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A CDMA Multiple Packet-Burst Capture Receiver Scheme

by

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A Thesis submitted in conformity with the requirements for the Degree of Master of Applied Science
Department of Electrical and Computer Engineering
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A CDMA Multiple Packet-Burst Capture Receiver Scheme

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ABSTRACT

A packet-based, spread-spectrum, multiple-capture receiver scheme is proposed for the reverse channel of a cellular communication system in which the terminals utilize common codes to spread the initial portion of their transmissions which is required for capture and a temporarily assigned long spreading code for the data portion of the transmissions. Access to the reverse channel is controlled through a busy tone signal in the forward channel in order to prevent excessive multiple access interference at the receiver. A model of the receiver scheme is developed and simulated using bit and chip rates similar to those in third generation mobile communication systems. Packet-transmission capture, packet throughput, access delay and packet-erasure rates in the receiver scheme are investigated. In addition, the effect of intercell interference, path diversity, antenna selection diversity and slow terminal motion is also examined.
Acknowledgments

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INTRODUCTION

The role of first generation mobile systems is to provide wireless local mobile speech services. However, due to the growing importance of data communications, future systems will also be required to provide a wide array of data services such as Internet access, paging and portable computing. In addition, research programs for third generation mobile communications systems aim to integrate voice, data and video (multimedia) services within one network and support much higher bit rates than is available in current cellular networks.

To provide integrated services, wireless network architectures that deliver a packet-switched system to the user are being considered. An example of this is “Wireless ATM,” which is a framework for a seamless wired plus wireless networking environment that utilizes ATM and some additional wireless specific protocols. While the service that the network provides is to be packet-switched, the actual transmission of the packets over the wireless links can be in a circuit-switched (connection-oriented) or a packet-switched (connection-free) mode [1].

In connection-oriented schemes, such as those employed in current digital cellular standards, a mobile terminal wishing to transmit to the base station must make a request on a separate channel dedicated to call setup and tear down. The terminal is then assigned an exclusive traffic channel (i.e. a frequency, time slot or code), which it gives up at the end of its session. There is a finite delay and transmission overhead associated with the connection procedure.

The suitability of a connection-oriented scheme for packet transmission is dependent on the type of traffic that must be supported. It is an acceptable method when the traffic is a steady, constant bit-rate data stream. On the other hand, when the traffic is from bursty, variable bit-rate sources such as typical data applications, it results in the inefficient utilization of the assigned traffic channel and a reduced system throughput. In connection-oriented CDMA systems such as IS-95, variable bit-rate traffic can be handled more efficiently by reducing the transmit power
during low bit-rate periods (i.e. between traffic bursts). However, this method is still hardware inefficient in that the receiver at the base station must continue to track a user’s signal between traffic bursts and is therefore unavailable to service packets from other users. A connection-oriented scheme is also unsuