and C belong to candidate set \( K_{src} \). Moreover, node C has the shortest backoff time and will reply first with a CTS. If the transmission fails, node A will reply while node B will not participate since \( \hat{D}_{src,B} > Range \) and consequently it does not belong in the candidate set.

As it can be inferred from Eq. (2.7), the closer the candidate is to the destination, the smaller the backoff time. After that time, the node will reply with a CTS. On the reception of the first CTS packet, the source node will forward DATA packet to this
Algorithm 1: Geographical forwarding.

1 if (isRTS(rts)) then
2     \( T_{RTS} = \text{CalculateBackoff}() \);
3     wait(\( T_{RTS} \));
4     Channel = ChannelSensing();
5     if (Channel == IDLE) then
6         SendCTS(rts.SenderNode);
7         interval = \( T_{DATA} \);
8         reason = Listen(interval);
9         if (reason == DATA) then
10            SendACK(DATA.SenderNode);
11        else
12            GoToSleepMode();
13        end
14    else
15        GoToSleepMode();
16    end
17 end

node and will ignore any of the following CTS packets for this DATA packet. Algorithm 1 illustrates the process.

2.4.1 Scalability of GEOR

In this section, the scalability of GEOR is examined. The network performance of traditional and opportunistic routing is compared, with respect to energy consumption and throughput under different network density, as in [62].

The network simulation was performed via the discrete event simulation system OMNeT++ [63]. The sensor nodes were uniformly randomly distributed over a \( 100 \times 100(m^2) \) network field. The number of the nodes in the field were 40, 80, 120, 160 and 200, leading to 5 different network topologies. Figures 2.5(a) - 2.5(e) shows the topologies.

During the simulation, the traditional route is identified by global optimization, and therefore, is the best route available. A global scheduler is implemented during the initialization phase in order to avoid collisions. The results can be an upper-bound for traditional routing protocols.
Each node has a transmission range of 12 meters. The communication parameters were chosen based on IEEE 802.15.4, while the simulation parameters are listed in Table 2.2. For traditional routing, the reliability threshold was set at $T_{PRE} = 20\%$ while for opportunistic routing a reliability threshold was set at $T_{PRE} = 80\%$.

2.4.1.1 Throughput

Throughput is the number of bits divided by the time needed to transport the bits. From the source node 100 packets were transmitted toward the destination. For each network density, the simulation runs 10 times. The average throughput for each density can be seen in Figure 2.6.

In traditional routing, the next node selection is based on the link quality. The transmitter will forward the packets to the neighbour node that is closer to the destination and over the link that has a PER smaller than the reliability threshold, $T_{PRE}$. As the number of the nodes in the network is increased, there are more nodes between the source and the destination and the average number of neighbour nodes is increased. Hence, there are more nodes that are closer to the destination and have PER smaller than the reliability threshold. Traditional routing find those nodes during the initialization phase.
and create a new routing path. That path will have the same or smaller number of hops toward the destination and will lead to less packet losses due to the more reliable links that it will be using. As a result, the throughput is increased.

In opportunistic routing the next relay node changes dynamically according to the network condition in each time slot. In a packet transmission, the next relay node is selected according to the link reliability at that time and node distance from the destination. Since the link reliability changes following the network conditions, opportunistic
routing can discover many different paths. Some of those paths will require less hops, toward the destination, than traditional routing. Moreover, consequent packet transmissions can follow different paths. If a node is busy, the transmission process will not need to wait as in traditional routing, till the node is available again. Other nodes can serve as relay nodes. In this way, the number of the packets that have been transmitted after a time $t$ is higher than the number of the packets that have been transmitted in the same time in traditional routing. The throughput in opportunistic routing is always higher than traditional for the same network density.

As the density is increased, there are more paths towards the destination with less hops. Opportunistic routing tends to discover most of those paths, increasing the throughput. Furthermore, the average number of neighbour nodes is also increased, hence during a packet transmission, the transmitter will have a wider range of available next relay nodes to select. In every time slot, there will be a packet transmission, decreasing the total time spent in buffering the packets in the nodes and increasing the throughput.

2.4.1.2 Energy consumption

Energy consumption is the total power that is needed from all the nodes in the network. From the source node 100 packets were transmitted towards the destination. Let the node power consumption in transmitting and receiving/idle modes be denoted as $P_t$ and $P_r/i$ respectively. The sleeping mode power consumption is practically 1000 times smaller than $P_t$ and $P_r/i$, which is negligible. Let $P_t = 15$mW and $P_r/i = 10$mW. For each network density, the simulation runs 10 times. The average energy for each density can be seen in Figure 2.7.

Traditional routing uses the same nodes for every packet transmission. As the network density is increased, the hops required for a packet to reach the destination are decreased. The number of the nodes that are required for a packet transmission is decreased leading to a decrease in the network energy consumption. However, when one of the nodes in the predetermined path is busy, the total packet transmission will be delayed. The nodes will have to remain active longer, consuming more energy.

Opportunistic routing copes with this problem by using different nodes. As a result, in a specific network density, the nodes have to remain active for less time with opportunistic than with traditional routing. Moreover, as the density increases, more nodes can be served as the next relay node while more paths with less hops can also be followed. In
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2.4.2 An Angle-based Dynamic Routing Scheme

In this section, an Angle-based Dynamic Routing Scheme (ADRS) is designed to extend the network lifetime in WSNs, as in [64]. ADRS is an extension of GEOR. The introduced scheme uses the location information of the nodes and calculates the inclination angle formed between the transmitter and the receiver and the transmitter and the destination to form a candidate set of neighbour nodes to forward the packet. One of the nodes in the candidate set is selected randomly and becomes the next relay node. The candidate set changes at every packet transmission, leading to multiple paths towards the destination. The candidate set is formed based on an inclination angle that can be used to control the latency of the protocol.

2.4.2.1 Scheme description

In ADRS, when a node has a packet to transmit it floods a Request To Send (RTS) message to all the neighbour nodes in the transmission range, $r_2$. On reception of the Clear To Send (CTS) messages from the neighbour nodes, the node calculates the distance to the neighbour node and the inclination angle $\phi$ between the source node and the
neighbour node with respect to the destination node, as shown in Figure 2.8. If the distance to the neighbour node is larger than a predefined distance $r_1$ and the inclination angle does not exceed a predefined angle $\theta/2$, the neighbour node is added to the candidate node set.

The nodes can reply with a CTS message after time $T_{\text{GEOR}}$ as in Eq. (2.7), which is inversely proportional to the distance between the sender node and the responding node. Following this approach, the sender node will receive the first CTS message from the neighbour node that is closest to the destination. At the same time and after receiving all the CTS messages, the sender node can prioritize the nodes in the candidate set with respect to their distance from the destination. In a network with high density, when the sender node waits for all the CTS messages, the energy consumption and the packet latency increase. Instead of waiting for all the CTS messages, the sender node can wait only for $C$ CTS messages and form the candidate set.

From the $C$ nodes in the candidate set, one will be selected randomly to be the next relay node. The next relay node will follow the same routing principles until the packet reaches the destination. Figure 2.8 depicts one step of the routing process.

The use of the RTS/CTS handshake also helps the network to quickly adapt to any changes in the number of the nodes in the network area. If a node leaves the network, this node will not participate in the handshake, whereas if a node joins the network it can acquire relative location information from its neighbour nodes. This way, there is no need for an initialization phase every time the source node or the network density changes.

The selection of $r_1$ and $\theta$ is important in ADRS. A small value of $r_1$ will increase the size of the candidate nodes set, but many candidate nodes will be close to the source node. Hence, the number of hops needed to reach the destination will increase, increasing the packet latency as well. On the other hand, a large $r_1$ will limit the number of candidate nodes. Therefore, the network density should be sufficient to guarantee connectivity. Similarly, a small inclination angle will require a higher network density while a large inclination angle might lead to paths that are of large distance from the shortest path, hence increasing the number of hops.
2.4.2.2 Selection of the next node

To determine the next node where a packet will be sent, a given node applies two criteria. First, the node should be at distance $R$ satisfying $r_1 \leq R \leq r_2$, where $r_2$ is typically the transmission range. Moreover, as can be seen in Figure 2.8, the inclination angle $\phi$ that is formed between the segment $CD$ connecting the current node $C$ to the destination node $D$ and the segment $CT$ connecting the current node $C$ to the candidate node $T$ should not exceed a given value $\theta/2$.

**Definition:** The inclination angle $\phi$ between any node and a neighbour node $T$ in the network is the angle formed by the line that connects the node and the neighbour node $T$ and the line that connects the node and the destination node $D$.

The value of $R$ is determined based on the topology of the network. $R$ is random, since the topology is random, but once the topology has been fixed it is assumed that a node knows or can determine its distance to its neighbour nodes.

The angle can be found using the inner (dot) product between two vectors. Let $\mathbf{v}_{CD}$ and $\mathbf{v}_{CT}$ be the vectors connecting a node $C$ to the destination $D$ and to a candidate node $T$ respectively, as shown in Figure 2.8. $\mathbf{v}_{CD}$ and $\mathbf{v}_{CT}$ can be calculated easily using the coordinates of points $C$, $D$ and $T$. Then
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2.4.2.3 Mean number of hops

Since it is assumed that the nodes follow the 2-dimensional Poisson distribution, they are uniformly distributed in the $x - y$ plane. Each node $C$ selects its neighbours based on their distance and the inclination angle. It is necessary to calculate the distribution of the distance by which a packet advances towards the destination at each hop. First, the distribution of the distance $R_i$ between the current node and the next node is calculated.

For simplicity from now on it is omitted the hop index, $i$, from $R$ and all other related quantities. Because the nodes follow the Poisson distribution and because the algorithm only selects nodes that form a maximum inclination angle $\pm \frac{\theta}{2}$, the angle $\phi$ of Figure 2.9 is uniformly distributed in the interval $\left[-\frac{\theta}{2}, +\frac{\theta}{2}\right]$. On the other hand, the distribution of $R$ can be found as follows:

\[ F_R(r) = \Pr\{R \leq r\} = \frac{\frac{r^2 \theta}{2} - \frac{r_1^2 \theta}{2}}{\frac{r_2^2 \theta}{2} - \frac{r_1^2 \theta}{2}} = \frac{r^2}{r_2^2} - \frac{r_1^2}{r_2^2}, \quad r \in [r_1, r_2]. \] (2.10)
In Eq.(2.10) the fact that the probability of finding a node in a given region is proportional to the area of the region was used, and the restriction imposed from the algorithm that the selected node be at a distance satisfying \( r_1 \leq R \leq r_2 \). Therefore, the probability density function equals:

\[
f_R(r) = \frac{d}{dr} F_R(r) = \frac{2r}{r^2_2 - r^2_1}, \quad r \in [r_1, r_2].
\]

Now, let \( R_a \) be the projection of \( R \) on the segment \( CD \) connecting the node to the destination, as shown in Figure 2.9. This is the distance by which the packet advances towards the destination along \( CD \) during a given hop. Clearly,

\[
F_{R_a|\phi}(r_a|\phi) = \Pr\{R_a \leq r_a|\phi\}
= \Pr\{R \leq \frac{r_a}{\cos(\phi)}\} = F_R\left(\frac{r_a}{\cos(\phi)}\right) = \frac{r^2_a - r^2_1}{r^2_2 - r^2_1}, \quad r_a \in [r_1 \cos(\phi), r_2 \cos(\phi)].
\]

Hence,

\[
f_{R_a|\phi}(r_a|\phi) = \frac{2r_a}{\cos^2(\phi)(r^2_2 - r^2_1)}, \quad r_a \in [r_1 \cos(\phi), r_2 \cos(\phi)].
\]

Given Eq.(2.13) the expectation of \( R_a \) can be calculated.

\[
\mathbb{E}[R_a] = \mathbb{E}_\phi[\mathbb{E}[R_a|\phi]]
= \mathbb{E}_\phi \left[ \int_{r_1 \cos(\phi)}^{r_2 \cos(\phi)} \frac{2r_a}{3 \cos^2(\phi)(r^2_2 - r^2_1)} dr_a \right]
= \mathbb{E}_\phi \left[ \frac{2r^3_a}{3 \cos^2(\phi)(r^2_2 - r^2_1)} \right]_{r_1 \cos(\phi)}^{r_2 \cos(\phi)}
= \mathbb{E}_\phi \left[ 2 \cos(\phi)(r^3_2 - r^3_1) \right]_{r_1 \cos(\phi)}^{r_2 \cos(\phi)}
= \frac{2(r^3_2 - r^3_1)}{3(r^2_2 - r^2_1)} \int_{-\theta/2}^{+\theta/2} 1 \cos(\phi) d\phi
= \frac{2(r^3_2 - r^3_1)}{3(r^2_2 - r^2_1)} \frac{\sin(\theta/2)}{\theta/2}.
\]

Therefore, the average projection of the distance that a packet covers towards the destination on the segment \( CD \) of Figure 2.9 is given by Eq.(2.14). If the packet is not very close to the destination, \( \tilde{R} \) in Figure 2.9 is approximately \( ||CD|| - R_a \). Hence, \( R_a \) is approximately equal to the distance by which the packet advances towards the
destination. Clearly, the accuracy of this approximation worsens as the packet nears the destination, and $\tilde{R} > \|CD\| - R_a$. However, it will be good for the majority of the hops towards the destination.

If the distance between the source and the destination is equal to $\|SD\|$, the average number of hops can be approximated by

$$\bar{H} = \frac{\|SD\|}{\mathbb{E}[R_a]}.$$  \hspace{1cm} (2.15)

Even if the value of $\mathbb{E}[R_a]$ were exact, the average latency from Eq.(2.15) would not be perfectly accurate either, since in the last hop when the last intermediate node locates the destination it will send the packet deterministically to the destination. However, as will be shown in later Section 2.4.3, leads to an estimate of the average number of hops that, although slightly optimistic, is fairly accurate.

### 2.4.2.4 Minimum and maximum number of hops

The minimum number of hops can be found easily by assuming that during each hop the packet progresses along the segment $SD$ of Figure 2.9 and by the maximum distance, $r_2$. Hence,

$$H_{\text{min}} = \frac{\|SD\|}{r_2}.$$ 

Similarly to the calculation of the average latency, the maximum latency can be approximated by assuming that $\tilde{R} \approx \|CD\| - R_a$, that the packet moves by the minimum allowed distance $r_1$ and that at every hop the packet moves away from the segment $SD$ with the largest possible angle. For the worst-case angle $\theta/2$, $R_a = r_1 \cos(\theta/2)$. Thus,

$$H_{\text{max}} \approx \frac{\|SD\|}{r_1 \cos(\theta/2)}.$$ 

### 2.4.3 Performance Analysis

ADRS is compared with traditional routing in terms of the average packet latency for different source-destination distances.

The latency of a packet depends on the length of the path that the packet follows towards the destination. The path can also be described in terms of the number of hops. The packet latency is equal to the number of hops that a packet needs to reach the destination. Figure 2.10 shows the average packet latency of the two algorithms as well as the theoretical mean for ADRS as calculated in Section 2.4.2.3. It can be seen that
Figure 2.10: Average packet latency over different distances.

the theoretical mean is slightly optimistic but very close to the simulation results. ADRS has lower packet latency than PSRS. This is because ADRS always uses nodes located towards the destination. Following the inclination angle approach, these nodes do not deviate significantly from the shortest path. Hence, the number of the hops is close to optimal.

2.5 Impact of the Next Node Selection Criteria

In this section, the effects of different next node selection criteria on the forward set prioritization and consequently on the network performance is examined, as in [22]. Three routing approaches are presented along with their routing algorithm and simulation results. The approaches are compared with geographical routing, as presented in Section 2.4, in terms of energy consumption, delivery ratio and average packet latency. The simulation results show that the selection criteria have a high impact on the performance of a dynamic multi-path routing scheme. As a consequence, different selection criteria can be used for different network applications.
2.5.1 Delivery-based Protocols

Delivery-based forwarding uses the PRR values (or similar metrics such as PER in [62]) to prioritize the candidate node list. To simulate a realistic channel model with Binary Phase-Shift Keying (BPSK) without channel coding, the log-normal shadowing path loss model derived in [65] was used:

\[ PRR(L_f, d) = (1 - \frac{1}{2} \exp^{-\frac{\gamma(d)}{0.64}})^8\rho L_f \]  \hspace{1cm} (2.16)

where \( L_f \) is the length of the frame, \( d \) is the distance between the transmitter and the receiver, \( \gamma(d) \) is the Signal to Noise Ratio (SNR) and \( \rho \) is the encoding ratio. This model considers several environmental and radio parameters, such as the path-loss exponent (\( \alpha \)) and log-normal shadowing variance (\( \sigma \)) of the environment, and the modulation and encoding schemes of the radio\(^1\).

On the reception of a CTS packet, the source node can extract useful information from the Received Signal Strength Indicator (RSSI) of the packet. This value can be used in Eq.(2.16) in order to calculate the PRR probability. According to this value, the source node can prioritize the candidate nodes.

There can be different implementations of the delivery-based approach. In one implementation, the source node can wait for all the candidates to reply with a CTS, and prioritize all the available links according to the PRR. In this case, the source node should have a waiting time which is related to the transmission range and the average number of neighbour nodes. However, if the network density is high, the source node will have to wait for many nodes to reply. As a result, the energy consumption increases.

Another implementation can use a threshold. The node that will reply first with a PRR value which satisfies a predefined threshold \( T_{h_{PRR}} \), will become the next relay node with the source node ignoring all the following CTS packets. In this second approach, the threshold should be carefully selected and it is based on the QoS requirements of the application. Algorithm 2 illustrates the process.

2.5.2 Memory-based Protocols

In this approach, the source node avoids using the same node for sequential packet transmissions. On the transmission of a packet, the source node keeps the ID of the relay

\(^1\)Please refer to [65] for a complete description of the model.
Algorithm 2: Delivery-based forwarding.

1 if (isCTS(cts)) then
2     if (cts.RSSI ≥ \( T_{h_{PRR}} \)) then
3         SendDATA(cts.SenderNode);
4     else
5         UpdatePRRvalue(cts.RSSI);
6     WaitForCTS;
7 end

node in a list. The next time the source node has a packet to transmit, on the reception of the CTS, it tries to forward the packet to a candidate node that is not on the list, i.e. it has not participated in previous packet transmissions. Only if this candidate node is on the list and is the only neighbour node, will the source node forward the DATA packet again to the same node. The size of the list is important on this approach. Moreover, the nodes should have sufficient memory to store this information.

Another way to implement a routing following this approach is with the use of a flag in the relay node. On the reception of a DATA packet, the relay node raises a flag. While the flag is on, this node does not participate in any transmission. The time that the flag will remain on can be related with the energy levels of the node. For instance, in a WSN where the energy for the nodes is derived from external sources (solar power, thermal energy, wind energy), the use of the flag can be carefully designed in order to give sufficient time to a node to perform energy harvesting and reach acceptable energy levels. Algorithm 3 illustrates the process.

2.5.3 Probabilistic Protocols

Probabilistic forwarding is used in highly lossy environments. The probability with which a candidate node will be chosen as a relay node, is independently decided. In one approach of this category, the source node can wait for all the CTS packets and then randomly choose the next relay node. The main drawback of this approach is that the selection criteria are completely random. Moreover, the source node has to wait for all the CTS packets and this increases the energy consumption per node and consequently the total energy consumption. Algorithm 4 illustrates this process.
Algorithm 3: Memory-based forwarding.

1 if (isRTS(rts)) then
2   if (flag!=TRUE) then
3     \[ T_{RTS} = \text{CalculateBackoff}(); \]
4     wait(T_{RTS});
5     Channel=ChannelSensing();
6     if (Channel==IDLE) then
7       SendCTS(rts.SenderNode);
8       interval=T_w;
9       reason=Listen(interval);
10      if (reason==DATA) then
11         SendACK(DATA.SenderNode);
12         flag==TRUE;
13      else
14         GoToSleepMode();
15      end
16   else
17     GoToSleepMode();
18   end
19 else
20   flag==FALSE;
21   GoToSleepMode();
22 end

A combination of geographical and probabilistic forwarding can deliver an efficient approach. On the reception of the CTS packet from the source node src, the candidate node cnd, will wait for time \( T_{bGEO} \) as in Eq.(2.7), along with a random interval, hence:

\[
T_{bGEO} = \frac{C_1\text{GeoProb}}{d_{src,cnd}} + C_2\text{GeoProb} \times \text{rand}(0,1) + SIFS, \; \text{cnd} \neq \text{dst} \quad (2.17)
\]

The selection of constants \( C_1\text{GeoProb}, \; C_2\text{GeoProb} \) is also important. If \( C_1\text{GeoProb} \leq C_2\text{GeoProb} \), the forwarding is based more on the location information while if \( C_1\text{GeoProb} \geq C_2\text{GeoProb} \), the forwarding is based more on the randomness. In any case, both the location information and the randomness are taken into consideration for the prioritization of the
Algorithm 4: Probabilistic-based forwarding.

```
if (isNewMessage(msg)) then
    BroadcastRTS();
    interval=TRA;
    reason=Listen(interval);
    while (reason!=TRA) do
        if reason==CTS then
            relaycandidateList.push(CTS.SenderNode);
        else
            BroadcastRTS();
            interval=TR;
            reason=Listen(interval);
        end
    end
    RelayNode= relaycandidateList(intrand(relaycandidateList.size()-1))
    SendMessage(msg,RelayNode);
    interval=TA;
    reason=Listen(interval) ;
    while (reason!=ACK) do
        SendMessage(msg,RelayNode);
        interval=TA;
        reason=Listen(interval) ;
    end
    GoToSleepMode();
end
```

candidate list. Algorithm 5 illustrates this process.

### 2.6 Performance Evaluation and Simulation Results

To evaluate the performance of the different approaches, simulations using OMNET++ [63] were pursued, followed by a discussion on the results. The different approaches were compared in terms of energy consumption, delivery ratio and average packet latency. Then, the performance of each approach and its potential application is discussed.
Algorithm 5: Geo-probabilistic forwarding.

1. if \( \text{isRTS}(\text{rts}) \) then
2. \( T_{\text{RTS}} = \text{CalculateBackoff}(); \)
3. wait\( (T_{\text{RTS}}) + \text{dbrand}(0,1); \)
4. Channel = ChannelSensing();
5. if \( (\text{Channel} == \text{IDLE}) \) then
6. SendCTS(\text{rts}.SenderNode);
7. interval = \( T_{\text{DATA}}; \)
8. reason = Listen(interval);
9. if \( (\text{reason} == \text{DATA}) \) then
10. SendACK(\text{DATA}.SenderNode);
11. else
12. GoToSleepMode();
13. end
14. else
15. GoToSleepMode();
16. end
17. end

2.6.1 Simulation Environments

The distance between the source and the destination is measured in hops. The number of the hops is decided through a simple traditional routing scheme, where each node forwards the packet to the closest neighbour node. For geographical forwarding it is assumed \( C_{\text{GEOR}} = 1 \). For delivery-based forwarding a high threshold equal to 80\% is assumed and for geo-probabilistic \( C_{1_{\text{GeoProb}}} = 1 \) and \( C_{2_{\text{GeoProb}}} = 1 \) are set so the location and the random factor are equally weighted. Communication parameters were chosen based on IEEE 802.15.4. The rest of the simulation parameters can be seen in Table 2.3.

2.6.2 Results and Analysis

Geographical forwarding, delivery-based, memory-based and geo-probabilistic routing are evaluated, in terms of energy consumption, delivery ratio and average packet latency.
### Chapter 2. Opportunistic Routing Protocols

#### Table 2.3: Simulation parameter for the four approaches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission range (Range)</td>
<td>m</td>
<td>12</td>
</tr>
<tr>
<td>Number of nodes</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Length of DATA packet ($L_d$)</td>
<td>bits</td>
<td>128 × 8</td>
</tr>
<tr>
<td>Length of ACK packet ($L_A$)</td>
<td>bits</td>
<td>8 × 8</td>
</tr>
<tr>
<td>Power consumption in transmitting ($P_t$)</td>
<td>mW</td>
<td>15</td>
</tr>
<tr>
<td>Power consumption in receiving and idling ($P_{r/i}$)</td>
<td>mW</td>
<td>10</td>
</tr>
<tr>
<td>$C_{GEOR}$</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Delivery-based forwarding threshold ($T_{h_{PRR}}$)</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td>$C_{1_{GeoProb}}/C_{2_{GeoProb}}$</td>
<td></td>
<td>1/1</td>
</tr>
</tbody>
</table>

#### 2.6.2.1 Energy consumption

Let the node power consumption in transmitting and receiving/idle modes be denoted by $P_t$ and $P_{r/i}$ respectively. The sleeping mode power consumption is practically 1000 times smaller than $P_t$ and $P_{r/i}$ which is negligible. Figure 2.11 shows the simulation results.

When the distance between the source and the destination is small, all the approaches have similar performance. However, when the distance increases, geographical and geo-probabilistic forwarding have better performance in terms of energy consumption. This is mainly because these two approaches try to find the node that is closer to the destination to forward the packet. As a consequence, in every packet transmission, the best available path at the time of the transmission, with the minimum number of hops is followed. Since geo-probabilistic forwarding has some randomness on the selection criterion, the source node has to remain active for a bit longer than in geographical forwarding. This can explain the small difference between the two approaches.

On the other hand, memory-based forwarding tends to avoid using the same nodes for sequential packet transmissions. Consequently, the best available path will only be selected a number of times and not always. Paths which lead to more hops towards the destination will be selected, increasing the total energy consumption. Delivery-based forwarding has the worst performance over all the other approaches. In this approach, the source node has to remain active for a long time in order to collect all the CTS packets. As a result, the energy consumption per packet is increased, increasing also the
total energy consumption.

2.6.2.2 Delivery ratio

Delivery ratio can be used as a metric for the number of the successfully transmitted packets. Delivery ratio is crucial in monitoring applications where all the messages should arrive to the destination correctly and on time. Figure 2.12 shows the results.

In general, delivery ratio drops when the distance between the source and the destination increases. This is primarily because of the traffic collisions and the packet losses caused by the high traffic volume. As the source-to-destination distance increases, geographical forwarding and geo-probabilistic forwarding performs worse than the other approaches. These two approaches tend to use the same node for message transmission leading to more collisions. As the number of the nodes that could participate in each transmission increases more packet losses and collisions take place. Geo-probabilistic forwarding performs a little better because of the random criteria for the next relay node. Memory-based forwarding manages to avoid most of the collisions because not all the nodes participate in the RTS/CTS handshake. Hence, the performance of this approach is better than the other two. Moreover, all these approaches might use unreliable links and many retransmissions will be required.

In contrast, delivery-based forwarding performs better than all the other approaches.
The use of the RSSI value as an indicator for the link reliability leads to a high delivery ratio. Only the most reliable links are selected and the packets are delivered to the destination without any packet lost.

2.6.2.3 Average packet latency

Packet latency is the number of hops that a message follows towards the destination. In our simulation, the source sent 1000 packets towards the destination. Figure 2.13 shows the results for the average packet latency of the four opportunistic approaches.

Geographical and geo-probabilistic forwarding have similar performances. Since location information is included in the selection criterion of these two approaches, their performance is better than the other two approaches. They try to use the shortest available path in every packet transmission by using the nodes that are closer to the destination.

Memory-based forwarding has worse performance than the previous two approaches. Even if this approach manages to follow the shortest path for a packet transmission, this path will not be followed for sequential packet transmissions, hence the packet latency is higher. Delivery-based forwarding has the worst performance over all the approaches. In this approach, the link that is more reliable is followed. It is expected that the more reliable link will be over the closest neighbour node. Although the packet will be
transmitted with high PRR, the progress of the packet towards the destination will be small. As a consequence the average packet latency is higher.

2.6.3 Discussion

The selection criteria has great impact on the obtained results. The routing approach should carefully design the selection criteria following the Quality of Service (QoS) of the application. For instance, in a WSN where the replacement of the batteries of the nodes is impossible, the first two approaches (geographical and geo-probabilistic) can be used because of the low energy consumption. However, these two approaches will keep using the same nodes while they also require some location information which can not always be available. If the sensors are also self-powered and their energy is derived from external sources, the memory-based approach can be used. This approach will not use the same nodes for every packet transmission and it will give all the nodes sufficient time to replenish their energy levels.

In a monitoring application, the geographical and geo-probabilistic approach can also deliver better results in terms of packet latency. The packets will arrive at the destination on time, which is important in such an application. On the other hand, in a complex indoor environment with high dynamic and lossy wireless links, due to obstacles, dis-
tractions etc. the delivery-based approach might be followed since it can guarantee the delivery of all the packets to the destination.

2.7 Summary

In this chapter, the main principles of OR were described. The mechanisms that required to design an OR and their advantages over traditional routing were illustrated. The different OR approaches were categorized and briefly described. Then, the scalability of geographical OR was examine along with another version which uses inclination angels. The algorithms and simulation results of three different OR approaches were provided. The different approaches were compared in terms of energy consumption, delivery ratio and packet latency. Finally, their potential applications were discussed. These unveiled properties of OR will enable us to design an efficient routing protocol following the energy requirements of Self-Powered WSNs.
Chapter 3

Opportunistic Spectrum Access

This chapter describes the main principles of Opportunistic Spectrum Access (OSA). It starts with a taxonomy of the different dynamic spectrum access strategies and gives a brief description of each strategy. Cognitive radio and cognitive networking are also described. Next, OSA and its design challenges are covered. Then, a survey on the OSA protocols is provided and some protocols are described. The advantages of OSA are important and can help in the design of energy efficient WSNs.

This chapter focuses on OSA and cognitive networking. Two different OSA protocols are examined and compared with single channel traditional and single channel opportunistic routing. The main focus is on the impact of spectrum awareness in the total energy consumption of the network. All the protocols that are presented in this chapter are examined through simulations in terms of energy consumption, throughput and delay.

3.1 Dynamic Spectrum Access

When spectrum allocation is based on services – e.g. land mobile, public safety and broadcast television – and regulations forbid a device from using an empty portion of the spectrum, this regulation regime results in large portion of unused spectrum. In a number of instances the spectrum is only used for small periods of time. Actual spectrum usage measurements obtained by FCC’s Spectrum Policy Task Force [66] point out that the majority of the time, the allocated spectrum lies idle. This indicated that the shortage of spectrum is provoked from inefficient spectrum management policies.

Meanwhile, the use of wireless communications continues to grow at a rapid pace, both in terms of number of users and their airtime. WSNs are increasingly gaining impact on
our day to day lives. They are finding a wide range of applications in various domains, including health-care, assisted and enhanced-living scenarios, industrial and production monitoring, control networks, and many other fields. As the number of the WSN nodes increases every day, the available spectrum for all the wireless communication is limited. Many of the WSNs operate in unlicensed spectrum bands while the worldwide available and commonly used 2.4 GHz band is shared by other applications such as Bluetooth and WiFi. As a consequence, WSNs have to face the problem of coexistence with other wireless applications.

There is a high demand to find an efficient way to access any unused period, in order to support the high growth of wireless communications. For WSNs it is important to explore additional capabilities in spectrum access. Efficient mechanisms should be applied to address the interference problem and decrease the number of the collisions.

Instead of static spectrum management policy, a more flexible and dynamic approach started to gain the attention. The term Dynamic Spectrum Access (DSA), is used to enclose all the diverse ideas as they were presented at the first IEEE Symposium On New Frontiers in Dynamic Spectrum Access Networks (DySPAN). We follow the taxonomy of the different strategies as proposed in [23]. This taxonomy is shown in Figure 3.1. In the following, a brief description of each strategy is provided.

Figure 3.1: A taxonomy of the dynamic spectrum access and its different strategies.
3.1.1 Exclusive Model

This model maintains the basic structure of the current static spectrum regulation policy: the different spectrum bands are licensed to service privileged users. However, this model tries to increase the flexibility of the static policy and make the spectrum management more efficient. There are two approaches which belong to this model:

- **Trade property rights.** In this approach, the licensees are allowed to sell and trade spectrum and freely choose technology [67]. Thus, the economy and the market play a crucial role in this approach. The more profitable user will have access to the limited resources.

- **Dynamic spectrum allocation.** In this approach, spectrum is dynamically assigned to the users, taking into account spatial and temporal traffic statistic of different services [68]. In a specific time slot and in specific region, the spectrum is allocated to a specific user.

Both these exclusive model approaches can not eliminate the white space in spectrum. More importantly, they can not serve efficiently the burst nature of wireless traffic and the unpredictable workload of many WSN applications.

3.1.2 Sharing Model

This model adopts an open sharing approach for a common spectrum. The peer users are the basis for managing a spectral region. The motivation behind this model came from technologies that works in the unlicensed industrial and scientific radio bands, such as Bluetoooth and WiFi. Centralized [69, 70] and distributed [71–73] spectrum sharing strategies have been initially investigated to address technological challenges under this spectrum management model.

3.1.3 Hierarchical Model

This model adopts a hierarchical access where there are Primary Users (PUs) and Secondary Users (SUs). The basic idea behind this model is to give the opportunity to SUs to access the spectrum when it is not used from the PUs (licensees). The interference they create is controlled. There are two main approaches in this model:
• **Spectrum underlay.** The underlay approach imposes severe constraints to the secondary users, as follows:
  
  – the transmission power of the SUs is severely limited,
  
  – SUs have to operate under noise floor of PUs and
  
  – SUs signals are spread over a wide frequency band (Ultra-wideband – UWB), their range is short, but can potentially achieve high data rate.

In the worst-case scenario where the PUs transmit all the time, the main drawback of this approach is that it does not detect and exploit the spectrum white space.

• **Spectrum overlay (Opportunistic Spectrum Access).** This approach has the following characteristics:

  – transmission power of SUs is not constrained and
  
  – where and when SUs may transmit is an important issue.

This second approach targets at the spatial and temporal spectrum white space. It lets the SUs identify and exploit the local and instantaneous spectrum availability in order to increase the spectrum usage efficiency.

In comparison with the other two models, the hierarchical model is the most compatible with the wireless systems and with most of the WSNs. The rest of this chapter focuses on this model and specifically on the Opportunistic Spectrum Access approach.

### 3.2 Opportunistic Spectrum Access

In recent years, the concept of Opportunistic Spectrum Access (OSA) has emerged as a way to improve spectrum utilization. OSA is a relative new access model, designed to extract unused spectrum from allocated, but underutilized frequencies. The main idea is to support newcomer traffic without affecting existing owners. In this model, wireless devices that need spectrum, they can locate and opportunistically (re)use unused frequencies ranges. These “secondary” devices take great precaution to avoid disrupting original or “primary” users, and immediately exit the frequency whenever they detect traffic from primary users. Through this carefully planned access model, secondary devices can increase spectrum utilization with zero or bounded disruptions to existing owners.
Figure 3.2: An illustrative example of OSA. The bold line shows the PU channel occupancy. The SU periodically senses the channel and determine whether to access it. A collision occurs when the SU is using the channel and the PU returns.

Note that compared to more liberal spectrum access rules [74], this “conservative” access model is easier to implement and much more likely to gain acceptance with regulators and primary users [75].

3.2.1 An Illustrative Example of OSA

There are two entities in OSA: Primary Users (PUs) and Secondary Users (SUs). PUs are the original owners of allocated but underutilized frequencies, while the SUs are trying to make use of any unused spectrum slot, under the constraints of avoiding disruptions to PUs.

Figure 3.2 shows an illustrative example of OSA with PUs and SUs. PU has access to the frequency at any time. SU tries to sense the channel to detect whether any PU is present. If the channel is occupied, SU does nothing and waits for the next slot. If the channel is free, SU has to decide if it is going to use it in this time slot or not. There is a risk that the PU tries to use the channel while the SU is using it. If PU needs the channel while SU is using it, there will be a collision. Sometimes, SU waits for a number of idle slots before it starts using the channel. In the following section, the basic component of OSA are covered.
3.2.2 Basic Components of OSA

OSA is based on the opportunity that the SU has to find an idle channel and use it. Assume there is a pair of SUs, let’s say A and B and node A has a packet to transmit to node B. A channel is an opportunity only if these two nodes manage to communicate successfully and there is limited interference with the PUs below a prescribed level, determined by the regulatory policy. This means that receiver B should not be affected by primary transmitters and transmitter A should not interfere with primary receivers.

It should be clear from the above that, spectrum opportunity is a local concept defined by a pair of communicating SUs. It depends on the location of the secondary transmitter and the location of the secondary receiver with respect to the location of the PU. Also, the final successful transmission is based on the PUs and not on the SUs. Even if a channel is an opportunity, meaning the channel is idle in a time slot, the communication between the SUs can be interrupted by the return of a PU.

The concept of OSA has three main processes: (1) spectrum identification, (2) spectrum exploitation and (3) regulatory policy. It is important to mention that if any of them fails, then the whole communication fails. In the following, these three components are presented.

1. **Spectrum identification.** It refers to the process of identifying and tracking idle frequency bands that are dynamical in time and space.

2. **Spectrum exploitation.** Once a spectrum opportunity is detected, there is a need for the spectrum exploitation. This process helps a node to decide whether and how transmission should take place. Decisions such as the modulation and the transmission power and how to share opportunities are made at this stage.

3. **Regulatory policy.** When the previous two processes have been accomplished successfully, before the final transmission, this process defines a set of rules that SUs should respect.

There are a number of signal processing and networking techniques in order to accomplish the above processes. In the following section, the challenges which these processes pose on the design of an OSA are discussed.
3.2.3 Challenges in OSA Design

While conceptually simple, the realization of OSA is challenging. Several problems must be solved: sensing over a wide frequency band; identifying the presence of PUs and determining the nature of opportunities; coordinating the use of these opportunities with other nodes; and most importantly, the definition and application of interference limiting policies, and adherence to these policies while utilizing the opportunities [76].

Fortunately, recent technological advances in a number of areas can be considered to solve this problem. First, the emergence of Software Defined Radios has enabled the RF-level programmability and spectrum agility essential to opportunistic spectrum access. Second, wideband sensing technologies have come a long way due to faster digital signal processors and tuneable filters. Third, the use of waveforms that can be adapted to fit a specified spectral profile e.g., waveforms that can occupy noncontiguous frequencies is beginning to be better understood. Additionally, there is widespread interest in this flexibility from regulatory bodies such as the FCC. Finally, the impetus to develop secondary markets for spectrum purchased at auction (at great expense), but not in use, is adding to the urgency for a change in the regulatory regime, and is making it worthwhile for organizations to invest in this technology.

3.2.4 Cognitive Radio and WSNs

The concept of cognitive radio was promoted by Mitola in [77]. A cognitive radio is an intelligent radio that can be programmed and configured dynamically. Its transceiver is designed to use the best wireless channels in its vicinity. Although DSA is certainly an important application of cognitive radio, cognitive radio represents a much broader paradigm where many aspects of communication systems can be improved via cognition.

It is possible to apply DSA models in WSNs to provide them with access to less congested spectrum. In general, a Cognitive Radio Sensor Network (CRSN) can be defined as a distributed network of wireless cognitive radio sensor nodes, which sense event signals and collaboratively communicate their readings dynamically over available spectrum bands in a multi-hop manner to ultimately satisfy the application-specific requirements [78].
3.3 Survey on OSA Strategies

Dynamic Frequency Selection (DFS), a method that was firstly specified by the ITU and later by the FCC, is a simple way of co-existing with primaries. The method is a harmonized set of rules for WLANs in order to share the spectrum with primary users. DFS scans the spectrum and tries to find other devices that use the same radio channel. Then it switches to a new and clean channel if required. The protocol has mechanisms for the access point to instruct the terminals to switch to the new channel. DFS is being developed by the IEEE 802.11h subcommittee.

The emergence of a number of different radio technologies e.g. 802.11.x, 802.15.x, Bluetooth, Hiperlan etc. that share the unlicensed spectrum has given rise to the problem of destructive interference between these systems. To address the problem, spectrum etiquette protocols have been designed [79–81], so that these technologies can co-exist in the same band. Spectrum etiquette is a set of rules followed by all users of the spectrum, so that fair and conflict-free access to the radio resource is enabled. For infrastructure-oriented networks, [82] proposes a coordinated, spatially aggregated spectrum access via a regional spectrum broker.

The next level of sophistication comes in generalizing such access to a much wider band with a multitude of diverse services, coordinating use of opportunities in cooperative and noncooperative modes, and utilizing non-contiguous frequency holes. A radio platform called the Adaptive Spectrum Radio (ASR) that demonstrates the principles for dynamically accessing the spectrum is described in [83]. The ASR adapts its frequency and modulation to exploit spectrum gaps both in frequency and time. The ASR uses an adaptive form of Orthogonal Frequency Division Multiplexing (OFDM) that exploits spectrum gaps through the use of non-contiguous carriers. A key part of such access is spectrum sensing, which is the subject of much recent interest [84, 85].

Opportunistic spectrum access, also referred to as dynamic spectrum access is part of the larger concept of cognitive radios. First developed by Mitola [77], cognitive radio refers to a device that has knowledge of its capabilities, internal state and the radio environment. Further, the knowledge is represented in a form that allows for automated reasoning to satisfy the needs of the user. It allows expressive negotiations among peers about the use of radio spectrum across fluent of space, time, and user context. A cognitive radio is self-aware and “knows that it knows”. In its extreme, the concept accommodates adaptation through learning.
3.4 OSA Impact Evaluation

In this section, a brief description of the traditional routing protocol is presented, followed by a description of the three different routing approaches that make use of OSA and cognitive networking. Traditional routing is the basic approach which is used to compare with the other three protocols.

3.4.1 Traditional Routing

Traditional routing starts with an initialization phase. Destination node broadcasts a number of packets and every node in the network keeps broadcasting these packets to its neighbour nodes. Each packet transmission over a channel is subjected to a Packet Error Rate (PER). To simulate a realistic channel model for lossy WSNs with Binary Phase-Shift Keying (BPSK) without channel coding, the \( \hat{P}ER(i) \) is [86]:

\[
P\hat{E}R(i) = 1 - \left(1 - Q\left(\sqrt{\frac{2P_t(i) \cdot \hat{G}(i)}{\sigma^2_n}}\right)\right)^{F_d},
\]

where \( F_d \) is the size of the data packet, \( \sigma^2_n \) is the noise power, \( P_t \) is the transmission power, \( Q(x) = \frac{1}{\sqrt{\pi}} \cdot \int_{x}^{\infty} e^{-t^2} dt \) and

\[
\hat{G}(i) = A \cdot \hat{D}_s(i)^{-n},
\]

where \( \hat{D}_s(i) \) is the distance between the sender node \( s \) and the next node \( i \), \( A \) is a constant, and \( n \) is wireless channel path loss component.

The \( P\hat{E}R \) function under three different \( P_t \) can be seen in Figure 3.3. It can be inferred that \( P_t \) is not only important for the total energy consumption of the network, but also for the network connectivity. It can be inferred that \( P_t \) is crucial for the network connectivity. When \( P_t \) is low, the network might have low or no connectivity. On the other hand, a high \( P_t \) may lead to waste of the limited energy of the nodes. Moreover, the number of collisions between neighbouring nodes will increase.

Some packets will be lost due to the \( P\hat{E}R \) between the communicating nodes. After the initialization phase, every node knows the \( PER \) over the links with its neighbour nodes and the number of the hops that are needed to reach the destination through different paths and the related distances.

This approach uses only one channel. The source node selects the path towards the destination according to the distance from the destination and the link reliability. The
selected path is the shortest path towards the destination and consists of links with PER less or equal to a predefined reliability threshold, $T_{h_{PER}}$. A link $i$ between a node and one of its neighbour nodes is considered to be in the path only if $PER(i) \leq T_{h_{PER}}$. From those links the node will always forward the packet over the one that leads to the neighbour which is closer to the destination. All the packets will be delivered to the destination following the same path.

Traditional routing uses two types of packets: DATA and acknowledgment (ACK). When a node transmits a packet, it stores a copy in its buffer and waits for the ACK. The time the node will wait for an ACK can be determined as:

$$T_{ACK} = d_{trans}(DATA) + SIFS + (2 \times d_{prop}) + d_{trans}(ACK)$$

(3.3)

where $d_{trans}(DATA)/d_{trans}(ACK)$ is the transmission delay for DATA/ACK, $d_{prop}$ is the propagation delay, and Short Interframe Space (SIFS) is the small time interval between the DATA packet and its ACK.

If there is no ACK after that time because the DATA or the ACK packet was lost, the node will retransmit the DATA packet. If two or more nodes transmit at the same time, there will be a collision and both packets will be dropped. To avoid that, there is a global scheduler that prioritizes packet transmission. The node that is closer to the destination...
will transmit the packet first while the other nodes will go back to sleep mode. Global scheduler will wake up a node only when it can transmit packets. The use of global scheduler excludes retransmissions due to collisions and the performance results can be considered as an upper-bound of this routing protocol.

### 3.4.2 Traditional Routing with N Channels

Traditional routing with N channels (traditional cognitive radio) is similar to traditional routing. An initialization phase has to take place before starting the packet transmission. The process that will be followed to find the path to the destination is the same as in traditional routing.

Instead of one single channel, this protocol uses N channels. When a node has a packet to transmit, it senses all the channels to find one available. If there is an available channel, it transmits the DATA over that channel and waits for the ACK. The receiver has to reply with an ACK \textit{at the same channel}. In this way, the transmitter will not sense all the channels for the ACK, but only the one through which it sent the DATA. If there is no channel available, the transmitter goes back to sleep mode.

Global scheduler is also used in this protocol to avoid collisions. Assuming that node A transmits a packet to node B over channel $i$, while node B is transmitting a packet to another node C, over channel $j$, with $i \neq j$. In that case, node B will drop the packet from node A because it tries to transmit a packet to node C. To cope with that problem, in every time slot, the global scheduler knows which of the neighbour nodes of the transmitter are available to receive a packet. If the neighbour node that should get the packet, following the routing protocol, is not available, the transmitter will remain in sleeping mode. The use of the global scheduler again in this approach helps to avoid any collisions. Every packet will have the best available scheduling and the results will be an upper-bound of this routing protocol.

### 3.4.3 Opportunistic Routing

Opportunistic routing follows similar approach to [62] while its algorithm is the same with geographical forwarding in Section 2.4. There are four types of packets: RTS, CTS, DATA and ACK. All the packets transmissions are subjected to PER, there is no global scheduler and there is only one channel in that approach.
When a node has a DATA packet to transmit, it stores the packet in a buffer and then broadcasts a RTS packet for that DATA packet to all the neighbour nodes. Transmitter waits for a CTS packet for time $T_{RTS}$ equals to:

$$T_{RTS} = \max(d_{trans}(RTS)) + SIFS + (2 \times d_{prop}) + \max(d_{trans}(CTS))$$

(3.4)

where $\max(d_{trans}(RTS))/\max(d_{trans}(CTS))$ is the maximum transmission delay for RTS/CTS to reach a node placed at the limit of the transmission range of the transmitter. This is the smallest time interval the transmitter has to wait before assuming that the RTS or the corresponding CTS packet was lost, even from a neighbour node that is located at the transmission range limits. If there is no CTS after time $T_{RTS}$, the node will broadcast a RTS for the same packet again.

When a neighbour node $n$, receives a RTS packet from the transmitter node $t$, it will reply with a CTS packet after time $T_{bGEOR}$ as in Eq.(2.7). In order for a node to reply with a CTS before the transmitter broadcast the same RTS from Eq.(3.4), $T_{bGEOR}$ should be smaller than $T_{RTS}$ plus the necessary transmission time for the CTS, i.e. $T_{bGEOR} \ll T_{RTS}$.

The transmitter node forwards the DATA packet to the neighbour node that replies first with a CTS packet. If there is no ACK after time $T_{ACK}$, Eq.(3.3), the node will transmit the DATA packet again.

As discussed in Section 2.4, $T_{bGEOR}$ is inverse proportional to the packet advancement $d_{src,cad}$. The neighbour node that is closer to the destination will have the smallest $T_{bGEOR}$ and will try to reply first with a CTS packet. Any CTS that will arrive to the transmitter after the first one, will be ignored. Any neighbour node that is still during its $T_{bGEOR}$ and hears a DATA packet transmission, will drop the CTS packet and go back to sleep mode.

As it can be inferred from Eq.(2.7), the selection criterion of this routing protocol is the distance between the node and the destination. That selection criterion is easy to be implemented in WSNs which have limited capabilities. Each sensor needs to know its own network address and the destination node network address to calculate the criterion.

In this approach, the routing path changes dynamically in every time slot according to the network conditions. Since there is no reliability threshold, this approach can follow paths toward the destination that needs less hops than traditional routing. Moreover, in every packet transmission the number of the successfully transmitted RTS and/or CTS packets is different, leading to different next relay nodes and different paths toward the
3.4.4 Opportunistic Routing with N Channels

Opportunistic routing with N channels tries to combine the advantages of opportunistic routing and opportunistic spectrum access (traditional cognitive radio). The routing process is similar to the single channel opportunistic routing.

When a node has a packet to transmit, it searches for an available channel. If there is a channel available, it will broadcast a RTS over that channel. All the consequent packets, CTS, DATA and ACK, will be transmitted over the same channel as the RTS. Moreover, since opportunistic routing can change the path dynamically following the network conditions, there is no need for a global scheduler. If node A transmits a RTS to node B over channel \( i \), while node B is transmitting a packet to node C over channel \( j \), with \( i \neq j \), node B will just ignore the RTS. Another neighbour node that hears this RTS will reply. As a consequence, in contrast to traditional routing with N channels, in opportunistic routing with N channels the packets will make progress toward the destination in every time slot, with higher probability.

3.5 Performance Evaluation and Simulation Results

We utilize simulation tools to study the performance of the different approaches. In this section, the simulation parameters are described, followed by the performance metrics that were used and the simulation results.

3.5.1 Simulation Parameters

Simulations were conducted in OMNeT++ [63]. The nodes were uniformly randomly distributed over a 350 \( \times \) 350 \( m^2 \) network field. Every node has 6 neighbour nodes on average and transmission range 12 meters. The communication parameters were chosen based on IEEE 802.15.4, and the remaining simulation parameters are listed in Table 3.1.

The number of the channels was set to 3. A higher number of channels was also tested, but the difference in performance was negligible while the algorithm complexity in each sensor node was increased. The nodes had to spend more time on sensing all the channels. When 2 channels were simulated, nodes spent less time on channel sensing.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the data ((F_d))</td>
<td>bit</td>
<td>100 × 8</td>
</tr>
<tr>
<td>Wireless channel path loss component ((n))</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Constant decided by the antenna gain ((A))</td>
<td>dB</td>
<td>−31</td>
</tr>
<tr>
<td>Noise Power ((\sigma_n^2))</td>
<td>dBm</td>
<td>−92</td>
</tr>
<tr>
<td>SIFS</td>
<td>µs</td>
<td>10</td>
</tr>
<tr>
<td>(L_{DATA})</td>
<td>bit</td>
<td>119 × 8</td>
</tr>
<tr>
<td>(L_{RTS}/L_{CTS})</td>
<td>bit</td>
<td>8 × 8</td>
</tr>
<tr>
<td>(L_{ACK})</td>
<td>bit</td>
<td>8 × 8</td>
</tr>
<tr>
<td>Transmission Rate ((R))</td>
<td>kbps</td>
<td>250</td>
</tr>
<tr>
<td>(C_{GEOR})</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.1: Simulation parameters for the three approaches

However, according to the acquired results they did not get full advantage of the cognitive radio concept because of the limited available channels for a high network density and high workload.

For the traditional routing schemes, the reliability threshold was \(Th_{PER} = 20\%\). During the simulation, 9 different source-destination distances were selected, starting from 50 m till 450 m with 50 m step. To explore the performance of the protocols in different locations of the network, in every distance 4 different destination nodes were simulated with deviation 1 m from the main distance. For instance, in 50 m from the source, 4 destination nodes were selected in distance between 49 and 51 meters from the source. For each source-destination pair, the simulation was run 5 times, on average. The performance metrics that were used, are the average values per distance of all the 4 destinations. The network topology with the different destination nodes in each distance can be seen in Figure 3.4.

### 3.5.2 Performance Metrics

The routing schemes will be compared with respect to energy consumption, throughput and delay.
3.5.2.1 Energy Consumption

Energy consumption is the total power that is needed from all the nodes in the network. From the source node 100 packets were transmitted toward the destination. Let the node power consumption in transmitting and receiving/idle modes be denoted by $P_t$ and $P_r/i$ respectively. The sleeping mode power consumption is practically 1000 times smaller than $P_t$ and $P_r/i$, which is negligible. Let $P_t = 15\text{mW}$ and $P_r/i = 10\text{mW}$. For each distance, there are 4 different destination nodes. The average energy consumption for each distance can be seen in Figure 3.5.

For traditional routing, an ideal sleeping mechanism was used. The nodes knew exactly when to go to sleep and when to wake up for a packet transmission. In most practical networks, the nodes will stay awake when there is traffic, and the network energy consumption will be approximately inversely proportional to the throughput. In our approach, with the ideal sleeping mechanism, which was used only in traditional routing, the upper bound of the performance of traditional routing was achieved.

Traditional routing with 3 channels consumes slightly more energy than the single channel. The two approaches use the same path toward the destination and the same scheduler. However, when there are 3 channels available, the nodes also have to scan the different channels, hence consume more energy. As the distance increases, the number of
the hops also increases, more nodes are used and the difference in energy consumption between the two traditional approaches, increases.

Opportunistic routing performs better than traditional routing. The path between the source and the destination may consist of links with any PER. This can lead to shorter paths than the traditional routing path, with fewer hops and node transmissions, decreasing the total energy consumption. As the distance between the source and the destination increases, there are more nodes in-between them, leading to even shorter paths towards the destination. As a consequence, the difference between the energy consumption of traditional and opportunistic routing is increased. Opportunistic routing with 3 channels has the smaller energy consumption over all the other protocols. It can discover shorter paths than traditional routing while at the same time it has higher probability to transmit a packet in every time slot. Compared to single channel opportunistic routing, in this approach, the packets can make progress towards the destination over multiple channels in every time slot. The time a node has to wait before transmitting a packet is smaller and as a result the energy consumption of each node is smaller.

3.5.2.2 Throughput

Throughput is the number of bits divided by the time needed to transport the bits. From the source node 100 packets were transmitted toward the destination. The average
throughput for each distance can be seen in Figure 3.6.

Traditional routing with single channel has the lowest throughput over all the other protocols. As the distance between the source and the destination increases, the throughput decreases. There are more hops needed to deliver a packet to the destination hence, the time needed is higher and the throughput is lower. Traditional routing with 3 channels performs better than the single channel. In one time slot, if one of the channels is occupied, a node can transmit a packet to a neighbour node over the any of the other two available channels. At a given time, more packets will be transmitted towards the destination over different channels, than with single channel traditional routing. A problem with both these two approaches is that, if a packet is lost, all the sequential packet transmission will have to wait because all the packets should be transmitted through the same nodes.

Opportunistic routing performs even better than traditional routing. The path between the source and the destination changes according to network conditions and node availability. Packets will be transmitted to different nodes in every time slot and paths with less hops than traditional routing will be discovered. The time needed to transport the bits will be smaller and the throughput will be higher. Opportunistic routing with 3 channels has the best performance over all. In every time slot, packets can be transmitted through the shorter available path at the time towards the destination, and
over multiple channels. The time needed to transport the bits is smaller than with single channel opportunistic, leading to a higher throughput.

### 3.5.2.3 Delay

Delay of a packet in the network is the time it takes the packet to reach the destination after leaving the source. The source node sent 100 packets towards each destination, with a transmission time of 6.4 ms. The results can be seen in Figure 3.7.

![Figure 3.7: Delay of the different schemes.](image)

Traditional routing with single and with 3 channels performs worse than opportunistic routing. The path that these protocols follow is the shortest available under the reliability threshold. Moreover, all the packets follow the same path hence, when a packet is lost or damaged, all the sequential packets will be delayed. Traditional routing with 3 channels performs better than traditional routing with single channel. The reason is that the probability of a packet being transmitted at a time slot is higher with the use of multiple channels. The packet can be transmitted over any of the 3 channels, if any of them is available. Hence, the time needed for a packet to reach the destination is smaller.

Opportunistic routing can discover shorter paths towards the destination than traditional routing. Each packet needs less time to reach the destination, leading to smaller packet delay. As there are more channels available, in opportunistic routing with 3 channels, the time is even less.
3.6 Summary

In this chapter, the main principles of OSA were described. It started with a taxonomy of the different strategies for dynamic spectrum access. One of the most promising for WSNs is OSA. A brief description of the design challenges of an OSA protocol was provided. The related work in the area was also reviewed. In addition the advantages of OSA on energy consumption were examined. Four different approached of spectrum access and routing protocols were evaluated. According to simulation results, the advantages of OSA can be beneficial Self-Powered WSNs, but pose some challenges which need to be addressed.
Chapter 4

Cognitive Networking with Multi-hop Routing

In this chapter, a cognitive networking with opportunistic routing protocol for WSNs is introduced. Most of the WSNs operate in unlicensed spectrum bands which have become overcrowded. As the number of the nodes that join the network increases the need for energy-efficient, resource-constrained and spectrum-efficient protocol also increases. Incorporating cognitive radio capability in sensor networks yields a promising networking paradigm, also known as Cognitive Radio Sensor Networks (CRSNs). A Cognitive Networking with Opportunistic Routing (CNOR) protocol for WSNs is introduced. The objective of the proposed protocol is to improve the network performance after increasing network scalability. The performance of the proposed protocol is evaluated through simulations. An accurate channel model is built to evaluate the signal strength in different areas of a complex indoor environment. Then, a discrete event simulator is applied to examine the performance of CNOR in comparison with two other routing protocols. Simulation results show that when compared with other common routing protocols, CNOR performs better with respect to throughput, packet delay and total energy consumption.

First, cognitive networking concept and its principles are described. Next, the Cognitive Networking with Opportunistic Routing (CNOR) protocol is explained. CNOR combines the advantages of opportunistic routing along with opportunistic spectrum access and cognitive networking.

In order to evaluate the performance of CNOR in a complex indoor environment, a wireless channel model was built. We describe the process to build an accurate indoor channel model. A deterministic wireless channel modeling tool is used to evaluate the
signal strength in different areas of the environment. The performance of the tool is evaluated through simulations. Next, a measurement campaign and the necessary steps in order to calibrate the channel model are presented. For the campaign prototypes with cognitive radio capabilities were used. Three different communication scenarios were examined. The results were used to calibrate the final channel model. The final channel model was used to evaluate the performance of CNOR. CNOR also implemented in hardware with the use of prototypes.

4.1 Cognitive Networking

In this section, the main principles of cognitive networking followed by a review of the related work is thoroughly presented. Cognitive network is a networking system of cognitive radios that makes use of cutting-edge technology from computer networks to solve the problems in traditional wireless networks. Cognitive networking research is different from cognitive radio, as it covers all the layers of the OSI (Open System Interconnection) model, beyond layers 1 and 2 as with cognitive radio.

4.1.1 Cognitive Networking Principles

One of the earlier attempts to define the concept of cognitive network was made in [87], where cognitive network is described as a network with a cognitive process that can perceive current network conditions, plan, decide, act on those conditions, learn from consequences of its actions, and follow end-to-end goals. This definition however, did not explicitly describe what the knowledge of the network is. In [88], cognitive networking is viewed as a communication network augmented by a knowledge plane that can span vertically over layers and/or horizontally across technologies. The knowledge plan is composed of at least two elements: 1) a representation of relevant knowledge about the scope; 2) a cognition loop which has the intelligence inside its states.

The concept of cognitive network is further detailed in [89], where the cognitive networking concept is interpreted as a network that can utilize both radio spectrum and wireless station resources opportunistically, based upon the knowledge of such resource availability. Since cognitive radio has been developed as a radio transceiver that can utilize spectrum channels opportunistically (or OSA), the cognitive network is therefore, a network that can opportunistically organize cognitive radios.
In [89], a detailed cross-layer network architecture was proposed for cognitive networks, based on a new definition of wireless linkage. The new abstract wireless links are redefined as arbitrary mutual co-operations among a set of neighbouring (proximity) wireless nodes. In comparison, traditional wireless networking relies on point-to-point “virtual wired-links” with a predetermined pair of wireless nodes and allotted spectrum. To support multi-hop wireless communications, a wireless unicast module is introduced under the cognitive networking architecture, which integrates opportunistic routing and opportunistic spectrum access in providing reliable and high performance end-to-end communications in large-scale wireless networks.

4.1.2 Related Work

In cognitive networking, a spectrum aware routing is proposed in [90]. Spectrum Aware Mesh Routing (SAMER), opportunistically routes traffic across paths with higher spectrum availability and quality. SAMER tries to balance between long-term route stability and short-term opportunistic performance. In [91], a Spectrum Aware Opportunistic Routing (SAOR) algorithm is introduced. SAOR uses an Opportunistic Link Transmission (OLT) metric, which is a combination of transmission delay, packet queueing delay and link access delay. By introducing channel access probability to characterize the opportunistic Cognitive Radio (CR) link, Multi-channel Spectrum Aware Opportunistic Routing (MSAOR) [92], improves the performance of SAOR. In [93], a novel opportunity-heterogeneous Cognitive Sensor Network (CSN) model is presented and cope with the problem of spectrum sensing in CSNs from a joint spatio-temporal two-dimensional detection perspective.

This work tries to fill the gap between opportunistic routing and cognitive networking for WSNs. An opportunistic routing protocol with opportunistic spectrum access for WSNs is proposed. A novel selection criterion is introduced, that has been designed by taking into consideration the limited computational capabilities and the limited energy resources of the wireless sensor nodes. The proposed network address mechanism is simple. A packet reception rate has been assigned to each communication link. A realistic channel model is used to evaluate the performance of the proposed protocol while the network scalability is changed. Although considering only the transmission distance may lead to inaccurate models [94], in this work a comparison between the calibrated and real results have show very similar and accurate performance.
Multi-hop wireless communications in cognitive networks is further investigated, under a WSN scenario. By the integration of OR and OSA, it is shown that the cognitive networking approach can improve the quality of wireless communications, as compared to the upper-bound of traditional wireless networks. Furthermore, it is studied how the network energy consumption is impacted which can be especially important for WSNs.

4.2 A Cognitive Networking with Opportunistic Routing

Most of the WSNs operate in unlicensed spectrum bands which have become overcrowded. As the number of the nodes that join the network increases the need for energy-efficient, resource-constrained and spectrum-efficient protocol also increases. Incorporating cognitive radio capability in sensor networks yields a promising networking paradigm, also known as Cognitive Radio Sensor Networks (CRSNs). In this section, a Cognitive Networking with Opportunistic Routing (CNOR) protocol for WSNs is introduced, as in [33]. The objective of the proposed protocol is to improve the network performance after increasing network scalability. The performance of the proposed protocol is evaluated through simulations. The accurate channel model that was built was used. A discrete event simulator is applied to examine the performance of the proposed protocol in comparison with two other routing protocols. Simulation results show that when compared with other common routing protocols, the proposed protocol performs better with respect to throughput, packet delay and total energy consumption.

4.2.1 System Model

In this section the basic functionality of the system model is presented. The network address mechanism is described, followed by the radio implementation of the wireless sensor nodes. The link model and the collision avoidance mechanism are also discussed.

4.2.1.1 Network address mechanism

The network address of each sensor node in the network is subjected to a delivery criterion and is related to the distance from the destination node. Given the address of a node $i$, and the address of the destination node $dst$, the delivery criterion $c_{i,dst}$ should be locally
obtained. Usually, in WSNs this delivery criterion is correlated with the distance between two nodes.

In the proposed protocol, the destination node broadcasts identity advertisement packets toward every sensor node in the network. This packet has the delivery criterion field $c_{dst,dst}$ equal to zero. On the reception of this packet, every sensor node $i$, updates the delivery criterion field according to its distance from the destination $c_{i,dst}$. When all the nodes have broadcasted all the packets, every node in the network knows its delivery criterion. As the network scalability changes, the nodes can update their delivery criterion locally. When a new node joins the network, it can estimate its address by acquiring the address of its neighbour nodes. When a node leaves the network or there is a different source node, the network addresses of all the nodes remain the same. Only if the destination node changes this network address mechanism should take place again.

After this, each node will advertise identity packets periodically, depending on the application. For instance, in a monitoring application, the time the identity packets are sent is related with the event occur probability. If a node is no longer available in the network, this node will not participate in any future transmission. In order to have a unique network address this address is also related to a hardware product number. Hence, any node that joins the network can not use any network address from a previous node.

4.2.1.2 Radio implementation

Cognitive radio is an ideal-omnipotent radio for user centric communications because it takes into consideration all the available parameters. In [89], two propositions were further suggested for large-scale wireless networks:

1. Collision avoidance with other simultaneous on-going transmissions can be achieved when the radio can sense the spectrum resource, opportunistically, before any transmission.

2. Useful information for local cooperation can be extracted by opportunistically polling one or more proximity radios onto the selected spectrum.

With the above proportions, the concept of cognitive radio can be extended to the area of cognitive network, which implements both dynamic spectrum and radio access. The proposed protocol is based on these propositions and the radio nodes that are used for simulation implement these two ideas.
4.2.1.3 Link model

There are three major factors that can affect the successful transmission of a packet between any two nodes: channel availability, channel access priority and packet reception ratio.

- **Channel availability.** In a link between two neighbour nodes there is a number of available channels $Ch_N$. When a node has a packet to transmit, it will search for the available channel between all these $Ch_N$ channels. If all the channels are occupied, the node has to wait for the next available channel. The number of the channels $Ch_N$ should be carefully selected. A large number of channels may not be useful while it can lead the nodes to spend time and energy on sensing all the channels. On the other hand, a small value in $Ch_N$ will not take full advantage of the cognitive radio concept.

- **Channel access priority.** When a channel $Ch_i$, is free, a number of nodes that have packets to transmit will compete for this channel. When a node is transmitting over a channel, none of the nodes in its transmission range can use this channel. As a consequence, the priority criterion is crucial. In this work, the distance from the destination was used as a priority criterion. The node which is closer to the destination, according to its network address, will have the highest priority to access the next available channel.

- **Packet Reception Ratio.** When a node sends a packet to a neighbour node over a channel $Ch_i$, there is a Packet Reception Ratio (PRR) for this channel. To simulate a realistic channel model for lossy WSNs with Binary Phase-Shift Keying (BPSK) without channel coding, the log-normal shadowing path loss model derived in [65], was used:

$$PRR(L_f, d_{i,j}) = (1 - \frac{1}{2} \exp \left( -\frac{\gamma(d_{i,j})}{\sigma^2} \right) )^{\rho L_f}$$

The Received Signal Strength Indicator (RSSI) measurements can be used to determine the SNR, as in [65]. RSSI measurement campaigns were conducted and will be described in Section 4.4.4. The main goal of these campaigns is a more realistic calculation of PRR, following Eq. (4.1).
4.2.2 Collision Avoidance Mechanism

The cognitive radio is used to prevent collisions. The radio can have access to a group of data channels. Each group is associated with two different frequency tones, one for sensing and one for polling which are also distinctive from the data channel frequency. Therefore, the radio hardware should be composed of two transceivers, one for sensing/polling and one for data.

Initially, when a node has to transmit a packet, it senses for an available channel and then broadcasts a polling tone. All the nodes which are in the range of the transmitter node, they can detect this polling tone. A neighbour node can decide to join the transmission based on its own autonomous availability. If a node decides to join the transmission it sends out a polling tone to its surrounding nodes. In this way, sensing and polling tones protect wireless link module from spectrum interference.

4.2.3 CNOR: Cognitive Networking with Opportunistic Routing Protocol

The proposed Cognitive Networking with Opportunistic Routing (CNOR) protocol for scalable WSNs, tries to combine the advantages of opportunistic routing and opportunistic spectrum access (traditional cognitive radio). It is a reactive routing protocol since it discovers routes only when desired. An explicit route discovery process takes place only when it is needed. In CNOR, that process is destination-initiated. The destination node of the network begins the route discovery process and this process ends when a routing path has been established while a maintenance procedure preserves it until the path is no longer available or desired. As the network scalability is increased, CNOR tends to discover more paths leading to the increase of the network performance.

In CNOR, multiple paths between the source and the destination are maintained. Packets can follow any of those paths, according to the dynamically changing network conditions, such as interference, channel and relay node availability. As the scalability of the network is increased, the number of the relay nodes also increases. Then, CNOR tries to discover more efficient paths towards the destination and increase the total network performance. Moreover, due to the probabilistic choice of the relay nodes, the protocol is able to evaluate different routing paths continuously and choose them according to the condition in every time slot.
4.2.3.1 Neighbour discovery process

Every sensor node $i$ in the network knows its relative location, hence it can categorize
the nodes around it into neighbour node set $N_i$, and candidate node set $K_i$.

*Neighbour node set* $N_i$ of node $i$, is a set of all the nodes in the transmission range
(*Range*) of node $i$:

$$N_i = \{ j \in S \mid \text{dist}(i, j) \leq \text{Range}, \ i \neq j \}$$  \hspace{1cm} (4.2)

where $S$ is the set of all the nodes in the network, $\text{dist}(i, j)$ is the distance between node $i$ and node $j$ and $R$ is the transmission range of the node.

*Candidate node set* $K_i$ of node $i$, is a set of those nodes that are in $N_i$ and they are
closer to the destination node $dst$ than the transmitting node $i$. Candidate node set is a
subset of neighbour node set, i.e. $K_i \leq N_i$ and can be defined as:

$$K_i = \{ j \in N_i \mid \text{dist}(j, dst) \leq \text{dist}(i, dst) \}, \ i \neq j$$  \hspace{1cm} (4.3)

The destination node initiates the neighbour discovery process by flooding a small
packet to its neighbour node set. Every node forwards the packet to its neighbour
node set and updates the delivery criterion field. In this way, the packet moves from
the destination towards every sensor node in the network, with each node counting the
delivery cost to the destination.

During this process, each node also creates a metric with the number of the neighbour
nodes around it, $N_i$. When a node receives the same packet from different neighbour
nodes, then it can count the number of the neighbour nodes. When all the sensor nodes
in the network have transmitted the packet, the neighbour discovery process is over.
After the end of the whole process, each sensor node in the network has all the necessary
information to start data transmission.

4.2.3.2 Packet transmission process

After the neighbour discovery process, the packet transmission process from any node
towards the destination can take place. There are four types of packets: RTS, CTS,
DATA and ACK. Every packet transmission is subjected to the PRR, as in Eq.(4.1).

When a node $i$ has a packet to transmit toward the destination node $dst$, there is
a RTS/CTS handshake between the transmitter node $i$ and the nodes at its candidate
set $K_i$. The transmitter searches for an available channel $Ch_i$, floods a RTS packet over one available channel and waits for time $T_{RTS}$ or till the first response. Since the transmitter floods the RTS packet to every neighbour node in its $N_i$ set, it might get a response from a node that belongs in $N_i$, but not in $K_i$. In this case, the transmitter will ignore the response and will accept response only from nodes in its candidate set $K_i$. The transmitter will wait for the response at the same channel $Ch_i$. Depending on the network conditions and the distance between the transmitter and each neighbour node, some of the nodes in the neighbour set will receive the RTS packet. Before the node $i$ retransmits the data, it has to wait for time:

$$T_{RTS} = \left(\frac{L_{RTS} + L_{CTS}}{R} + (2 \times d_{prop})\right) \times \exp(N_i) \times C1_{CNOR} + SIFS$$ (4.4)

where $L_{RTS}/L_{CTS}$ is the size of RTS/CTS packet, $R$ is the transmission rate, $d_{prop}$ is the propagation delay needed to reach a node placed at the limit of the transmission range ($Range$) of the transmitter, $SIFS$ is the Short Interframe Space, the small time interval between the RTS and CTS transmission and $C1_{CNOR}$ is a constant related to the number of the neighbour nodes.

After time $T_{RTS}$ the transmitter assumes that the RTS packet was lost and it retransmits it. In CNOR protocol, as the number of the neighbour nodes $N_i$ is increased, $T_{RTS}$ also increases so the transmitter will wait longer for a response. This way, there is enough time for all the neighbour nodes to reply to the RTS before the transmitter assumes the RTS packet has been lost. Hence, energy is saved because of the avoidance of retransmissions.

On the reception of a RTS packet, neighbour node $k$ will respond with a CTS packet to node $i$, if it is available for immediate packet transmission and there are no other packets waiting to be transmitted. Before the transmission of the CTS packet, neighbour node $k$ will wait for time:

$$T_{bCNOR} = \frac{C2_{CNOR}}{d_{i,k} \times \exp(N_i)} + SIFS$$ (4.5)

where $C2_{CNOR}$ is a constant related with the transmission range and the number of the neighbour nodes.

As the number of the neighbour nodes increases, the $T_{bCNOR}$ decreases. There are more available neighbour nodes, hence the backoff time for each of them should be smaller, so they can reply to the transmitter node on time, before the end of $T_{RTS}$. 


Figure 4.1: $T_{RTS}$ and $T_{bCNOR}$ when the communicating nodes are in 10m distance. Maximum value in this configuration is 200$\mu$s and minimum 50$\mu$s.

From Eq.(4.4) and Eq.(4.5), it can be inferred that for a specific distance from the transmitter and as the network scalability changes, there is an optimal number of neighbour nodes that can minimize the total time spent on $T_{RTS}$ and $T_{bCNOR}$. Figure 4.1 shows an example for a specific configuration. There are maximum and minimum values of $T_{RTS}$ and $T_{bCNOR}$. The maximum value of $T_{RTS}$ is to ensure that a node will not wait after an upper bound limit for a CTS packet, even under a high network density. This value is the same with the maximum $T_{bCNOR}$ of a network with low density. The minimum value of $T_{bCNOR}$ is to ensure that there is enough time for the node to process the packet before it replies with a CTS packet. This value is the same with the minimum $T_{RTS}$ which is the minimum time needed only for one node located in the limits of the transmission range to reply with a CTS packet. CNOR tends to be as close as possible to that number under different network densities by taking into account the average number of the neighbour nodes when each node calculates those times.

After that time, neighbour node $k$ will check if the channel $Ch_i$ is available, in order to respond with a CTS packet over the same channel as the RTS packet. If the channel is unavailable, it will wait. Since the CTS packet transmission is also subjected to the PRR, some packets might be lost. On successful reception of a CTS packet, the transmitter will forward the DATA packet to the node that replied first with a CTS packet and will ignore
any consequent CTS packets for the same DATA packet. However, it can use all the CTS packets for the same DATA packet to update the $A_i$ metric for future transmissions. The DATA packet transmission will take place again over the same channel as the RTS/CTS handshake and the transmitter will wait for an ACK for this DATA packet.

When a node transmits a packet, it will store a copy in its buffer and will wait for the ACK. The time that the node will wait for an ACK can be determined as:

$$T_{ACK} = \frac{L_{DATA} + L_{ACK}}{R} + (2 \times d_{prop}) + SIFS$$  \hspace{1cm} (4.6)

where $L_{DATA}/L_{ACK}$ is the size of the DATA/ACK packet. If there is no ACK after $T_{ACK}$, following Eq.(4.6), the node will transmit the DATA packet again. Each intermediate node follows the same packet transmission process. Consequent packet transmissions might use different paths and different channels. This process continues till all the packets reach the destination node.

In Eq.(4.5), $T_{bCNOR}$ is inverse proportional to the packet advancement $d_{i,k}$. Thus, the neighbour node that is closer to the destination will have the smallest $T_{bCNOR}$ and will try to reply first with a CTS packet. Any CTS packet that will arrive to the transmitter after the first one, will be ignored. Any neighbour node that is still during its $T_{bCNOR}$ and senses a DATA packet transmission, will drop the CTS packet for this DATA packet and go back to sleep mode. Moreover, $T_{bCNOR}$ considers the number of the neighbour nodes. When the network density is high, the node should spend less time waiting before replying with a CTS packet, as in Eq.(4.5). On the other hand, the transmitter should wait longer for a CTS packet before retransmitting the data, as in Eq.(4.4).

The selection criterion of CNOR is the distance between the node and the destination, enhanced with information about the network density. This selection criterion is easy to be implemented in WSNs which have limited capabilities. Each sensor node needs to know its own network address and the destination node network address to calculate the distance. The neighbour node metric can be obtained during the neighbour discovery process and is updated with the CTS packet responses without any extra overhead. If a sensor node joins or leaves the network the neighbour nodes will notice it immediately without the need of a neighbour discover process. Moreover, the opportunistic spectrum access increases the performance of the opportunistic routing. Before every packet transmission, the nodes sense for the best available channel. Packet transmissions can take place simultaneously while the number of the collisions is decreased. A flowchart of the
CNOR protocol can be seen in Figure 4.2.

### 4.2.3.3 Route maintenance

Localized flooding is performed infrequently to keep all the information about the different routing paths updated. Sensor nodes, that do not participate in any transmission at a time slot, help collect maintenance information. This process also helps to check if any new node joins the network or any other node runs out of energy and stops operating. The nodes can then update their neighbour node metric.

### 4.3 Wireless Channel Modeling

Wireless multi-hop networks have attracted much attention due to their flexibility and connectivity possibilities. In an indoor environment, such as a building, the deployment of such a network is relatively straightforward, and with low cost. A wireless multi-hop network consists of spatially distributed autonomous nodes for data acquisition. Typical applications include monitoring of physical or environmental conditions.
Chapter 4. Cognitive Networking with Multi-hop Routing

One of the main challenges of these networks in indoor environments, such as a building, is the Non-line-of-sight (NLOS) problem. In indoor environments, the Line-of-sight (LOS) path can be blocked and the communications are conducted through reflections and diffractions.

In this section, the effect of an arbitrary indoor infrastructure environment on the performance of a wireless multi-hop network is investigated, as in [95]. An accurate channel modeling tool based on 3D ray tracing is used first to evaluate the signal strength in different areas of the environment. Then, a discrete event simulator is applied to examine the performance of the network with two classes of routing protocols: traditional vs. opportunistic. It is shown that for an indoor environment, opportunistic routing performs better based on the obtained results, with respect to throughput, delay and delivery ratio.

This approach, which consists of a judicious combination of the two modeling and analytical tools, permits an accurate and practical evaluation of the performance benefits due to improved routing mechanisms. In particular, the channel model utilized is not only based on mathematical abstraction, but also endowed with experimental characteristics as measured from a corresponding physical environment. This means that the obtained simulation results should have excellent correspondence to actual behaviours in the physical application scenario. Furthermore, the discrete event simulator allows for a comprehensive evaluation of the benefits of intelligent routing in a network. Indeed, the value of opportunistic routing, which can adapt rapidly to changes of the network conditions, is manifested in a number of perspectives: throughput, delay and delivery ratio. These enhanced characteristics are achievable due to the strategy of selecting the optimal path between the source and the destination for each packet transmission, based on the network conditions at that particular time.

4.3.1 Channel Modeling Tool

For channel modeling Volcano Lab was used. A wireless network is analyzed in a realistic environment. Radio nodes are distributed over an area, for example a building. Our approach consists of modeling the indoor wireless channels based on an accurate ray-based simulator. This propagation prediction tool computes the radio links between each node. Thus, the full space-time channel behaviour is available for each link: radio signal strength, delay spread, and angular spread.
The most sophisticated deterministic solutions, such as the predictor used in this work, to model multi-floor indoor propagation are generally based on 3D ray-tracing. The trajectory of the reflected, transmitted and diffracted rays is constructed by 3D ray-tracing from the image theory. The ray-tracing technique allows a fine accuracy in the calculation of the multi-path trajectories. Multiple contributions between radio nodes are thus constructed by reflections, transmissions and diffractions on the building structures. Each interaction will create attenuated rays. The simulator outputs are, for each radio node, a set of time-delayed attenuated rays. The combination of these attenuated rays yields to the radio signal strength prediction. The field strength, which is usually expressed in terms of received power in \( dBm \), is given by the Uniform Theory of Diffraction (UTD). A post-processing of these multiple ray set of predictions gives estimated angular and delay spreads.

The simulations are based on a 3D Digital Building Model (DBM) where the floors, the walls, the windows, the doors and any other kinds of partition are precisely represented. The location of these partitions, their width and the material characteristics are obtained from architect plans which may be corrected using recent pictures taken in the field. Figure 4.3 gives the layout of the building under consideration in the work, and the topology of the radio nodes. The 3D DBM are available in Computer-Aided Design (CAD) files. The location and width of all partitions are generally given with high accuracy, on the order of a few centimetres. Figure 4.3 also depicts the building layout with the exterior and internal walls represented here by segments. A nature of material and a width are assigned to any segment.

### 4.3.2 Simulation Evaluation

In this section, traditional routing and opportunistic routing will be compared with respect to throughput, delay and delivery ratio. The channel model that was built as described in the previous section is used.

The channel model provided the link quality and the propagation models for the studied area. This information is important for the performance of both the protocols.

Simulation tools were utilized to study the performance of the proposed schemes. The network simulation was performed via the discrete event simulation system OMNeT++ with 30 nodes, with radio transmission range 10 m, uniformly randomly distributed over an indoor environment. The communication parameters were chosen based on IEEE
Chapter 4. Cognitive Networking with Multi-hop Routing

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Table 4.1: Link model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_d$</td>
<td>bit</td>
<td>$128 \times 8$</td>
</tr>
<tr>
<td>$n$</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>$A$</td>
<td>dB</td>
<td>$-31$</td>
</tr>
<tr>
<td>$\sigma_n^2$</td>
<td>dBm</td>
<td>$-92$</td>
</tr>
</tbody>
</table>

802.15.4 and the link model parameters can be seen in Table 4.1.

The channel modeling simulation was performed via the network planning tool Volcano Lab. The indoor model was used, which is a building with a number of rooms. There are wooden walls and doors, glass and plasterboard. The infrastructure of the network area, with the nodes and the topology of the building can be seen in Figure 4.3.

The simulation was conducted in two steps: In the first step, the Volcano Lab was used to calculate the power of the received signal between all the nodes in the network. In the second step, the simulation results from Volcano Lab were used in OMNeT++ to calculate the PER of the different links and apply the routing strategy of the two protocols.

Figure 4.3: Building model and network topology.
4.3.2.1 Throughput

Throughput is the number of bits divided by the time needed to transport the bits. From the source node 1000 packets were transmitted toward each of the 10 different destinations $d_1 - d_{10}$, as in Figure 4.3. The packet size is 200 bytes and the bit rate is 250 kbps hence, the packet transmission time is 6.4 ms. The results can be seen in Figure 4.4.

Traditional routing follows the path that was discovered during the initialization phase for all the packet transmission. For the indoor environment of the simulation, traditional routing follows paths around the different rooms, avoiding the plasterboard.

Opportunistic routing tends to find the best available and shorter path in each time slot towards the destination, leading to better throughput compared with the traditional approach. The path changes dynamically in each packet transmission and it uses nodes that are not used from traditional routing. As a result, the path for each packet might be different and shorter than that of the traditional routing. In this manner, it can achieve better performance in terms of throughput.
4.3.2.2 Delay

Delay of a packet in the network is the time it takes for a packet to reach the destination after leaving the source. The source node sent 1000 packets towards each destination $d_1 - d_{10}$, with transmission time is 6.4 ms. The results can be seen in Figure 4.5.

In traditional routing every packet transmission needs exactly the DATA transmission time to be transmitted between any two nodes.

Opportunistic routing needs also the RTS/CTS handshake hence, the time needed for one transmission between two nodes is:

$$T_{trans} = T_{RTS} + T_{bCNOR} + T_{CTS} + T_{DATA}$$  \hspace{1cm} (4.7)

where $T_{RTS}$ and $T_{CTS}$ is 0.1 ms while $T_{bCNOR}$ can be derived from Eq. (4.5) and is inversely proportional to the distance between the sender and the receiver node.

Traditional routing utilizes the same nodes for each packet transmission. Every packet follows the same path toward the destination and the delay for all the packets, to the same destination, is the same.

Opportunistic routing tends to transmit toward nodes that are closer to the destination in each time slot. Following this routing strategy, opportunistic routing can find shorter paths toward the destination and reduce the packet delay.
4.3.2.3 Delivery Ratio

Delivery ratio is the percentage of the packets that successfully reaches the destination. The source node sent 100 packets to each of the 10 destination nodes. The results are the average delivery ratio toward all the destinations. The source traffic rate was 3, 5 and 7 packets per slot meaning that, during one simulation slot time 3, 5, or 7 packets were transmitted from the source node towards the available neighbour nodes. Each node has a buffer to store the packets. When the buffer of a node is full, the packet is discarded. Figure 4.6(a) shows the results for traditional routing and Figure 4.6(b) shows the results for opportunistic routing, under different buffer sizes and packet frequencies.

Traditional routing has a predefined routing path. When the source traffic rate is greater than the buffer size of a node, the node starts discarding packets. When the traffic rate is same or less than the size of the buffer, the delivery ratio is perfect.

Opportunistic routing performs better in terms of delivery ratio. When the buffer of a node is full, this node does not participate in the RTS/CTS handshake. The transmitter will try to find an available node for data transmission. If all the nodes have full buffer, or there are no more neighbour nodes, the packet is discarded. As it can be inferred from Figure 4.6(b) even in high source traffic rates, opportunistic routing can deliver almost all the packets.

4.4 Measurement Campaign and Calibration

In order to increase the accuracy of the channel model for the simulation environment, a number of measurement campaigns were conducted. The campaigns took place in a complex indoor environment. The results were used to calibrate a novel channel model. The channel model was built in OMNeT++ [63].

Inside a complex indoor environment, multiple contributions between radio nodes are constructed by reflections, transmissions and diffractions on the building structures. In order to build an accurate channel model for a complex indoor environment, the initial channel model was calibrated with real time data. For the collection of the real time data, 24 radio nodes were used during three measurement campaigns.

The procedure can be divided into three phases: In the first phase, the dimension of the simulation area and of the different obstacles is measured. Then, the simulation area is built in OMNeT++ and a simple channel model is implemented. In the second phase,
Figure 4.6: Delivery ratio under different traffic rates.
Figure 4.7: Simulation Environment, the 4th floor of BCIT building at the University of Toronto. It is a complex indoor environment with a number of classrooms, offices and open areas. The materials have been categorized into 6 types: Thin, medium and thick concrete, metal, glass and wood. Each material has a different effect on the wireless signals.

Nodes are distributed in a fraction of the simulation area. The nodes collect useful data for the available channels in different locations of the area, under different communication scenarios. In the third phase of the channel model procedure, the collected data are used to calibrate the simple channel model which was built during the first phase, for the specific environment.

### 4.4.1 Simulation Environment

The studied area is the 4th floor of the Bahen Centre for Information Technology (BCIT) building located at the University of Toronto. The examined floor is a good example of a complex indoor environment and presents a lot of scatterers and obstacles such as walls, pillars, wooden doors, etc. These are of great influence when the radio links in such areas are examined. The channel modeling has to take into consideration those objects to correctly predict the communication link availability in the area.
A 3D DBM of the simulation environment was built. It accurately represents every part of the building, including, floors, walls, doors, windows, etc. Each entity is described by its size – on the order of a few centimetres – and its material, the latter being used to calculate transmission, reflection and diffraction coefficients. The location of these partitions, their width and the material characteristics are obtained from architect plans and were further corrected using recent pictures taken in the field. The 3D DBM are available in CAD files. The location and width of all partitions are generally given with high accuracy, on the order of a few centimetres. The 3D DBM was used in order to design an accurate representation of the building in OMNeT++. Figure 4.7 shows the simulation environment with the different materials that will affect any wireless communication in the area.

### 4.4.2 Simple Channel Model

An initial channel model was built in OMNeT++ with the use of the DBM model. The simple obstacle model was used for the different wall materials. The simulation environment was described with the use of concrete walls, glass windows and wooden doors. This is the simplest description of a complex indoor environment, hence it was used as a simple channel model.

Since the simulation took place in a real environment, it was essential to make sure that the digital simulations accurately reproduced the real propagation of electromagnetic waves. To this aim, a measurement campaign with radio nodes has been realized, leading to the calibration of the initial channel model.

### 4.4.3 Cognitive Radio Nodes

OPM15 radio nodes from OMESH Networks [96] shown in Figure 4.8(a), were used during the data collection. The OPM15 radio is based on IEEE 802.15.4 standard to realize OPM (Opportunistic Mesh) dynamic networking with multi-frequency. The communication rate is 250 kbps and the frequency band is 2.4 GHz.

A node could serve either as stationary or as mobile node. A stationary node frequently broadcasts data packets during the campaign. A mobile node moves around the stationary nodes and collects these packets. The collected data packets include the RSSI value from the different stationary nodes. The data were stored in a file with the ID of the stationary node, along with a timestamp of the measurement.
4.4.4 Measurement Campaigns

Three measurement campaigns were contacted, simulating different communication scenarios. The novelty of the measurement campaigns is the use of the RSSI information from 2.4 GHz wireless nodes to calibrate the channel model as in Eq.(4.1), instead of expensive Continuous Wave (CW) equipment. This approach may lack accuracy, but remains good enough for the purpose of this work. The different campaigns took place on the 4\textsuperscript{th} floor of the BCIT building, to study numerous effects along the corridors and the complex propagation situation.

- **Scenario 1:** Line-Of-Sight path campaign. For the Line-of-Sight (LOS) path measurement campaign, two radio nodes were used. One node served as stationary and the other as mobile. The mobile node kept recording data from different locations while the stationary node kept on broadcasting packets with RSSI data.

The stationary node was located at the one end of the central corridor of the floor. The initial distance between the two nodes was 1 m. Ten different pairs of source and destination nodes were chosen. The distance between them was from 1 m up to 10 m, increased by 1 m in every pair. A spatial averaging configuration was followed: for each distance, 5 locations were measured – central, left, right, up and down – for a more accurate measurement and better calibration. At 2.4 GHz, the wavelength (lambda) is 12.5 cm, hence each location is 12.5 cm from the central.
Figure 4.9: Variation of the received power in time for a node located at the central point of the orientation in 5 different distances between the stationary and the mobile node during the LOS measurement campaign.

Figure 4.8(b), shows the different positions of the mobile node at one location. For each location, the measurement lasts approximately 30 sec and an average number of 240 RSSI values were collected. Figure 4.9, shows the variation of the RSSI values of the LOS path campaign for 5 distances between the communicating nodes.

- **Scenario 2**: Non-Line-Of-Sight path campaign. For the Non-Line-Of-Sight (NLOS) path measurement campaign, 2 radio nodes were used. The communication between the radio nodes was corrupted by four types of obstacles. In the first case, the obstacle was a wooden door of the simulation environment. In the second case, the nodes were placed in the opposite sites of a glass window while in the third case, a plasterboard was between the communicating node. In the fourth case, the nodes were trying to communicate behind a concrete wall of the simulation environment.

In this campaign, one of the nodes was broadcasting packets and the other was recording the data. For each material, the distance between the nodes was increased till there was no communication between them. The initial distance between them was 1m and kept increasing by 20 on each site of the obstacle. In each location, the nodes remain for 1 minute and an average of 410 RSSI values were collected.
• Scenario 3: Building campaign. This measurement campaign covered a large part of the central corridor of the floor. For the network data collection, 24 nodes were used and the communication between them includes LOS as well as NLOS paths. During the measurements, 10 of those nodes were used as stationary nodes. Those nodes continuously broadcast during the whole measurement. The remaining 14 nodes were mobile nodes. These nodes were moving around the stationary nodes and were collecting data. Each node collected data from any stationary node that it could receive. The topology of the stationary nodes and the collecting nodes can be seen in Figure 4.10. In contrast to the two previous campaigns, in this campaign many transmission took place simultaneously from the stationary nodes towards all the mobile nodes. The stationary nodes scanned for the best available channel before any transmission while the mobile nodes listened periodically to the different channels and recorded the data.

The measurement time was 2 minutes for each location. RSSI information was collected from the mobile nodes and used to build the channel model. Between each communicating pair of stationary and mobile node, an average of 630 RSSI values were collected.

4.4.5 Calibration

The calibration is the connection between real measured data and simulated data. It is an essential step to produce realistic information through digital simulations. The main goal is to optimize the simulator to predict a specific metric, such as the received power, as close as possible to the measured data. The exact reproduction of the measured data from the simulated model is difficult because of the discrepancies between the real indoor environment and its digital representation, and because of the fluctuations of a time-variant channel. To measure the degree of exactitude of a model, the standard deviation of the metric difference for the various scenarios was calculated.

In the simple channel model, the description of the different materials and their impact on the communication links between the nodes is generic. After the measurement campaign and the collection of the real measured data, a more accurate description of the material and their impact on the radio was built. For example, it was found that the description of the concrete wall in the simple obstacle model in OMNeT++ is not accurate enough to describe the material of the walls of the simulation environment. This
There are four different materials: wood and glass along with their size as well as concrete and plasterboard along with their attenuation values. There are also 10 stationary and 14 mobile nodes.

description was tuned in order to provide results close to the collected data.

Another very important aspect of the calibration procedure is the readjustment of the floor map data. The best results would be obtained by drawing accurately every piece of furniture on the map. However, a trade-off has to be found between the computation time and the complexity of the map. During the calibration procedure, the points where the real and the simulated data had great difference, more than 5 dBm, were built again in the simulated floor map. The main reason for the great differences was usually factors that affected the signals, such as electric panels inside rooms, which can not be predicted. The measurement campaign followed by the calibration procedure helped to tune the model in those points.

Figure 4.11, shows a comparison among the data from the simple model, the mean value of the data from the LOS measurement campaign and the data from the calibrated
Figure 4.11: Comparison of the LOS measurement campaign data with data from the simple model and the calibrated model that was built based on the mean of the measurement data. The standard deviation between the measured received power and the simulated received power is $\sigma = 1.26$.

channel model. In the LOS measurement campaign, the data points of the simple model follows Eq.(4.1). Figure 4.12, shows similar data for the building campaign. After calibration, the standard deviation between the measured received power and the simulated received power for the LOS and the building campaign is $\sigma = 1.26$ and $\sigma = 2.85$ respectively. The low standard deviation indicates that the simulated points tend to be very close to the mean of the measured points, hence the calibrated channel is accurate enough for the purpose of the simulation. A RSSI measurement campaign leads to an accurate calibration of the initial simple channel model, for an indoor complex environment. With the calibrated model obtained, realistic simulations performed in the entire described area.

### 4.5 Performance Evaluation and Simulation Results

In this section, the proposed protocol with geographic opportunistic routing and simple opportunistic spectrum access routing are compared in terms of throughput, packet delay and total energy consumption. Geographic opportunistic routing (GEOR), follows a
similar approach with GeRaF [14], while every packet transmission is subjected to the PRR. GEOR uses only one channel. Simple Opportunistic Spectrum Access (s-OSA) tries to use multiple channels for packet transmission while it forwards the packet only over reliable links, i.e. links with PRR > 0.8. Identity packets were sent every 100 DATA packet transmissions.

Indoor air quality data are used in the simulation. The data were collected with a wireless sensor node prototype, as described in [37].

The calibrated channel model was used as the wireless channel model. The destination node is located on the very east side of the floor map, as in Figure 4.7. Every sensor node in the network can be a source node that collects and transmits data. The sensor nodes were randomly distributed over simulation environment, inside the classrooms and the offices as well as in the open areas. For every configuration, ten different source–destination pairs were simulated and below are the average simulation results. The communication parameters were chosen based on IEEE 802.15.4. All the simulation parameters are listed in Table 4.2.
### Table 4.2: Simulation Parameters of CNOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{DATA}$</td>
<td>bit</td>
<td>$100 \times 8$</td>
</tr>
<tr>
<td>$L_{RTS/L_{CTS}}$</td>
<td>bit</td>
<td>$8 \times 8$</td>
</tr>
<tr>
<td>$L_{ACK}$</td>
<td>bit</td>
<td>$8 \times 8$</td>
</tr>
<tr>
<td>SIFS</td>
<td>µs</td>
<td>10</td>
</tr>
<tr>
<td>Transmitting Power</td>
<td>mW</td>
<td>15</td>
</tr>
<tr>
<td>Receiving Power</td>
<td>mW</td>
<td>10</td>
</tr>
<tr>
<td>Transmission Rate (R)</td>
<td>kbps</td>
<td>250</td>
</tr>
<tr>
<td>$C_{1_{CNOR}}$</td>
<td></td>
<td>$10^5$</td>
</tr>
<tr>
<td>$C_{2_{CNOR}}$</td>
<td></td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>

Figure 4.13: Throughput under different network density.

#### 4.5.0.1 Throughput

Throughput is the number of bits divided by the time needed to transport the bits. From each of the 10 different source nodes 1000 packets were transmitted towards the destination. The network density was increased from 50 to 400 nodes leading to an average of 3 to 8 neighbour nodes. As the network density increases, the number of the active nodes that can transmit data increases. Figure 4.13 shows the results.
The s-OSA routing protocol follows the most reliable links over multiple channels. As the network density increases, there are more reliable links for that approach. GEOR performs better than s-OSA because it tries to take advantage of the non-reliable links in the network as well. However, the use of one channel, makes that approach worse than CNOR. CNOR can achieve the highest throughput in comparison with the other two approaches because it combines the advantages of the other two. As the number of nodes in the network increases, the number of the relay active nodes also increases, leading to more paths toward the destination. CNOR tries to follow the best available paths in every time slot, and it also uses multiple channels for the packets transmissions.

### 4.5.0.2 Packet end-to-end delay

End-to-end delay of a packet in the network is the time it takes the packet to reach the destination after leaving the source. Each of the 10 different source nodes sent 1000 packets towards the destination, in a network with 200 randomly distributed nodes and with 5 average neighbour nodes and a transmission time of 6.4 ms. Each node can store up to 5 packets in its buffer while if the buffer of a node is full, it can not participate in any packet transmission. The average end-to-end delay of the packets under different packet arrival rates is shown in Figure 4.14.

When the packet rate is higher than the buffer size, the average end-to-end delay in all
the three approaches is increased. The buffer of many nodes tends to be full, decreasing the number of the available relay nodes. The s-OSA uses only the most reliable channels for similar relay nodes while GEOR uses different available relay nodes at the same channel. The introduced CNOR protocol has the best performance in terms of average end-to-end delay. As the number of the packets per second increases, this approach tends to find multiple paths toward the destination and over multiple channels, in order to keep the delay low. It tries to use all the available nodes and all the available channels. This approach uses nodes with available slots in their buffer while nodes with full buffer try to forward their packets through multiple channels to a number of neighbour nodes.

4.5.0.3 Network energy consumption

Network energy consumption is the amount of energy consumed from all the nodes in the network. Every source node sent 100 packets towards the destination while the network density was increased from 50 to 400 nodes. Let the node power consumption in transmitting and receiving/idle modes be denoted by $P_t$ and $P_r/i$ respectively. The sleeping mode power consumption is practically 1000 times smaller than $P_t$ and $P_r/i$, which is negligible [96]. Let $P_t = 15\text{mW}$ and $P_r/i = 10\text{mW}$. For each distance, there are 4 different destination nodes. The energy consumption during the identity packets transmission is also considered, but it is negligible compared with the total energy. Figure 4.15 shows the results.

As the number of the nodes in the network is increased the total energy consumption is increased. The s-OSA protocol keeps using the same relay nodes and the number of the collisions is increased. As a consequence, the number of the retransmissions is also increased leading to a high total energy consumption. The GEOR protocol performs better than s-OSA because it uses different relay nodes. The number of the necessary retransmissions is decreased and the total energy consumption is lower than s-OSA. The CNOR protocol performs slightly better than GEOR. In this approach, when a node is active and has a number of packets to transmit, it can forward them over multiple channels without the need to go back to sleep mode if the channel is occupied, as in GEOR. Although in CNOR the nodes spend some energy on scanning the different channels, the total energy consumption is lower than the other two approaches, as it is shown in Figure 4.15.
4.6 Summary

In this chapter, a novel opportunistic routing protocol for CRSN was introduced. To evaluate accurately the protocol a realistic channel model was built with the use of information from measurement campaigns with wireless nodes. Real data were collected with the use of a prototype of a wireless sensor node and used for experiments. The complexity of the proposed protocol is acceptable enough for a WSN network, however, the cognitive aspects of the protocol may increase the cost per unit.
Chapter 5

Energy Efficiency of Opportunistic Routing

Survivability is crucial in WSNs especially when they are used for monitoring and tracking applications with limited available resources. WSNs are characterized by multi-hop lossy wireless links and severely resource constrained nodes. Usually sensor nodes are inch scale devices that have been designed to work unattended with limited power requirements for long periods of time. Compared to portable devices, such as cellular phones and laptops, where batteries can be recharged frequently, sensor node battery recharging or replacement is sometimes not feasible or even impossible. The lifetime of any individual node, and as a consequence, of the whole network, is determined by how the limited amount of energy is utilized. An energy aware dynamic routing protocol can help combat this issue.

In this chapter, the energy efficiency of the OR protocols for WSNs is examined. First, a novel metric for node prioritization is introduces. This metric tries to keep a balance between the packet advancement and the residual energy in the nodes. An Energy Aware Opportunistic Routing (EAOR) protocol which uses this metric is presented. Then, this protocol is further extended to the cognitive area. An Efficient Cognitive Unicast Routing (ECUR) is introduces. ECUR uses a similar metric, but also has cognitive principles. Both protocols performances are examined and compared through simulations. ECUR is further implemented in hardware and used in an indoor application as it will be described in Chapter 6.
5.1 Problem Formulation

One of main critical concern in almost every Self-Powered WSN protocol design is energy efficiency. A lot of research effort focuses on the energy conservation at every layer in the traditional protocol stack.

Among the energy consumption factors, wireless communication has been identified as the major source of energy consumption and costs significantly more than computation in WSNs [97]. Opportunistic routing has shown its advantage on energy efficiency compared to traditional routing [14, 16, 98]. However, the existing opportunistic routing schemes like GeRaF [14,16] typically include all the available next-hop neighbours as forwarding candidates, which does not lead to optimal energy efficiency. There is a need to design a protocol with special characteristics for this special sub-category of WSNs.

5.1.1 Energy Consumption Model

In energy consumption model that is used, the nodes consume energy only to listen to transmissions intended for themselves. In order to achieve energy efficiency, it is not assumed that every node “overhears” any transmission within its range. To achieve this, a second low power radio [99] is used to wake up the nodes that should participate in the transmission. In this way, a node will shut down its data radio if it does not participate in the transmission, hence, it saves energy. Moreover, a node consumes energy during packet transmission and reception. The energy consumption for transmission is comparable with this of the reception [96, 100]. For simplicity, it is assumed that it is the same. Finally, it is assumed that the energy consumption for the control packets and for idle/sleep mode is negligible. For the control packets, there are protocols that have high energy consumption. However, the energy consumption is likely a non-decreasing function of the number of forwarding candidates. Consequently, ignoring it will not affect the upper bound analysis of the energy efficiency in this work.

Following the above assumption, the total energy consumption $E_t$, for one opportunistic forwarding attempt is [98]:

$$E_t = E_{tx} + E_{rx}$$  \hspace{1cm} (5.1)

where $E_{tx}$ and $E_{rx}$ are the packet transmission and reception energy consumption, respectively.
5.1.2 Trade-off Between Packet Advancement and Energy Consumption

One of the most important factors in every OR is the next node selection criterion, as discussed in Chapter 2. In a Self-Powered WSN this criterion should also include the residual energy level in the node. When the transmitter has a forwarder set, it needs to decide the next relay node. This selection can be complicated, as illustrated in Figure 5.1.

The selection of a node with high residual energy might lead to more transmissions. On the other hand, a node which provides higher packet advancement, might not have sufficient residual energy. In both cases, the PER can affect any packet transmission.

It is clear that there is a trade-off between the packet advancement and the residual energy. In a Self-Powered WSN with energy harvesting mode, the residual energy can reach acceptable levels after a certain time. Every protocol design should be aware of this trade-off. An approach that we use in this work is based on a novel prioritization metric which tends to optimize the balance between these two factors.

The novel metric is based on a prioritization over successful RTS packets. When a node receives a RTS, it backoffs for a time before it replies with a CTS. This CTS time is calculated in order to optimize the energy balance in the network while it keeps high throughput. Two different protocols were designed with the use of this metric. The main
difference between the protocol is the use of cognitive radio. The protocols are described in the following sections.

5.1.3 Related Work

An Energy Efficient Opportunistic Routing (EEOR) was introduced in [101]. In EEOR, the forward list is prioritized to minimize the total energy cost. A continuous-time Markov model was introduced in [102] to analyze the problem of the energy-efficient optimal opportunistic forwarding policies in the delay tolerant networks. A comprehensive and systematic summary of energy conservation schemes for WSNs is presented in [103].

In comparison to these schemes, we propose the use of opportunistic routing along with cognitive networking for an indoor monitoring system. The relay node prioritization combines energy and location information. A prototype is also designed to show the performance of the proposed protocol.

5.2 An Energy Aware Opportunistic Routing

In this section, an Energy Aware Opportunistic Routing (EAOR) for WSNs is introduced, as in [104]. EAOR keeps balance between the QoS and the energy consumption. The main objective is to maximize the network lifetime without increasing the packet delay.

Simulations were conducted to evaluate the performance of EAOR protocol against simple opportunistic routing and traditional routing. These three protocols were compared in terms of throughput, total energy consumption, network lifetime and network distribution. The experimental results demonstrated that the EAOR can deliver better energy distribution, extends the network lifetime up to 25% compared to simple opportunistic routing protocols and decreases the total energy consumption by 35% compared to traditional routing.

5.2.1 Routing Protocols

The two protocols which are used is traditional routing and OR from Section 3.4.1. and Section 3.4.3 respectively. These two protocols are compared with EAOR. Traditional routing was used as an example of a single hop routing while opportunistic is a multi-hop routing protocol.
5.2.2 EAOR: Energy Aware Opportunistic Routing

The Energy Aware Opportunistic Routing (EAOR) follows a similar transmission approach as the opportunistic routing. However, the main difference of this approach is the next relay node selection criterion. The relay node that replies first to a RTS packet is different than that of opportunistic routing. The difference is on the backoff time definition and affects the whole routing scheme. The backoff time of EAOR is equal to:

\[ T_{bEAOR} = \frac{C_1^{EAOR}}{d_{src,cnd}} + \frac{E_{cons}}{C_2^{EAOR}} + SIFS, t \neq d \]  

(5.2)

where \( E_{cons}(t) \) is the consumed energy of the neighbour node up to the time that it received the RTS packet, \( C_1^{EAOR} \) is a constant related to the transmission range and \( C_2^{EAOR} \) is a constant related to the energy. Figure 5.2 shows the backoff time for EAOR under different \( E_{cons} \).

When the nodes have similar \( E_{cons} \) level, the prioritization is based on their location. However, nodes that are in the same distance, but have different \( E_{cons} \) level are prioritized based on their remaining energy. Nodes with high energy levels (and low \( E_t \) levels), reply first.

As it can be inferred from Eq.(5.2), in EAOR a node checks its energy consumption before replies with an RTS. If the energy consumption is high, it does not reply with a
CTS. In this way, the lifespan of each node is extended. When a node has high energy consumption, the probability to get a DATA packet is lower. However, the node can still participate in some of the DATA packet transmissions. If a neighbour node has low energy consumption, but it is not that close to the destination in comparison with other neighbour nodes, it will participate in packet transmissions when some of the neighbour nodes have consumed too much energy.

EAOR tries to transmit the packets over nodes that are close to the destination and also have high energy level. In this way, it discovers more routing paths compared to the OR. These paths do not always have similar number of hops with the OR paths however, they consist of nodes that have not been used that much and have high energy levels.

5.2.3 Performance Evaluation

The discrete event simulation system OMNeT++ [63], was used for simulations. The three routing protocols were examined in terms of throughput, total energy consumption, network lifetime and energy distribution.

5.2.3.1 Simulation Setup

The nodes were uniformly randomly distributed over a 120 × 120 m² network field. Each node has a transmission range of 12 m. For traditional routing the reliability threshold was set at 20% while for the two other protocols we considered links with PER up to 80%. The communication parameters were chosen based on IEEE 802.15.4. The simulation parameters are listed in Table 5.1.

5.2.3.2 Performance Metrics

The performance of the three routing protocols will be examined in terms of throughput, total energy consumption, network lifetime and energy distribution among the nodes.

5.2.3.3 Throughput

Throughput is the number of bits divided by the time needed to transport the bits. A number of 100 packets were successfully transmitted from the source node towards the destination node. The throughput for each protocol and for each network configuration can be seen in Figure 5.3.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the data ($F_d$)</td>
<td>bit</td>
<td>$100 \times 8$</td>
</tr>
<tr>
<td>Wireless channel path loss component ($n$)</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Constant decided by the antenna gain ($A$)</td>
<td>dB</td>
<td>$-31$</td>
</tr>
<tr>
<td>Noise Power ($\sigma_n^2$)</td>
<td>dBm</td>
<td>$-92$</td>
</tr>
<tr>
<td>$L_{DATA}$</td>
<td>bit</td>
<td>$100 \times 8$</td>
</tr>
<tr>
<td>$L_{RTS/LCTS}$</td>
<td>bit</td>
<td>$8 \times 8$</td>
</tr>
<tr>
<td>$L_{ACK}$</td>
<td>bit</td>
<td>$8 \times 8$</td>
</tr>
<tr>
<td>SIFS</td>
<td>$\mu$s</td>
<td>10</td>
</tr>
<tr>
<td>Transmitting Power ($P_t$)</td>
<td>mW</td>
<td>15</td>
</tr>
<tr>
<td>Receiving Power ($P_{r/n}$)</td>
<td>mW</td>
<td>10</td>
</tr>
<tr>
<td>Transmission Rate ($R$)</td>
<td>kbps</td>
<td>250</td>
</tr>
<tr>
<td>$C_{1EAOR}$</td>
<td></td>
<td>0.001</td>
</tr>
<tr>
<td>$C_{2EAOR}$</td>
<td></td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 5.1: Simulation parameters for EAOR.

Traditional routing has the lowest throughput over the other two protocols. All the packets follow the same path which is the shortest path that consists of the most reliable links. A packet error or a node failure will delay all the consequent packet transmissions, increasing the delay of the packets and decreasing the throughput. As the number of the nodes in the network increases, there are more reliable paths towards the destination that require less hops and the throughput increases.

Opportunistic routing performs better over the other two approaches. The next node selection criterion of this approach is the location. It tries to transmit each packet over the path that has the smallest number of hops under the network conditions at the transmission time. For a large number of nodes, the number of the paths is increased and as a consequence the throughput increases.

EAOR performs worse than OR. The reason is that the selection criterion of this approach is a combination of the smallest available path at the transmission time and the energy of the nodes that are in this path. When a neighbouring node has participated in many packet transmissions and it has low energy level, this approach will not use this node, even if it can deliver the packets to the destination in less number of hops. It is obvious that this affects throughput performance. However, as the number of the
nodes increases, there are more paths that consist of nodes with high energy levels. Consequently, EAOR tends to have similar performance with OR.

5.2.3.4 Total energy consumption

The energy consumption is evaluated by simplifying the power consumption of the battery operated nodes. For simulation purposes, the node power consumption in transmitting and receiving/idle modes are denoted by $P_t$ and $P_r/i$ respectively. The sleeping mode power consumption is practically 1000 times smaller than $P_t$ and $P_r/i$, which is negligible. The source node transmits 100 packets toward the destination node. Figure 5.4 shows the total energy consumption of the network for the three different protocols.

Traditional single hop routing has the worst performance over all the three protocols. This approach uses the same nodes for every packet transmission. If a packet is lost or damaged and has to be rescheduled, all the consequent packet transmissions have to be buffered and delayed. The nodes have to remain active for higher time and the energy consumption is higher. The other two protocols are multi-hop and are able to discover different paths toward the destination, leading to better performance in terms of total energy consumption.

EAOR performs up to 35% better than traditional routing and slightly better than simple opportunistic routing. The reason is the next node selection criterion. EAOR
tries to discover paths towards the destination that have less number of hops, but also consist of nodes that have high remaining energy. As the number of the nodes in the network increases, the number of the nodes with high remaining energy increases, leading to more paths toward the destination for the energy aware protocol. As a consequence, the difference in the total energy consumption between the two protocols also increases.

5.2.3.5 Network lifetime

Network lifetime has plenty of definitions [105], depending on the application. In this work, network lifetime is defined as the interval between the beginning of a packet transmission of the network time until the first node failure due to battery depletion. Under the assumption that the sensor nodes operating on a pair of AA batteries with 1000 mAh capacity, each sensor node will have an initial energy of:

\[
\text{Initial Energy (J)} = \text{capacity}(Ah) \times \text{voltage}(V) \times \text{time}(s)
\]

\[
= 1 \times 2 \times 1.5 \times (60 \times 60) = 10800J
\]  

(5.3)

Figure 5.5 shows the network lifetime under the different protocols. Traditional routing uses the same nodes for packet transmission, resulting in lower network lifetime. Moreover, when one of the nodes that participate in the packet transmission runs out of energy, the packets can not reach the destination and there should
be another initialization phase in the network to find another path. The other two approaches do not require an initialization phase after the first node battery depletion because they can dynamically change the path and use nodes that they do have energy to transmit the packet.

Opportunistic routing performs better than traditional routing, but worse than EAOR while EAOR performs up to 25% better than single opportunistic routing. Energy aware opportunistic routing tries to maximize the network lifetime. It can discover paths that consist of nodes with high energy level while it avoids using nodes that already have participated enough times in packet transmission. As the number of the relay nodes increases, the number of the possible paths also increases, leading to an increase at the network lifetime.

5.2.3.6 Energy distribution

Energy distribution is used to illustrate the energy consumption of each node in the network. The network consist of 300 nodes, uniformly and randomly distributed. The results of the energy distribution, the network topology with the energy consumption per node, as well as the histogram of the energy consumption per node, can be seen in Figures 5.6, 5.7 and 5.8.

As illustrated in Figure 5.6, traditional routing uses the same nodes toward the des-
tination. Energy consumption in those nodes is high, while the rest of the nodes in the network consume negligible energy during idle state.

Opportunistic routing uses different paths toward the destination by using different
nodes, as shown in Figure 5.7. The selection criterion of these nodes is in the distance of each node from the destination. Hence, the energy distribution is better than traditional routing. The nodes that are used are close to the shortest path between the source and the destination.

EAOR performs better over the other two approaches in terms of energy distribution, as shown in Figure 5.8. It uses nodes that are close enough to the destination and also have enough energy consumption. Some of the nodes that are used, might be away from the shortest path between the node and the destination. However, the total energy consumption is better than opportunistic routing, as it was shown in Figure 5.4.

According to the simulation results depicted in Figures 5.6, 5.7 and 5.8, after transmitting the same number of packets the maximum energy consumption in a single node in traditional routing is 15J, in opportunistic routing it is 12J and in EAOR it is 7J. If it is assumed that the total energy of each sensor with a pair of AA batteries is 10800J then the first node that will run out of energy in traditional routing will be after 720 hours, in opportunistic routing after 900 hours and in energy aware after 1542 hours.

5.3 An Energy Efficient Cognitive Unicast Routing

An Energy Efficient Cognitive Unicast Routing (ECUR) protocol is also developed, which was introduced in [34]. In this section, the principles of this protocol are highlighted. The protocol is also implemented in hardware and used for an indoor monitoring application, and will be described in the following chapter.

5.3.1 System Model

This section describes the implementation of the ECUR protocol.

5.3.1.1 Network address mechanism

Each node in the network has a unique network address which is related to the unique radio serial number of each node. When the network is deployed for the first time, there is an initialization phase which is run to establish the initial network connections. As described in the protocol, during this phase the nodes discover their neighbour nodes as well as their distance in hops from the destination. This information is stored in each node and is updated, if necessary, during the periodic network maintenance phase.


5.3.1.2 Radio implementation

ECUR uses cognitive networking aspects to increase network performance and the OPM15 nodes [96] support cognitive network principles. The nodes are equipped with two chip antennas which are placed orthogonal to each other at the edges of the board. One antenna is used for data transmission and the other is for controlling and spectrum sensing. The radio uses this special architecture to realize opportunistic spectrum selection at the millisecond level, and opportunistic routing on a per-packet level.

5.3.1.3 Collision avoidance mechanism

The radio on the OPM15 node implements a Carrier sense multiple access with collision avoidance (CSMA/CA) method and the ECUR protocol follows a RTS/CTS handshake between neighbour nodes. In this way, the problem of hidden nodes can be alleviated. In addition, ECUR uses the RTS/CTS mechanism for the relay node prioritization process described later.

5.3.2 ECUR: Efficient Cognitive Unicast Routing

ECUR is a reactive routing protocol since it discovers routes only when desired. It has three phases:

5.3.2.1 Initialization phase

After the nodes have been deployed at the monitoring area, the network goes through the initialization phase. From the control room, a number of small packets are broadcasted to the network. In this way, each node can find:

- minimum distance from the destination in hops,
- neighbour nodes, its relative location and the required transmission energy $E_{tx}$ towards them, and
- the candidate nodes that can serve as relay nodes.

The neighbour nodes are the nodes that are within the transmission range of a node. The candidate nodes are those neighbour nodes that are located towards the destination and can serve as relay node. The initialization phase helps the nodes to discover multiple
paths towards the destination. For every path, the node has an approximation of the required energy for transmission and the number of hops. This information is important for the ECUR protocol and is updated, if necessary, during the periodic route maintenance process.

### 5.3.2.2 Transmission process

After the initialization phase, the nodes can start the packet transmission.

When node $i$ has a packet to transmit, it senses for an available channel. When an idle channel is found, node $i$ broadcasts a RTS packet. If a neighbour node $j$ receives the packet, based on the link PRR, it might respond with a CTS packet over the same channel. Node $j$ will respond only if it is available for immediate packet transmission and there are no other packets waiting to be transmitted. Node $i$ will forward the candidate node that replies first with a CTS. Node $i$ will ignore any CTS packets that it might get from neighbour nodes that are not in the candidate node set. However, these packets are used later during the route maintenance phase.

The candidate node prioritization is based on their energy level and their distance from the destination. On the reception of the RTS packet, the neighbour node $j$ will wait for time:

$$T_{ECUR} = C_{1ECUR} \times \frac{E_{cons}}{E_{init}} + C_{2ECUR} \times \frac{1}{d_{i,j}} + SIFS, i \neq j$$ (5.4)

where $C_{1ECUR}$ is a constant related to the initial energy at the node, $C_{2ECUR}$ is a constant related to the transmission range, $E_{init}$ is the initial energy at the node and $E_{cons}$ is the total energy consumption of the node up to the current time slot which can be calculated as:

$$E_{cons}(t) = a \times P_t + b \times P_{scan} + c \times P_s + d \times P_{r/i}$$ (5.5)

where $P_t$ and $P_{r/i}$ are the transmitting and receiving/idle power respectively, $P_{scan}$ is the energy consumed on scanning the different channels, $P_s$ is the power consumption of a node on the sleep mode, and $a, d, b, c$ are the total transmission/reception time, scanning time and idle/sleep time respectively. The energy consumption during processing and queuing is also included in the $b$ time and

$$t \simeq a + b + c + d$$ (5.6)
Figure 5.9: The routing mechanism of the ECUR protocol. When a node has a packet to transmit, it becomes the source node and some of its neighbour nodes are the candidate nodes. Only one of those nodes will become the next relay node.

because there is also some processing/queuing time. When $E_{\text{cons}}$ is equal to $E_{\text{init}}$ the sensor node runs out of energy and stops participating in any transmission.

On the reception of a CTS packet from a node $j$, node $i$ will forward the DATA packet to this node and will wait for an ACK. The routing mechanism is shown in Figure 5.9.

### 5.3.2.3 Comparison of EAOR and ECUR

ECUR is an extended version of EAOR in the cognitive area. As it can be inferred, Eq. (5.2) and Eq. (5.4) are similar. However, there is a great difference. In Eq. (5.4) and in ECUR, the consumed energy is compared with the initial energy, while in EAOR it is not. The reason is the application behind these protocols. ECUR is designed for Self-Powered WSNs with energy harvesting capabilities. These networks have fixed initial energy and can not be changed. Specifically, as it is covered in the following Chapter, ECUR is designed for WSNs with solar panels. The battery capacity of those nodes is fixed and well-known at the beginning of the network operations.

On the other hand, EAOR is designed for WSNs with limited energy resources. The initial energy is not fixed and the size of the batteries can vary between nodes. In the following Chapter, there are nodes that are equipped with 3AA batteries and nodes with 2 or 1 AA battery. In this case, it is important to balance the energy in the network in comparison with the energy that each node consumes.
### Table 5.2: Simulation parameters of ECUR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the data ($L_f$)</td>
<td>bit</td>
<td>$100 \times 8$</td>
</tr>
<tr>
<td>$L_{RTS}/L_{CTS}/L_{ACK}$</td>
<td>bit</td>
<td>$8 \times 8$</td>
</tr>
<tr>
<td>SIFS</td>
<td>µs</td>
<td>10</td>
</tr>
<tr>
<td>Transmission Range (Range)</td>
<td>m</td>
<td>10</td>
</tr>
<tr>
<td>Transmitting Power ($P_t$)</td>
<td>mW</td>
<td>15</td>
</tr>
<tr>
<td>Receiving Power ($P_{r/i}$)</td>
<td>mW</td>
<td>10</td>
</tr>
<tr>
<td>Transmission Rate ($R$)</td>
<td>kbps</td>
<td>250</td>
</tr>
</tbody>
</table>

#### 5.3.2.4 Route maintenance

When there is no traffic in the network, or when some of the nodes do not transmit packets for a long time, the route maintenance phase takes place. The nodes use information from RTS/CTS and DATA packets to update their variables regarding their neighbour nodes. Information such as relative location can be extracted through the RSSI from the packets. Moreover, information about nodes which leave or join the networks is exchanged.

#### 5.3.3 Performance Evaluation

In this section, the proposed protocol is compared with geographic opportunistic routing in terms of total energy consumption, network life time and average end-to-end delay. The next relay node selection criterion in geographic opportunistic routing is the distance from the destination only, hence, in that approach, the first factor in Eq.(5.4) is equal to zero.

The discrete event simulation system, OMNeT++ [63], was used for simulations. The sensor nodes were uniformly randomly distributed over a $100 \times 100$ $m^2$ network field. The communication parameters were chosen based on IEEE 802.15.4. All the simulation parameters are listed in Table 5.2.

#### 5.3.3.1 Total energy consumption

The energy consumption is evaluated by simplifying the power consumption of the battery operated nodes. The sleeping mode power consumption is practically 1000 times smaller
than $P_{TX}$, which is negligible for simulation purposes. The source node transmits 100 packets toward the destination node while the network density is increased.

The total energy consumption of the two approaches can be seen in Figure 5.10. In terms of total energy consumption for 100 packet transmissions, ECUR performs better than geographic opportunistic routing. This is mainly because of the cognitive aspect of the proposed protocol. In geographic opportunistic routing, every node has to wait for the channel to be available before transmitting. During that time, the node remain active and consumes energy. On the other hand, in ECUR a number of different channels are used to forward the packets to the destination. Every node can select an available channel to forward the packet to an available candidate node. As a consequence, the time that the sensor nodes have to remain active in order to transmit a packet is smaller, leading to a better total energy consumption.

As the number of the neighbour nodes increases, the number of the available paths also increases. Some of those paths can lead to the destination in less hops, leading both the protocols to decrease their total energy required. ECUR uses all these new path in a more energy efficient way and because of its cognitive aspect the difference between the two protocols increases as the number of the neighbour nodes increases.
5.3.3.2 Network lifetime

Network lifetime is defined as the interval between the beginning of a packet transmission of the network time until the first node failure due to battery depletion.

Figure 5.11 shows the results. The next node selection criterion in geographic opportunistic routing is the location of the nodes. When the network conditions remain stable, the same nodes are selected to forward the packets. Following this routing approach, these nodes will transmit most of the packets and eventually they will run out of energy.

On the other hand, ECUR tries to discover paths that consists of sensor nodes that are closer to the destination, and also with the high energy levels, according to Eq.(5.4). The location of the next node is important, but the energy level of the next node is also crucial. Nodes that have not participated in many packet transmissions are preferred. As long as there are neighbour nodes in comparable distances with high energy levels, these nodes are preferred over nodes with lower energy levels. When all the nodes in a distance reach a similar low energy level, then the proposed protocol will use the remaining level of a node for a transmission and that node will run out of energy. In this way, network lifetime is higher than geographical routing. Moreover, as the network density increased there are more neighbour nodes in similar distances from the transmitter, extending the network lifetime. Furthermore, compared to geographic routing, the transmission takes place over multiple channels with a cognitive collision avoidance scheme.
5.3.3.3 End-to-end delay

End-to-end delay is the time required for a packet from the source to reach the destination. In our simulation a number of 1000 packets were transmitted from the source to the destination for each network density and the average end-to-end delay was calculated. The results are shown in Figure 5.12.

ECUR does not perform as well as geographic opportunistic routing when the network density is low. The main reason is that the cognitive aspect of that approach needs a sufficient number of neighbours in similar distances in order to perform as well as geographic routing. Without enough neighbours around, ECUR tends to use nodes with high energy levels, even if these nodes lead to paths with more hops, increasing the packet delay. As the network density increased, both the protocols perform better. More routing paths can be discovered, with less number of hops hence the packet delay is smaller. As the density increases ECUR starts having similar performance with geographic opportunistic routing. There are more neighbour nodes in similar distances that can deliver the packets at comparable times and ECUR uses these nodes.
5.4 Performance Comparison of EAOR and ECUR

To evaluate the performance of the introduced ECUR protocol, the discrete event simulator OMNeT++ was used. Four routing protocols were implemented following the prototype requirements [37–39]. The protocols were compared in terms of total energy consumption, energy distribution, network lifetime and packet latency.

5.4.1 Simulation Parameters

The sensor nodes are randomly deployed in a $100 \times 100 \text{m}^2$ area using a Poisson distribution with a $\lambda = 0.101$. Every node has an average 8 neighbour nodes and the transmission range of each node is 12 m.

In traditional routing, a node transmits the packets over the same, reliable link. In the simulation, a link is considered reliable if the PER is less than 10%. The other three approaches can try to use links with a PER up to 80%.

The communication parameters were chosen based on IEEE 802.15.4 and all the simulation parameters are listed in Table 5.3. It is important to notice that for EAOR the distance factor is equal to zero, $C2_{EAOR} = 0$. Hence, the results is an energy exclusive version of EAOR.

Ten topologies with the number of nodes in each ranging between 900 to 1100 were evaluated. The distance between the source and the destination was varied between 20 to 200 meters. For each topology the source generated 1500 packets towards the destination. In every topology, 10 different source-destination pairs were selected, each with different distances between them.

5.4.2 Performance Analysis

The protocols are compared in terms of total energy consumption, energy distribution, network lifetime and average packet latency.

5.4.2.1 Total energy consumption

Total energy consumption of all the protocols is shown in Figure 5.13. ECUR has a similar performance to the geographic routing primarily because of the opportunistic principles that govern both. Nodes that are closer to the destination are selected as relays, hence there are fewer packet transmissions. At some distances, ECUR consumes
<table>
<thead>
<tr>
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</tr>
<tr>
<td>$L_{DATA}$</td>
<td>bit</td>
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<tr>
<td>$L_{RTS/LCTS/LACK}$</td>
<td>bit</td>
<td>$8 \times 8$</td>
</tr>
<tr>
<td>$C_{2EAOE}$</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>$C_{1ECUR}$</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>$C_{2ECUR}$</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>SIFS</td>
<td>$\mu$s</td>
<td>10</td>
</tr>
<tr>
<td>Transmitting Power</td>
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<td>15</td>
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<tr>
<td>Receiving Power</td>
<td>mW</td>
<td>10</td>
</tr>
<tr>
<td>Transmission Rate</td>
<td>kbps</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 5.3: Simulation parameters for comparison of the four protocols.

Figure 5.13: Total energy consumption of the different protocols.

a bit more energy because of the channel scanning and the energy level parameter in the calculated backoff time. However, it performs better than the other two approaches. Traditional routing uses the same reliable links for multiple packet transmissions and
these reliable links consist of neighbour nodes which are close to the transmitter. As a result, the number of hops and the number of transmissions is increased when compared with using neighbour nodes closer to the destination as is the case for the first two methods. The exclusive energy aware performs worst overall. This approach uses nodes with the highest energy levels without considering their location. Hence, the number of transmissions is increased leading to higher energy consumption.

5.4.2.2 Energy distribution

Energy distribution refers to the energy consumption of each node in the network. At the end of all the packet transmissions for one of the topologies, we measured the remaining energy in each node. We then subtracted this from the initial energy to calculate the energy consumption of each of the nodes. The energy distribution for all the protocols can be seen in Figures 5.14, 5.15, 5.16 and 5.17.

Traditional routing always uses the same nodes to forward the packets and these are the nodes that consume the most energy in the network, shown in Figure 5.14. On the other hand, the exclusive energy aware routing tries to use all the nodes in the network, leading to paths with many nodes. However, the energy consumption in almost all the nodes in the network is similar, as shown in Figure 5.16. Geographic routing tends to use nodes that are closer to the destination. Due to its opportunistic nature, geographic routing also uses a number of different paths toward the destination, as shown in Figure 5.15. However, the number of the paths is limited under stable network conditions. Finally ECUR, shown in Figure 5.17, uses many paths toward the destination and balances the energy consumption among the nodes on these paths. These results, along with the fact that ECUR has a similar performance with geographic routing in terms of total energy consumption, makes ECUR a promising routing approach. It consumes almost the same energy as the geographic routing and it has a higher energy distribution among the nodes.

5.4.2.3 Network lifetime

Network lifetime has plenty of definitions [105], depending on the application. In this work, and for a monitoring application, the network lifetime is considered as the time until “connectivity” or “coverage” is lost, i.e. there are no paths between the source and the destination or if one of our monitoring boards is drained of its energy.
Figure 5.14: Traditional routing distribution of energy consumption in the network.

Figure 5.15: Opportunistic routing distribution of energy consumption in the network.

Figure 5.16: EAOR distribution of energy consumption in the network.

Figure 5.17: ECUR distribution of energy consumption in the network.
Each relay sensor nodes operates on three AA batteries with 1000mAh capacity, hence it will have an initial energy of:

\[
E_{\text{init}\_\text{relay}} = \text{capacity}(Ah) \times \text{voltage}(V) \times \text{time}(s) \\
= 1 \times 3 \times 1.5 \times (60 \times 60) = 16200 J
\] (5.7)

Similarly, each monitoring node operates on one 9V battery:

\[
E_{\text{init}\_\text{mon}} = 1 \times 9 \times (60 \times 60) = 32400 J
\] (5.8)

The network lifetime of all the protocols is shown in Figure 5.18.

Traditional routing uses the same nodes for every packet transmission, hence the network lifetime is almost the same under any distance. The other three approaches perform better mainly because of their next relay node selection process. The greater the distance between the source and the destination, the more nodes that are between them and, as a consequence, the more paths these approaches can discover. As shown before, ECUR uses the same energy, in total, compared with geographic routing, however, ECUR tends to also discover nodes with sufficient energy levels in addition to good geographic location. Consequently, ECUR extends the network lifetime compared with geographic
5.4.2.4 Average packet latency

Average packet latency in our simulation is the number of the hops that are required in order for a packet to reach the destination. The average packet latency of all the protocols is shown in Figure 5.19. These are the average values for all the source–destination pairs and for all the 10 different topologies.

As like some of the performance criteria before, ECUR and geographic routing have similar performance in terms of their latency. Geographic routing takes advantage of opportunistic principles and chooses relay nodes on the shortest available path towards the destination. Similarly, ECUR uses its cognitive aspect to transmit to nodes that are closer to the destination, which also have sufficient energy level and are available for immediate transmission. The other two approaches perform worse since they have different selection criterion for the next relay node that does not involve the location of the node.
5.5 Summary

In this chapter, the energy efficiency of opportunistic routing was examined. Although OR has great advantages in network throughput, it does not optimize the energy consumption. To address this problem, a novel prioritization metric for the neighbour nodes was introduced. The metric balances the residual energy level in the node and the packet advancement. EAOR and ECUR protocols for WSNs which use the novel metric were presented. The first has a single channel OR in order to extend the network lifetime. The latter has cognitive capabilities and performs better than EAOR in terms of average packet latency.
Chapter 6

Self-powered WSNs for Environmental Monitoring Applications

This chapter focuses on environmental monitoring applications. First, the challenges in environmental monitoring are discussed. Then, the Self-Powered Sensor Network (SPSN) testbed is described. SPSN was developed to simulate most of the introduced protocols. Next, three different monitoring applications are described: an indoor carbon dioxide system, an outdoor gas leak detection system and a video surveillance system. All the three applications are designed and tested in the proposed SPSN framework.

6.1 Environmental Monitoring Though WSNs

Environmental monitoring describes the processes and activities that need to take place to characterize and monitor the quality of the environment. Traditionally, environmental monitoring is achieved by a small number of expensive and high precision sensing units. Collected data are retrieved directly from the equipment at the end of the experiment and after the unit is recovered. The design and implementation of a WSN provides an appealing alternative solution. Although the nodes might be equipped with sensors with less precision, the network can provide spatial resolution of the area. The users can have remote access to the monitoring area.

Nowadays, the use of WSNs for monitoring application covers a great area of the environmental monitoring [106], from air and water quality monitoring to rainforest and biodiversity monitoring. Sensor nodes are the elementary components of an WSN and they can provide many functionalities including [107]: signal conditioning and data acqui-
sition, temporary storage for the data, data processing, analysis of the processed data, self-monitoring (e.g., supply voltage), scheduling, receipting and transmission of data packets and coordination and management of communications and networking.

However, they also pose a number of challenges. Survivability is one of the most crucial. The lifetime of any individual node and as a consequence, of the whole network, is solely decided by how the limited amount of energy is utilized. Energy harvesting can alleviate the problem. Self-powered WSNs provide the possibility of very long sensor node lifetimes while their deployment would have the least impact on the existing infrastructure. The total network lifetime can be extended compared with traditional battery-powered WSNs.

In the following sections, a Self-Powered Sensor Network testbed is introduced, followed by three monitoring applications that have been developed.

6.2 The SPSN Testbed

Motivated by the WSN tremendous potentials, coupled with the technological limitations affecting the current WSN platforms as described in previous chapters, in this section, a Self-Powered Sensor Network (SPSN) testbed is introduced. The SPSN testbed consists of self-powered wireless sensor nodes. The nodes can operate indoor with batteries [37–39] and outdoor with a solar system [108, 109], depending on the application requirements. They also have two antennas for cognitive networking [110] and implement a number of routing protocols.

6.2.1 System Framework

In this section, an application scenario is described, followed by the system requirements and the system models of the introduced SPSN system, as in [36].

6.2.2 Application Scenario

A Self-Powered WSN for monitoring application is considered. The application can be indoor or outdoor. A number of wireless sensor nodes along with a number of simple relay nodes are deployed in the monitoring area. Each node is equipped with a sensor module and a wireless transmission module while the relay nodes have only communication capabilities. The data from the sensor module are passed to the transmission module
which will forward all the necessary data to the control room, through the relay nodes. Both the sensor units and the relay nodes are powered by batteries for indoor or by a solar system for outdoor applications. As an indoor application, a wireless monitoring system for $CO_2$ levels in a building is considered while as an outdoor application a gas leak detection system is examined.

### 6.2.3 System Requirements

A monitoring system has a number of requirements, depending on the application scenario. Apart from general system requirements, such as the size of the units and the cost per unit, at the network level, the proposed system has the following requirements:

- **Real-time data aggregation.** The packets related to the $CO_2$ levels or the gas leakage, should be delivered to the destination on time with a minimum delay.

- **Energy efficient sensor units.** The units should operate unattended for long periods of time and hence, the network lifetime is important. An energy conserving routing protocol should be applied.

- **Drop-and-play units.** The units should be able to join or leave the network at any time.

- **Location information.** The location of the even should be included in the packet towards the destination.

- **Coexistence problem.** The system should have minimum interference with other infrastructures. Especially in the indoor case, the system should be flexible in the spectrum selection and not interfere with other WLANs.

Following the above requirements the SPSN framework was designed.

### 6.2.4 System Modules

SPSN framework has three important modules: the sensor units, the relay nodes and the control room. In the following, a brief description of each module is given.

- **Sensor unit.** The sensor unit is the monitoring module. It consists of a prototype radio board that has two antennas and performs the spectrum sensing and
the routing protocol. Also, it has a sensor node attached. The sensor can monitor the concentration of \( CO_2 \) as well as gas leakages, temperature and humidity. The development board (the sensor and the radio), is connected either to a 9V battery (indoor) or to a solar system (outdoor) depending on the application. The solar system consists of a photovoltaic solar panel with operating voltage 5V and operating current 560mA. The panel is connected to the rechargeable battery through a charger. The battery is a polymer lithium ion battery of 6600mAh and 3.7V.

- **Relay node.** The relay node has the same radio board with the sensor unit. This module however, does not have a sensor. Hence, the total energy consumption is lower. It performs the main packet forwarding and uses either 2AA batteries or a solar system. Periodically, the relay nodes broadcast advertisement packets. In this way, the network maintains location information about the sensor units, through RSSI values and information about nodes which joined or left the network.

- **Control room.** This is a radio board connected to a computer. This radio board is the destination of all the packets. When a packet arrives, the radio decomposes it and forwards the necessary information to the GUI. The GUI displays location and monitoring information regarding the relay nodes and the sensor units in real time. For the location, the RSSI values of the different packets was used with a simple triangulation method.

### 6.2.5 System Evaluation

SPSN represents our second generation CRN routing testbed architecture. In particular, SPSN testbed provides:

- 50 relay nodes and 20 sensor units,
- nodes can work outdoor with solar panels or indoor with batteries,
- remote access to the testbed units for centralized control and management,
- open source protocol library for easy deployment and
- enhanced GUI for localization and monitoring applications.

To evaluate the performance of SPSN, experiments were performed. A channel estimation in an outdoor environment was examined. Three channels for the radio boards
were used. 31 relay nodes were deployed in an outdoor field. The nodes were placed in a straight line with 1 m distance between them. Each unit broadcasted packets for 2 min. From the packets we extract the RSSI value [28]. We collected 4480 values with an average of 154 values in each distance. Table 6.1 shows 10 distances, the theoretical value, the average RSSI value and the standard deviation (SD). The results for all the distances can be seen in Figure 6.1.

As it can be inferred from the results, the experimental results are close to the theoretical for an outdoor application. Hence, SPSN can provide realistic results for channel estimation in an outdoor environment.

### 6.2.6 ECOR: Energy Conserving Opportunistic Routing Protocol

The first protocol that was implemented in SPSN was the Energy Conserving Opportunistic Routing (ECOR) protocol, as in [109]. ECOR is similar to EAOR. The backoff time of ECOR is:

\[
T_{b_{ECOR}} = \frac{1}{d_{src,cnd} + C1_{ECOR} \times E_{lv} + SIFS},
\]

only if \( E_{lv} \geq E_{th} \)
Figure 6.1: Comparison of theoretical and experimental RSSI.

Figure 6.2: Backoff time for ECOR.

where $E_{lv}$ is an approximation of the percentage of the remaining energy of the node, and $C_{1_{ECOR}}$ is a constant related with the energy of the node. Figure 6.2 shows the backoff time for different percentages of residual energy.

The use of approximation $E_{lv}$ in Eq. (6.2) is preferred because it is easy to be...
implemented in the hardware, it does not need to be the exact value of the remaining energy and if the energy source changes (from 2 batteries goes to 3 or solar panels etc.) the routing can adapt quickly to changes. This is the main difference between ECOR and EAOR.

As it can be inferred from Eq.(6.2), $ECOR$ tends to use less nodes with low energy levels. For every packet transmission, it checks the energy level of the remaining nodes. When the energy level of a node is low, it will not participate in packet transmission and can switch to energy harvesting mode. The energy level in which the node will switch to harvesting mode depends on the $E_{init}$, and hence on the energy source requirements of the self-powered WSN.

### 6.2.7 Future Works

In this section, a Self-Powered Sensor Network (SPSN) testbed was introduced. The main components of the system were described. Also, the performance of the system for a channel estimation in an outdoor environment was examined. The experimental results are promising for an outdoor environment.

Further examination of the performance of SPSN in a complex indoor environment is necessary. Moreover, the performance of the nodes under a non-line-of-sight model should be investigated. We plan to perform some optimizations on the tool and make the SPSN testbed publicly available for research projects.

### 6.3 An Indoor System for Carbon Dioxide Monitoring

Indoor air quality (IAQ) refers to the quality of the air within and around buildings and structures. It is an issue of great importance since it relates directly to the health and comfort of building occupants. Common issues associated with IAQ include improper or inadequately maintained heating and ventilation systems as well as contamination by construction materials (glues, fibreglass, particle boards, paints, etc.) and other chemicals. Moreover, the increase in the number of building occupants and the time spent indoors directly impact the IAQ [111]. Air quality can be expressed by the concentration of several pollutants such as carbon monoxide ($CO$), carbon dioxide ($CO_2$), tobacco smoke, perfume, sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), and ozone ($O_3$). Some of these pollutants can be created by indoor activities such as smoking and cooking and
IAQ problems are more prevalent in indoor infrastructures such as houses, offices and schools. As can be inferred from this, the development of an accurate system for IAQ monitoring is of great interest.

WSNs can be an ideal solution to this problem as they generally consist of inch scale and low cost nodes that can integrate sensing, data processing, packet formation as well as wireless transmission. Therefore, the potential of an easily deployed and inexpensive WSN consisting of thousands of these nodes has attracted a great deal of attention. Furthermore, the IAQ monitoring system should integrate ad hoc principles and not interfere with any existing networks in the monitoring area further strengthening the choice of using a WSN.

Usually sensor nodes are inch scale devices that have been designed to work unattended with limited power requirements for long periods of time. Compared to portable devices, such as cellular phones and laptops, where batteries can be recharged frequently, sensor node battery recharging or replacement is sometimes not feasible or even impossible. The lifetime of any individual node, and as a consequence, of the whole network, is determined by how the limited amount of energy is utilized. An energy aware dynamic routing protocol can help combat this issue.

Since the IAQ monitoring network deployment must have a minimal impact on the existing infrastructure and be designed to operate autonomously for an extended period of time, the routing protocol applied in such a network should be carefully designed to minimize power consumption. A dynamic routing protocol specifically designed following the requirements of a wireless ad hoc and sensor network application and that is aware of the energy consumption of the network can significantly extend the network lifetime compared with traditional battery-powered WSNs.

In this section, an indoor self-powered WSN system is introduced. The ECUR protocol –Section 5.3– is extended and redesigned specifically for a wireless ad hoc and sensor network. ECUR tends to keep a balance between the energy consumption and the packet delay. It chooses nodes for packet transmission that have high energy levels and the packet delay remains similar to simple opportunistic routing.

### 6.3.1 System Concept and Design Goal

In this section, the proposed monitoring application scenario is described. The system requirements are highlighted and then, followed by a brief description of the system
6.3.1 Application scenario

An indoor monitoring application for $CO_2$ gas leak detection is considered, as illustrated in Figure 6.3. A number of wireless sensor nodes with gas leak detection capabilities and simple relay nodes, are deployed in a complex indoor environment. The wireless sensor nodes are equipped with a gas sensor module and a wireless transmission module. The data from the sensor module are passed to the transmission module. The transmission module will forward all the necessary data to the control room, through the relay nodes. The relay nodes have only communication capabilities. Both the sensor units and the relay nodes are powered with batteries.
6.3.1.2 System requirements

A $CO_2$ monitoring system has a number of requirements, depending on the application scenario. Apart from general system requirements, such as the size of the units and the cost per unit, at the network level, the proposed system has the following requirements:

- **Real-time data aggregation.** The packets related to the $CO_2$ levels should be delivered to the destination on time within a minimum delay. There is a maximum delay, after which the data are not useful any more. The routing protocol should be able to meet the packet delay requirements.

- **Energy efficient sensor units.** The replacement of the units batteries might be impossible. Moreover, the units should operate unattended for long periods of time and hence the network lifetime is important. An energy conserving routing protocol should be applied.

- **Drop-and-play units.** The units should be able to join or leave the network any time. Furthermore, since it is for a complex indoor environment, they should minimize the interference with other infrastructures and be able to adapt quickly to dynamic changes such as people and furniture which block the communication between units. An ad hoc network with cognitive principles can alleviate the problem.

Moreover, the system should be easy to be deployed and should minimize interference with other indoor infrastructures such as WLANs. The routing protocol should provide real-time communication between the monitoring nodes and the control room. In order to support multiple QoS metrics, most notably delay and reliability, local decisions should be accomplished and the system should be able to adapt dynamically to network conditions. Furthermore, local information aggregation should be used to reduce the load on the network and to enhance the energy harvesting between neighbour nodes. As a result, a multi-hop, dynamic routing should be used. ECUR protocol was used. The protocol follows the system requirements and the hardware limitations.

These are the minimum network requirements for the proposed system. For different monitoring applications, there might be some more specific requirements. The proposed infrastructure can be scaled to meet many more requirements. This is mainly because only the network infrastructure is strict and the sensor and the power source can easily change, as will be explained in Section 6.3.2.
6.3.1.3 System framework

The system concept and the design principles were built into an application specific framework, aiming to deal with specific scientific and technological challenges. The proposed framework has the following three important units:

- **Sensor units**: Carbon dioxide sensors should combined with radio modules and form a WSN. The data from the sensor should be passed to the radio, form packets and transmit, following cognitive network principles. Each sensor node should continuously monitor the area around it.

- **Relay nodes**: A wireless ad hoc network system composed from easy-to-use devices. The devices implement the developed ECUR protocol. The protocol supports transmission of real-time sensed data from various sources towards the destination. The number of the devices vary over time and nodes can join or leave the network at any time.

- **Control room**: The data aggregation and network maintenance takes place at the destination. All the collected data should be processed and expressed in a summary form at the control room. Also, useful network information should be collected and used for better network maintenance.

The system framework is shown in Figure 6.4. The system presented and specifically developed in this study, can be decomposed into the following three parts:
1. Transmission module: The main module of the system. It forwards all the packets towards the destination, following the ECUR protocol.

2. Sensor module: It senses the gas concentration in the area around it. It passes all the data to the transmission module.

3. Control room: It is the destination of all the data in the network. It can be a simple transmission module attached to a laptop. The data processing takes place at the control room.

The hardware components will be presented in the next section, while the related algorithms will be described in the following one.

6.3.2 System Architecture

In the introduced system, an opportunistic mesh radio board is used in the context of a cognitive monitoring application. The proof-of-concept is achieved via prototyping, where a real-time CO₂ monitoring application is supported. In this section, the different modules of the proposed system will be described. Indoor air-quality sensors will be used and batteries will power the units. The proposed system is flexible and adaptable to the needs of the monitoring environment. Although the core communication architecture remains the same, most of the system components, such as the type of the sensor or the power supply can easily be adjusted to meet any other application requirements.

6.3.2.1 Transmission module

The transmission module performs all the data exchange between different nodes. The functions necessary to achieve this can be divided into two distinct levels, namely the communication and application levels. Communication between different transmission modules is done at communication level while the data formatting and processing is done at the application level.

At the communication level, the radios have been implemented using a CSMA/CA method. First, the transmitter waits to assemble the packet. When the packet is ready, it checks if the channel is idle and available for immediate transmission. If another transmission was heard, the transmitter has to wait for a period of time for the other node to stop transmitting before listening again for an available channel. At the application
level, there is a unicast transmission that transmits any data received from the Universal Asynchronous Receiver/Transmitter (UART) to the radio. In unicast mode, radios only establish point to point transmission where the transmitter sends the data to the destination.

A typical relay node is shown in Figure 6.5. The specification of the board, as they were carefully selected for this application, can be seen in Table 6.2. A RapidMesh OPM15 board [96] is used as radio module. The frequency range is $2.405 - 2.483 GHz$.

The radio is based on the IEEE 802.15.4 standard to realize OPM dynamic networking with multi-frequency. The microchip power requirement is $3.3V$ and is supplied by an onboard power regulator which can accept up to a $6V$ input.

The sensor units are powered with one $9V$ battery and the relay nodes with 3 AA batteries of $1.5V$ each. The maximal air interface radio rate is $250kbps$, whereas the radio transmitting power is programmed to a lower level $-25dBm$, giving the radio the range of about $15 - 20$ meters.

The modules are programmed to implement opportunistic utilization hence, any module can join or leave the network at any time, without the need of special configuration. In a complex indoor infrastructure, the air quality monitoring of a room can be enhanced by adding a number of radio modules between the monitoring area and the control room. On the other hand, modules can be moved to different locations without any special configuration procedure. Moreover, through opportunistic routing, efficient throughput and delay can be achieved.

Table 6.2: OPM15 Specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio range</td>
<td>$20m$</td>
</tr>
<tr>
<td>Frequency range</td>
<td>$2.405 - 2.483GHz$</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$5MHz/\text{channel}$</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>$-94dBm$</td>
</tr>
<tr>
<td>Transmitting power</td>
<td>$-25dBm$</td>
</tr>
<tr>
<td>Power Cons. (Sleep)</td>
<td>$1\mu A$</td>
</tr>
<tr>
<td>Power Cons. (Work)</td>
<td>$25mA$</td>
</tr>
</tbody>
</table>

Figure 6.5: OPM15 relay node.
6.3.2.2 Sensor module

For gas leak detection, indoor air quality sensor modules from Applied Sensor [112] are used. iAQ-2000 sensors can measure \( CO_2 \) levels as well as temperature and humidity. It is a sensitive, low-cost solution for detecting poor air quality in an indoor environment. The module uses micro-machined metal oxide semiconductor (MOS) gas sensor components to detect a broad range of volatile organic compounds (VOCs) while correlating directly with \( CO_2 \) levels in the range. A change of resistance in the presence of these gases generates a signal that is translated into parts per million (ppm) \( CO_2 \) equivalent units. The module also has an energy saving scheme. A threshold can be defined to alert that the climate has changed when the limits are exceeded or to decrease ventilation on minimum VOC levels. Figure 6.6(a) shows an iAQ-2000 sensor node.

The sensor module continuously monitors the gas concentration (\( mol/m^3 \)) in the environment. The integration of the sensor module with the transmission module creates the final monitoring board. The monitoring board uses one 9V battery as the power source and hence there is a 5V voltage regulator to reduce the voltage before supplying the RapidMesh board and the iAQ-2000 sensor (which requires a 5V supply). Next, the TXD serial output of the sensor is connected to the RXD serial input of the RapidMesh board via a resistor voltage divider. The divider is to reduce the 5V output of the sensor to 3.3V for the RapidMesh board. The assembled monitoring board is shown in Figure 6.6(b). The collected data are fed to the radio module, through the electronic circuit shown in Figure 6.6(c). The data packets will then be transmitted towards the control room through a number of relay nodes.

6.3.2.3 Data packet process

Data packet formation and processing takes place at every monitoring board. Packets are created every second at the same rate as the sensor sends out data. A packet consists of the following four fields:

- Sensor identifier: This identifier comes from the sensor module and it is related with its product serial number. It is unique for every sensor module in the network. The identifier stores the number of the transmitter that sends the packet and allows the receiver to identify the origin of the packet. For every sensor ID there is a corresponding location stored at the control room. The location can be updated if the sensor is moved to a new location.
Figure 6.6: The indoor version of the prototype with (a) an iAQ-2000 sensor module to (b) the assembly kit of the prototype connected through (c) a simple electric circuit.

- **Time**: The time comes from the radio module. This field stores the exact time when the packet was created. When the receiver receives the packets, it can order their transmission based on the timestamps. For a CO$_2$ monitoring application, the time is of high importance since it shows the variation of the CO$_2$ levels over time.

- **Sensor monitoring data**: The data passed from the sensor module to the transmission module. The data field stores all the crucial information related with the CO$_2$ concentration.

- **Local information data**: This information comes from the radio module. This field includes information such as the remaining power level of a unit and average RSSI for location information maintenance.

Figure 6.7(a) shows the packet format and from which module each piece of information comes from. The data processing, transmission and reception is shown in Figure 6.7(b).
6.3.2.4 Control room

The control room is where the final data processing takes place. All the data packet from the sensor units are forwarded towards the destination node at the control room. In the proposed system, one simple radio module is connected with a laptop. This module decodes the packets and extract all the useful information. A Graphical User Interface (GUI) was developed and runs at the control room. The radio module passes all the data
Figure 6.8: The developed GUI with (a) graphical and (b) numerical representation of the $CO_2$ concentration as recorded from different sensors.

Figure 6.9: The developed GUI with location tracking.

to the laptop which displays all the data in real-time through the GUI. The collected data is also stored in files for later retrieval and review. If the collected $CO_2$ concentration exceeds a user-defined threshold, the application notifies the system administrator. The application can support large scale networks with simultaneous packet decoding from multiple sensors. Figure 6.8 shows some screenshots of the developed GUI. A location tracking GUI has also been developed as in Figure 6.9.

6.3.2.5 Indoor monitoring system

In the proposed monitoring system application, cognitive networking is used along with opportunistic routing in a wireless multi-hop network, for $CO_2$ monitoring. The networking technology is based upon cognitive networking architecture which utilizes both spectrum and networking radios opportunistically [89] to establish reliable communication in large wireless networks. An overview of the system can be seen in Figure 6.10.
The final indoor monitoring board has two types of nodes: the wireless sensor nodes (monitoring boards) and the relay nodes. The wireless sensor nodes as well as relay nodes are deployed in a complex indoor environment. The wireless sensor nodes know their relative location. The relay nodes will find their location during the initialization phase of the proposed protocol. Each wireless sensor node is able to monitor the area around it, form packets and forward these packets to one of the neighbour relay nodes which will then opportunistically forward the packet to the destination.
6.4 An Outdoor System for Gas Leak Detection

An outdoor self-powered WSN system was further developed. The primary application is gas leak detection. The power source of the nodes has to change to make use of the solar energy. Changes were necessary to the routing protocol as well. Another routing protocol was developed and a prioritization metric was used and designed for outdoor networks. Spectrum and Energy Aware Opportunistic Routing (SEA-OR) tends to optimize the use of the energy of nodes which draw power through solar panels.

6.4.1 System Architecture

The introduced SEA-OR protocol [35] was developed for our second generation CRN testbed architecture. The protocol was designed for an outdoor monitoring system for gas leak detection. The system has three important components: the sensor units, the relay nodes and the control unit.

- Each sensor unit has a gas sensor connected with our radio board. The radio board has two antennas to perform the cognitive networking: one for channel sensing and one for transmission. The board is connected with a rechargeable battery which draws energy from a solar panel. During the daylight, when the rechargeable battery is fully charged, the board draws energy straight from the solar panel. When there is no sufficient sunlight for the panel, the board draws energy from the battery. The sensor unit forwards all the crucial information to the relay nodes over wireless communication and follows the SEA-OR protocol.

- The relay nodes have the same radio board with the sensor units. They forward all the packets towards the control room. Since there is no sensor attached to the board, the total energy consumption of the relay node is significantly smaller in comparison with the energy consumption of the sensor units. Hence, the solar panel and the battery capacity in the relay nodes are smaller.

- The control room is a radio board connected to a computer. This is the destination of all the packets. The radio board decomposes all the packets and displays the information on the GUI which has been developed.

Figure 6.11 depicts the outdoor system and its main components. Whenever there is a gas leakage in the monitoring area, the sensor units transmits packets with information
regarding the leakage. The packets will reach the control room and notify the system administrator. A monitoring system like that poses a number of challenges:

- **Challenge 1: Network lifetime.** Take Figure 6.11 for example. If the sensor units keep forwarding all the packets over the same relay nodes, these nodes will run out of energy after some transmissions. In this case, there will not be network connectivity which is a challenge for monitoring systems. Even though the nodes are powered with solar panels, they will acquire extra time to recharge their batteries to a level so that they can participate in packet transmission again.

- **Challenge 2: Location information.** There are many geographical routing protocols in the literature that can optimize the network performance. Usually, they use the distance between the communicating nodes as prioritization metric. The more accurate the location the better the performance of the metric. However, in networks with high density and without advanced location estimation technologies, this metric might not be easy to use. On the other hand, if an advanced location estimation technique is used...
system is used, then the cost and the power consumption per unit will increase.

- **Challenge 3: Wireless network coexistence.** Heterogeneity and coexistence are characteristics of every unlicensed band. As more and more wireless devices use the 2.4 GHz radio spectrum, the coexistence of 2.4 GHz wireless devices which operate at the same place has become a challenging topic. The system should be able to cope with issues such as spectrum availability detection, interference mitigation and spectrum sharing.

- **Challenge 4: Dynamic changes.** The monitoring system is deployed and should work unattended for long periods of time. Hence, it needs mechanisms to adopt successfully to a rapidly changing environment. For instance, the link between nodes might not be available due to obstacles from the environment. The system should be able to transmit the necessary packets to the destination on time.

These are the main challenges with a monitoring system consists of self-powered sensor nodes. To cope with these challenges we designed the SEA-OR protocol.

### 6.4.2 System Modules

The system modules are the same with indoor framework and the SPSN testbed. The main difference is the power source. The sensor units draw energy from solar panels. The sensor unit with the solar system is shown in Figure 6.12(a) along with the schematic diagram with the connection of the different components in Figure 6.12(b).

### 6.4.3 SEA-OR: Spectrum and Energy Aware Opportunistic Routing Protocol for Self-Powered WSNs

In this section, a Spectrum and Energy Aware Opportunistic Routing (SEA-OR) protocol for self-powered WSNs is introduced. A novel metric is used to prioritize the neighbour nodes. This metric balances the packet advancement, the residual energy and the link reliability. SEA-OR achieves to extend network lifetime while it retains a high delivery ratio through its OR principles. The protocol is simulated and compared with Geographic Opportunistic Routing (GOR) [61]. Moreover, SEA-OR has applied to prototypes at our SPSN testbed.
Figure 6.12: SPSN can operate both indoor and outdoor. In (a) is an example of an outdoor sensor unit along with its circuit schematic in (b).

6.4.4 SEA-OR Design

Central to the design of SEA-OR is a novel neighbour prioritization metric for self-powered WSNs. The protocol tries to address the four challenges as mentioned above.

**SEA-OR Overview.** SEA-OR discovers multiple paths towards the destination according to the spectrum dynamics as well as node availability and energy level. The paths are centred around the shortest path. However, the protocol opportunistically expands or shrinks these paths, based on the spectrum availability and the residual energy of the neighbour nodes. The discovery and coordination of the forwarder set follows the RTS/CTS handshake approach. The transmitter senses for an available channel and
broadcasts a RTS packet. SEA-OR opportunistically forwards packets across the links with the highest spectrum availability. The candidate node that replies first with a CTS packet, will become the next relay node.

The novelty of this protocol is on the prioritization mechanism. When a candidate node receives a RTS packet, it will wait for a backoff time $T_{bSEAOR}$ before it replies with a CTS packet. This time is designed for self-powered sensor nodes with limited computational capabilities. The nodes are prioritized based on a combination of the channel quality, the distance and the residual energy of the node. The formula to calculate the $T_{bSEAOR}$ is as follows:

$$T_{bSEAOR} = C_{SEAOR} \times (E_{th} - E_{res}) \times \log\left(\frac{RSSI(d)}{C_{SEAOR}}\right) + SIFS$$

where $E_{res}$ is the percentage of the residual energy of the node, $E_{th}$ is the threshold for a node to start energy harvesting, $C_{SEAOR}$ is a constant and is related with the capacity of the battery, $C_{SEAOR}$ is another constant and is related with Received Signal Strength Indicator (RSSI) value in 1m distance. RSSI can also be calculated as:

$$RSSI(d) = -10 \times n \times \log(d) + A$$
where $n$ is the propagation path loss exponent, $d$ is the distance from the sender and $A$ is the received signal strength at one meter of distance. An example of the $T_{SEAOR}$ can be seen in Figure 6.2.

From Eq.(6.2), the two important factors are the residual energy and the RSSI. The first can be acquired with a simple circuit on the sensor units and the relay nodes. The RSSI value can be found on every packet captured from the node. Also, it can be used to calculate the distance between nodes, but it is not of high accuracy. It is however, accurate enough to prioritize the nodes based on their location and link quality. The constant values for this examples are the values used in SPSN testbed and are related with the developed prototypes. When the nodes have similar $E_{res}$, the introduced approach tends to use nodes which are in greater distance and hence, closer to the destination. However, as the $E_{res}$ decreases, the protocol uses nodes that are closer to the transmitter. In this way, the nodes have sufficient time to perform energy harvesting and not run out of energy.

**Extend network lifetime.** SEA-OR uses the residual energy of the nodes for prioritization of the forwarder set. The nodes participate in packet transmission according to their remaining energy. When the $E_{res}$ is under a threshold, the node does not participate in any transmission. This mechanism is adopted in order to avoid nodes running out of energy completely.

When a node has low energy levels, the probability of this node receiving a packet is low. As the node increases the energy levels through the energy harvesting phase, it increases its probability of becoming a relay node for a packet transmission.

**Use of RSSI.** This indicator has been used for indoor localization and proven not to be accurate enough. In this approach however, RSSI is used as an indicator of the relative location of the nodes. SEA-OR makes use of this information and not the exact location. The indicator is used to find nodes close to the transmitter. Most importantly for the system implementation, RSSI information does not add any extra overhead. RSSI can also be used as link quality indicator. As an example of its use, if the RSSI value is below some threshold, the node knows that the channel is idle.

**Opportunistic spectrum access.** Before every packet transmission the sender senses for the best available channel. The packet transmission takes place over the link with the highest spectrum availability at the time of the transmission. This approach also decreases the interference with other devices that use the same band and alleviates the problem of network coexistence.
Opportunistic routing. The SEA-OR protocol discovers paths towards the destination on demand. There is no predefined routing. For every packet transmission, the best available path is selected. This path is based under the network conditions at the transmission time. Any dynamic changes, like node and link availability, will change the best path. SEA-OR quickly adapts to these changes and does not require any reconfiguration on the nodes.

6.4.5 Preliminary Results of SEA-OR

A preliminary evaluation of SEA-OR performance was conducted and its performance was compared with GOR. OMNeT++ simulator was used. The sensor nodes are randomly deployed in a $100 \times 100$ m$^2$ area using a Poisson distribution with a $\lambda = 0.101$. Every node has on average 8 neighbour nodes and the transmission range of each node is 12 m.

Ten topologies were evaluated. The number of nodes in each topology varies between 900 to 1100. The distance between the source and the destination was varied between 20 to 200 meters. For each topology the source generated 1000 packets towards the destination. In every topology, 10 different source-destination pairs were selected.

Network Lifetime and delivery ratio. Network lifetime has plenty of definitions [105], depending on the application. In this work, and for a monitoring application, network lifetime is considered as the time until “connectivity” or “coverage” is lost, i.e. there are no paths between the source and the destination or one of our monitoring board is drained of its energy. The network lifetime of the two protocols is shown in Figure 6.14(a).

SEA-OR significantly improves network lifetime over GOR. As the distance between the source and the destination increases, there are more nodes in the routing path. The spectrum awareness of SEA-OR forwards the packets in shorter time than GOR. As a consequence, the nodes have to remain active for shorter time and the energy consumption per node is smaller.

SEA-OR improves the delivery ratio performance of GOR, as shown in Figure 6.14(b). The use of RSSI in the prioritization metric, helps SEA-OR to decrease collisions and to forward the packets over reliable links. Consequently, the number of retransmissions decreases.
Figure 6.14: Performance comparison between SEA-OR and GOR in different source-destination distances.

6.5 Video Transmission over WMSNs

Wireless Multimedia Sensor Networks (WMSNs) are considered as one of the most prominent infrastructures for human-centric multimedia applications due to the wide availability of low-cost hardware such as microphones and Complementary metal–oxide–
semiconductor (CMOS) cameras. By virtue of the energy limitations on sensor nodes alongside the explicit highly demanding bandwidth requirements of real-time multimedia applications, these particular networks foster a set of non-trivial challenges that need to be confronted. In this section, a level of relevance in regards with the content of a multimedia packet is defined and further a dynamic routing protocol is introduced. This protocol optimizes the overall network performance in terms of energy efficiency and packet delay. The design, implementation and applicability of the Content Relevance Opportunistic Routing (CROR) protocol is presented, as in [113]. Experimental results show an increase in network lifetime of up to 20% compared with traditional routing. The following highlights our contributions:

- A Content Relevance Opportunistic Routing, (CROR) protocol is introduced. CROR is designed for WMSNs that addresses the demanding requirements of network performance, application-specific packet prioritization and energy efficiency.
- A generic Packet Relevance Level Scheme, (PRLS) is proposed. PRLS may be easily configured for the needs of any human-centric QoS prioritization in WMSNs.
- The scalability and reliability aspect of prioritized multimedia content transmissions are improved, since the proposed protocol may adequately adapt whilst the density of a given WMSN increases.
- The performance of CROR is evaluated. Simulation results have shown an extend up to 20% to the lifetime of a WMSN in comparison with traditional routing protocols under stressful human-centric multimedia content.

6.5.1 PRLS: Packet Relevance Level Scheme

The Packet Relevance Level Scheme (PRLS) is considered as a core component for the overall performance of the proposed protocol. A number of relevance schemes have been proposed for different network types [114]. Similarly with the labelling existing in QoS schemes (e.g. MPLS), in this scheme a field within a packet’s header is labeled with its relevance from a source node leading an indication to the neighbour nodes regarding the importance of the packet. However, at this stage it should be clarified that the proposed PRLS scheme can be tuned according to the explicit nature of a multimedia human-centric environment and the exemplar insight given in this work is simply illustrating
Table 6.3: Relevance levels and example of packet classification arriving on a smart phone device.

<table>
<thead>
<tr>
<th>Level $L_k$</th>
<th>Relevance</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Irrelevant</td>
<td>General advertisements.</td>
</tr>
<tr>
<td>1</td>
<td>Low Relevance</td>
<td>Notification from social media.</td>
</tr>
<tr>
<td>2</td>
<td>Medium Relevance</td>
<td>Regular video stream, image transmission, chat.</td>
</tr>
<tr>
<td>3</td>
<td>High Relevance</td>
<td>Event notification, real time game engines notification.</td>
</tr>
<tr>
<td>4</td>
<td>Maximum Relevance</td>
<td>Breaking news, weather/traffic alerts.</td>
</tr>
</tbody>
</table>

the intuitive aspect of this generic scheme. Therefore, an irrelevant, low, medium, high or maximum relevance level packet should be adjusted based on the QoS requirements imposed by the operator(s).

For instance, in a scenario where a packet holds a low relevance level, it will be transmitted through nodes nearby the transmitter since time delay is not crucial for this packet. As an example may be considered, a human-centric network composed of smart phone devices, where packets related with games and advertisements [115], can be classified as of low relevance or irrelevant. Advertisement notifications can be delivered with a delay to the user, while the energy levels of the network should not be decreased sufficiently with an increase of the advertisement volume.

In PRLS, a packet with a medium relevance level, will be transmitted to the destination over one of the available paths that holds the minimum number of hops along with sufficient energy to the transmitting nodes. In most cases, the path is not necessarily the shortest but due to the energy constraint it is considered reliable with respect to service. Paths that have not been used frequently and are usually defined by nodes with unused energy, can deliver the packet on a minimum delay and are preferred over the default shortest path. By virtue of the opportunistic and reactive path discovery embedded within the introduced protocol, the number of these paths increases with respect to the increment of the network’s density. In general, medium relevance level packets may be labeled as those that carry information and are considered as regular and do not trigger or require any “on the fly” event processing mechanism. Examples of such information may be image, temperature or pressure data on monitoring environments or social media data of smartphones within a WMSN.

On the other hand, a packet with a high relevance level is required to be delivered
at the destination node with the minimum end-to-end delay. The nodes that are on the shortest path or close to it and are available for immediate transmission will be used. Since the nodes availability and the network condition varies over time, different shortest paths consisting of different nodes will be available in different time frames. At the same time, if another packet with smaller relevance level requires transmission, it is placed in a prioritization queue and gets served as soon as the rest of the packets with higher relevance levels are transmitted. Thus, the higher the relevance level, the higher the priority. Hence, in the scenario of images or video stream packets that captured a crime event within a surveillance sensor network should be delivered promptly to the central station and in parallel the network should have sufficient energy to deliver those packets. Similarly, a video of the breaking news or the current traffic condition is of the highest importance and should be delivered to the smartphone user on time and over reliable links. Table 6.3 shows the five types of relevance levels as implemented in the introduced protocol accompanied by exemplar labelling that could be used to human-centric mobile sensor networks (e.g. with smartphone devices). Although the depicted examples are focused on specific scenarios, we again clarify that the proposed scheme may be easily tuned for any WMSN scenario where packets hold different QoS requirements.

6.5.2 CROR: Content Relevance Opportunistic Routing

The proposed Content Relevance Opportunistic Routing (CROR) for WMSNs is a reactive opportunistic protocol due to its ability to discover routes only when desired. Thus, an explicit route discovery process is initiated only when needed. Hence, in CROR the destination node triggers and terminates the route discovery process when a routing path has been established. The established path is maintained via a preserving procedure until it is no longer available or requested.

Within CROR there is the capability of maintaining multiple paths between a source/destination pair and packets can follow any of those paths after considering dynamic network condition changes. Varying network conditions such as interference, channel and relay node availability and energy levels are considered. Moreover, due to the probabilistic choice of the relay nodes, the protocol is able to evaluate different routing paths continuously and select them based on the changing network condition in every time slot. Overall, the proposed protocol is composed by three phases that are presented next.
6.5.3 Neighbour Discovery Process

The first phase includes a neighbour discovery process. Every sensor node $i$ in the network knows its relative location, hence it can categorize the nodes around it into neighbour node set $N_i$, and candidate node set $K_i$, as in Section 4.2.3.1.

6.5.4 Packet Relay Mechanism

Subsequent to the neighbour discovery process, there is the packet transmission process which follows a packet relay mechanism. There are four types of packets: RTS, CTS, DATA, and ACK. Every packet transmission is subject to the PER, as in Eq.(3.1).

Every node in the network can be the source node. When a node $i$ needs to transmit a DATA packet, it first tries to find an available neighbour node from its candidate set $K_i$, through a RTS/CTS handshake. The node $i$ floods a RTS packet and waits for the first CTS response from any node in the $K_i$ set. Since the node floods the packet over the wireless medium, which is an open medium, every neighbour node in its $N_i$ set might receive the RTS packet. If a node which belongs to $N_i$ and not to $K_i$ set replies to the transmitter, the transmitter will ignore the response. The transmitter node $i$ will wait for time $T_{RTS}$ before it considers the RTS packet was lost and retransmits it. The time $T_{RTS}$ before the node retransmits data is equal to:

$$T_{RTS} = \left( \frac{L_{RTS} + L_{CTS}}{R} + (2 \times d_{prop}) \right) \times \exp(N_i) \times C_{1CROR} + SIFS$$

where $C_{1CROR}$ is a constant related to the number of the neighbour nodes.

After time $T_{RTS}$ the transmitter assumes that the RTS packet was lost and it retransmits it. In the proposed protocol, when the number of the neighbour nodes $N_i$ increases, $T_{RTS}$ also increases in such way that the transmitter will wait longer for a response. In this way, there is enough time for all the neighbour nodes to reply to the RTS before a retransmission of the packet. Thus, energy is saved from reducing the number of the necessary retransmissions.

Some nodes from the $K_i$ set will receive the RTS and will reply with a CTS. In the proposed CROR protocol, on the reception of a RTS packet a node $j$ will wait for time:

$$T_{bc\text{CROR}} = (\frac{L - L_k}{k} \times \log(d_{i,j})) \times C_{1CROR} + C_{2CROR} \times SIFS$$
Figure 6.15: The $T_{bCROR}$ for nodes in different distances from the transmitter and for packets with different PRLS values $L_k$, following Eq.(6.5) for $C_0 = 10^{-5}$ and $C_1 = 7$.

where $\bar{L}$ is the mean of the explicitly applied PRLS, $L_k$ is the packet relevance level $k$ of the current packet, and $C1_{CRO}R$ and $C2_{CRO}R$ are constants defining the response timing of a node and may be tuned according to the particular QoS requirements of a given network.

Figure 6.15 shows an example of the $T_{bCROR}$ under different distances between the communication nodes and packets with different PRLS values. As shown, while the PRLS value increases, the $T_{bCROR}$ decreases for the nodes at a distance. Furthermore, for PRLS values higher than the mean, nodes that are in greater distance from the transmitter will wait less time and target to reply first. For lower than the mean PRLS values, nodes that are closer to the transmitter will try to reply first, since these nodes have smaller $T_{bCROR}$.

When $T_{bCROR}$ terminates, the node $j$ will respond with a CTS packet. On successful reception of a CTS packet, the transmitter will forward the DATA packet to the node that replied first with a CTS and will ignore any of the consequent CTS packets for the same DATA packet. The transmitter then will wait for an ACK of the packet. Since the CTS transmission is also subjected to the PER, some packets might be lost.

Given Eq.(6.5), the selection criterion of the next relay node is a combination of the distance from the destination and the packet PRLS value. When the PRLS value
decreases, it implies that the closer a node is to the transmitter the smaller the $T_{\text{CROR}}$. Hence, neighbour nodes that are close to the transmitter will serve packets with low PRLS value and the required number of hops will be higher. If a packet with a higher PRLS needs to be transmitted through the same nodes, the nodes will store all the packets in their buffer and will prioritize their transmission according to their PRLS value. The higher the relevance, the higher the transmission priority.

On the other hand, packets with high PRLS value will be forwarded to nodes that are located close to the limits of the transmitter’s transmission range. These nodes will forward the packets to the destination in less number of hops than any other available node at the time. If a packet with lower PRLS value needs to be transmitted through the same nodes, it will have to wait for any other packet with higher PRLS to be transmitted first. In parallel, each intermediate node follows the same packet transmission process where consequent packet transmissions might use different paths and different channels. Overall, the aforementioned process continues until all packets reach the destination node.

### 6.5.5 Route Maintenance

Localized flooding is performed infrequently in order to keep all the information about the different routing paths updated. Sensors that are not participating in any transmission at that time, help with the collection of maintenance information. This process also helps to check if any new node joins the network or if they run out of energy and stop operating. The nodes can then update their neighbour node metric.

### 6.5.6 Performance Evaluation of CROR

The proposed protocol is compared with traditional routing in terms of network lifetime, energy distribution and average end-to-end packet delay and presented herein. The experiment was achieved after using a version of a prototype sensor node [37] and OPM15 boards [96] and aimed at comparing our CROR over traditional routing. The studied area is the 4th floor of the Bahen Centre for Information Technology (BCIT) building located at the University of Toronto. For the experiment 40 nodes were used and uniformly distributed over the studied area.

Traditional routing utilizes nodes that can deliver the packet over reliable links (i.e. links with PER < 10%) and with the minimum number of hops. On the other hand, the proposed CROR protocol tends to use links with PER < 80%. In addition, it checks the
link performance and availability for every packet transmission where traditional routing has a pre-fixed path for all the transmissions. The experiment took place 5 times with raw data, equally distributed among all the levels of the proposed PRLS. Two different sources and one destination were used and the communication parameters between the experiments were similar.

6.5.6.1 Network lifetime

Network lifetime is the time interval between the first packet transmission until the first node failure due to battery depletion. The sensor nodes operating on 3 AA batteries with 1000mAh capacity, hence each sensor node will have an initial energy of:

$$E_{\text{init}} (J) = \text{capacity(Ah)} \times \text{voltage(V)} \times \text{time(s)}$$

$$= 1 \times 3 \times 1.5 \times (60 \times 60) = 16200J$$

(6.6)

As indicated by Figure 6.16, traditional routing forwards all the packets through the same routing path. The nodes on this path keep transmitting packets and eventually they all run out of energy. Consequently, this approach leads to a decrease of the network lifetime. On the other hand, the CROR protocol has a better performance. The main reason is that CROR utilizes the shorter paths only for packets with high PRLS values. For packets with low PRLS value, nodes which have not participated in many packets transmissions have high energy levels, therefore they are preferred. As the network density increases, there are more neighbour nodes on the best path from the source toward the destination, thus extending the network lifetime.

6.5.6.2 Energy distribution

Energy distribution refers to the energy consumption of each node in the network. The energy consumption on each node after the end of each of the 5 experiments was measured.

Figure 6.17 and Figure 6.18 depict the energy distribution for the two protocols. Traditional routing uses the same nodes for all the packet transmissions. Consequently, only 9 nodes in the experiments have consumed energy. It is evident that the energy distribution is better with the CROR protocol since it allows the utilization of more used sensor nodes for different packet transmissions. Only the different source nodes and the destination node have high energy consumption. Eventually, the remaining nodes have consumed almost equal energy. The proposed approach tries to exploit all the available
nodes at the network and leads to a much more efficient routing scheme in terms of energy distribution.

6.5.6.3 Average end-to-end packet delay

In the experiments a number of 600 packets with PRLS values 0, 2 and 4 were transmitted from different sources to the destination for each network density and the average end-to-end packet delay was calculated, as indicated in Figure 6.19.

Traditional routing has the same performance for every packet transmission whereas
the CROR protocol does not perform as well as traditional routing for packets with low PRLS. The main reason lies with the fact that this approach tries to conserve energy to transmit packets with higher PRLS values. Hence, it tends to use nodes that have not been used that often for packet transmission. These nodes lead to paths with more number of hops than traditional routing and as a consequence the average end-to-end packet delay is higher than in traditional routing. Therefore, while the network density increases, the difference between the two approaches is smaller since the CROR protocol can discover more neighbour nodes that can lead to paths with similar performance as traditional routing. The performance of the two routing schemes for packets within the medium PRLS values is close to similar. CROR protocol urges to find any path and not the shortest one towards the destination under an opportunistic nature. Hence, it can deliver the packets over nodes and links that traditional routing does not use. These links might be unreliable for traditional routing, while it can be reliable for the CROR at the time of the transmission, leading to a path with less number of hops. On average, the performance for these packets is similar. Finally, for maximum PRLS labeled packets, the introduced CROR holds a much better performance than traditional routing. This outcome is mainly related with the opportunistic aspect of this protocol since it takes advantage of the broadcast nature of wireless communications. In addition, the CROR manages to deliver the packets over any available node at the time of the transmission.
Consequently, these nodes can deliver the packet in less time to the destination, leading to a significant smaller average end-to-end packet delay.

6.6 Summary

In this chapter, self-powered WSN for environmental monitoring application were examined. First, the developed SPSN testbed was introduced. SPSN can be used for a variety of applications. Next, an indoor monitoring system along with its routing protocol was presented. The system was implemented with the use of prototypes from the SPSN testbed. An outdoor monitoring system was also described. A protocol following the restrictions of the outdoor system was introduced. Last, a video transmutation application over WMSNs was examined. A protocol was proposed along with a packet prioritization scheme.
Chapter 7

Conclusions

This thesis presented new ideas at the design and implementation of routing protocols for self-powered Wireless Sensor Networks. These networks require energy efficient routing while they have limited memory and processing capacity. After revisiting the theory behind opportunistic routing and opportunistic spectrum access in Chapter 2 and Chapter 3 respectively, a new protocol that combines these ideas was proposed in Chapter 4. The protocol was simulated and evaluated with real collected data and with the use of prototypes.

Proceeding into self-powered and energy efficient networks, Chapter 5 presented a protocol that keeps balance between the residual energy of the nodes and the packet advancement. A novel prioritization metric was introduced to achieve this balance. Lastly, Chapter 6 reviewed three different application scenarios that was used to evaluate the performance of the different protocols of this dissertation.

7.1 Summary of the Introduced Protocols

The different opportunistic protocols that were designed and implemented in this thesis are summarized in Table 7.1. In all the protocols, the prioritization is over the RTS/CTS handshake between the nodes. The node which replies first with a CTS becomes the next relay node. There are two broad protocol categories that have been implemented: geographic protocols and energy efficient protocols.

In geographic protocols, GEOR and CNOR were introduced, in Chapter 2 and Chapter 4 respectively. The two approaches have been designed for general WSNs. GEOR is a geographic opportunistic routing protocol which uses the location information of
<table>
<thead>
<tr>
<th>Protocol</th>
<th>Metrics</th>
<th>Cognitive</th>
<th>Evaluation</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOR [62]</td>
<td>Location</td>
<td>No</td>
<td>Simulation + Hardware implementation</td>
<td>General WSNs</td>
</tr>
<tr>
<td>(Section 2.4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADRS [64]</td>
<td>Location +</td>
<td>No</td>
<td>Simulation</td>
<td>General WSNs</td>
</tr>
<tr>
<td>(Section 2.4.2)</td>
<td>Inclination angle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CNOR [33]</td>
<td>Location +</td>
<td>Yes</td>
<td>Simulation + Hardware implementation</td>
<td>General WSNs</td>
</tr>
<tr>
<td>(Section 4.2)</td>
<td>Average neighbour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EAOR [104]</td>
<td>Location +</td>
<td>No</td>
<td>Simulation</td>
<td>Self-powered WSNs</td>
</tr>
<tr>
<td>(Section 5.2.2)</td>
<td>Energy consumption</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECOR [109]</td>
<td>Location +</td>
<td>No</td>
<td>Simulation + Hardware implementation</td>
<td>Self-powered WSNs</td>
</tr>
<tr>
<td>(Section 6.2.6)</td>
<td>Energy level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECUR [34]</td>
<td>Location +</td>
<td>Yes</td>
<td>Simulation + Hardware implementation</td>
<td>Self-powered WSNs</td>
</tr>
<tr>
<td>(Section 5.3)</td>
<td>Residual energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEA-OR [35]</td>
<td>Residual energy</td>
<td>Yes</td>
<td>Simulation + Hardware implementation</td>
<td>Self-powered WSNs</td>
</tr>
<tr>
<td>(Section 6.4.3)</td>
<td>Link reliability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CROR [113]</td>
<td>Location +</td>
<td>No</td>
<td>Simulations</td>
<td>WMSNs</td>
</tr>
<tr>
<td>(Section 6.5.2)</td>
<td>Packet relevance level</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1: Classification of protocols proposed in this thesis.
the neighbour nodes as prioritization metric. The neighbour node that is closer to the
destination and provides better packet advancement becomes the next relay node. The
protocol uses one channel for the packet transmission. The protocol performance has
been evaluated through simulations and hardware implementation with OPM15 radios.

CNOR is a cognitive networking with opportunistic routing protocol. The neigh-
bour node prioritization metric is a combination of the location and the number of the
neighbour nodes. The protocol adapts quickly to changes on the network scalability.
CNOR uses 3 different channels for packet transmissions. It has been evaluated through
simulations and hardware implementation.

In energy efficient protocols, EAOR, ECOR, ECUR and SEA-OR were introduced,
in Chapter 5 and Chapter 6. All the four approaches are designed for self-powered
WSNs. EAOR is an Energy Aware Opportunistic Routing which uses location and energy
consumption information to prioritize the neighbour nodes. It operates over a single
channel and has been evaluated only through simulations.

The implementation of EAOR in the OPM15 radios had some difficulties as explained
in Section 6.2.6, hence the ECOR protocol was developed. ECOR is an Energy Conserving
Opportunistic Routing protocol that uses the location information and the energy
level to prioritize the neighbour nodes.

ECUR is an energy Efficient Cognitive Unicast Routing protocol which prioritizes
the neighbour nodes according to their location and their residual energy. ECUR is
different from EAOR as described in Section 5.3.2.3. Moreover, ECUR has cognitive
networking aspects and operates over multiple channels. ECUR has been evaluated
through simulations and hardware implementation.

SEA-OR is a Spectrum and Energy Aware Opportunistic Routing protocol. It uses
the residual energy and the link reliability to prioritize the neighbour nodes. It operates
over multiple channels and it has been evaluated through simulations and hardware
implementation.

Final, CROR protocol in Chapter 6, was designed for WMSNs. CROR is a Context
Relevant Opportunistic Routing protocol that prioritizes the nodes based on their loca-
tion. It forwards the packets based on their relevance: the higher the priority of a packet,
the higher the packet advancement through the relay node. CROR has been simulated
only.
Chapter 7. Conclusions

7.2 Process for Protocol Implementations

The process that was followed for the introduced protocols has three steps:

1. theoretical design,

2. simulation evaluation and

3. hardware implementation.

These three steps were followed in sequence. However, there were many times that after checking the simulation results or the hardware implementation, it was necessary to go back and make changes to the theoretical design. The most common reason was the model assumptions.

For instance, for the geographic routing, the accuracy of the location information has a great impact on the performance results. In theory, when the location information has high accuracy, the performance of geographic routing can be optimized. However, during real-time experiments it was realized that this high accuracy is not feasible. The main reason derives from the hardware limitation. The nodes have limited computational and memory capabilities hence, advance location techniques cannot be applied. Moreover, through simulation it was clear that as the network density increases, the accuracy of the metric decreases. Measuring the energy consumption in some of the protocols posed similar difficulties. The hardware limitation, the complexity restriction and the small size of the nodes, made some of the design assumption of the theoretical models not feasible.

A number of other useful feedback was gained through simulations and implementation. For example, an accurate theoretical model should explain the simulation results however, it might be different in comparison with the real-time experiments. The reason is usually unpredictable parameters such as network interference and the coexistence problem which cannot be applied to the theoretical design or the simulation. In this case, the protocol should be designed again to cope with these problems.

Finally, the hardware limitation always poses challenges to the protocol design. For an efficient design, the hardware details and the network field or the application scenario should be carefully studied in advance. Many switches back and forth between the 3 steps are necessary for a successful final design.
7.3 Recommendations on Routing Design

The design and implementation of efficient routing protocols for WSNs is an important research topic that poses significant challenges. Based on the experience gained through the design and implementation of the above protocols, in this section a few suggestions are presented.

**Application specific protocols.** As the number of the applications that make use of WSNs increases, the number of the proposed protocols increases as well. However, the more specific the application is, the more clear are the challenges and hence, optimization techniques can be applied. General routing protocols might be applicable to a number of application scenarios however, routing protocols that are designed to make use of the unique characteristics of the application can be more efficient. For instance, there is a plethora of routing protocols for WSNs. In general, WSNs have common characteristics such as energy limitations and computational complexity. On the other hand, a sub-category of WSNs such as self-powered WSNs through energy harvesting, poses the unique challenge of an efficient use of the energy harvesting mode and its limitations. Another example is a monitoring WSN. The workload is not always high and efficient duty cycle techniques and routing protocols can be applied. These techniques are specific and might not have appealing results in a general WSN application. Moreover, some applications have unique field characteristics. For instance, indoor monitoring applications have the NLOS and the coexistence problems while an outdoor monitoring might not face these challenges. The details regarding the network field can also help for an efficient routing design.

**Importance of hardware limitations.** Following the previous suggestion, some applications can use general hardware or specific sensor nodes. At any case, the hardware limitation should be reviewed in depth before the routing design. For instance, the use of a cognitive aspect of the different proposed protocols is feasible only through nodes with cognitive radios. For the experiments presented in this thesis, two antennas were used. If the hardware does not have cognitive radio, some of the protocols could not be implemented. On the other hand, if the hardware has one antenna, maybe the use of cognitive aspects is not efficient. The complexity of the protocol should increase, while the spectrum might not be used efficiently. Moreover, information regarding the storage capabilities and the power requirements of the nodes can have great effect on the final routing design.
Opportunistic routing and prioritization metric accuracy. It is clear that the prioritization metric accuracy is important for the hardware implementation and evaluation of an opportunistic routing protocol. For a hardware implementation of the protocol, a metric that uses available information should be used. This information is related to the hardware used as well as the type of the network. For instance, in a static network with accurate location information, many geographic opportunistic routing techniques can be applied. If there are dynamic changes in the network and a random topology is used, then the challenge moves to the hardware limitations. If the hardware can provide accurate location information – through GPS for example – the use of the protocols is feasible. However, the cost per unit of these nodes should be considered. On the other hand, information such as energy consumption and link reliability can be combined to increase the metric accuracy.

Analytic and experimental evaluation. An efficient routing protocol design requires not only theoretical analysis but also experimental evaluation. There are many challenges that can not be predicted during the theoretical analysis. During the hardware implementation these challenges will be cleared and maybe a design from scratch is required. On the other hand, experimental results might not be accurate due to mistakes in the implementation. Theoretical results in this case can held to predict what experimental results should be expected. Simulation evaluation is an important step that connect these two important processes.

7.4 Open Issues and Future Work

In the near future, WSNs are expected to be integrated into the “Internet of Things” (IoT) and consequently the “Internet of Everything” (IoE). The sensor nodes can join the internet dynamically and use it to collaborate and accomplish their tasks. The sensing infrastructures have a major role in the IoT and great research opportunities. The future internet, designed as an IoT is foreseen to be “a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols”. The sensor node market continues to grow rapidly, as the cost to build custom nodes decreases due to technology scaling. Moreover, the use of embedded sensors in smartphones, phablets, tablets and mobile devices has enabled a number of popular applications.

The flexibility of sensor nodes permits fast time-to-market, which is crucial in the development of new sensor network applications. From the cost perspective, embedded
sensors in mobile devices are already superior to application specific hardware. As an example, the indoor positioning system (IPS), which is based on magnetic and other sensor data or a network of devices, is more flexible, secure and inexpensive in comparison to Global Positioning System (GPS). Naturally however, the programmability of sensors and their integration with multiple application involves an overhead. More research is needed to narrow the gap between sensors and their potential application. Doing so will broaden the scope of sensor applications and allow more innovation to happen, whether it be in small start-ups, established industry, or in academia. Enabling greater innovation will ultimately benefit the economy and society at large.

Beyond improving sensor integration, the concept of sensor in the IoE opens the door to a yet unexplored applications that cannot be conceived using specific/devoted hardware, especially in the field of mobile devices. A flexible embedded sensor framework can be programmed and re-programmed in real-time, based on application needs. This is a unique characteristic that can be exploited for varied purposes, including improving application speed, power and cost.

**Performance and area optimization.** There is considerable room for further optimization on self-powered WSNs. One direction is to take advantage of the improvement in computational capabilities of the sensors. Advance duty cycle and packet relay mechanism can be applied to the nodes. Also, the increase of the memory per node can improve the performance of the routing protocols and the programmability of each node.

**Location Based Social Networks (LBSNs).** There is a great potential in the area of social network analysis, mainly in location-based social networks (LBSNs). The ability of mobile handled devices with many sensors to estimate their position has enabled mobile systems to bring into the equation of digital social networks another dimension, that of location. Location-based Social Networks (LBSNs) tie the virtual and physical worlds through the location information. There is a great research interest to identify the way that users interact with an LBSN and model the underlying trends. There are many different types of relations that can be identified between users and/or places, bonding together the virtual and physical worlds. Given social and spatial information, we can determine how people behave in real space. Not only to analyze the flat friendship graph, but also to study it in conjunction with the behaviour of people in the physical space. Sensor networks and their capabilities can be used in LBSNs.

**Security threats in mobile devices and smartphones.** Embedded sensor frameworks exist in all the recent mobile devices and their operating systems. However, little
work has been done on the security and privacy treats coming with smart devices. If an attacker or malware gets access to the sensor data, such as to the position sensor, camera or microphone, this is a serious threat to privacy.

Another idea is the integration of different types of sensors and their data for more accurate performance metrics. For instance, the inexpensive use of an IPS through sensor nodes can increase the potential of a geographic routing.

**Smart grid communication and smart cities.** Sensors have a major role in the smart grid and the smart cities. The WSN technologies are among the technologies characterized as “digital evolution” because they are able to create networked artifacts (human and non human) that can sense their environment and accordingly adapt their behaviour.

An example is the case of a demand response sensor system for distributed energy resources, cost efficient, energy efficient and secure power management for smart grids. Effective energy governance is augmented by the deployment of a large scale network of multi-purpose sensors and a smart radio network. The rational for such technologies is that such added networking makes us “smarter”, more “aware” and “responsive”. A distributed monitoring capacity may give us a novel visualization of the energy environment that allows more effective planning: the ability to respond in a more timely fashion and to develop more effective actions to resolve power supply and demand problems. The social and economic implications can be enormous for public, but also private organizations. Clearly, the implications and impact of such smart infrastructures have a strategic value not only for Ontario and Canada, but also globally.

### 7.5 List of Publications

The work described in this thesis has been presented in the following publications:

**Journal Publication**


**Book Chapters**

Conference Publications


**Posters and Demonstrations**


Bibliography


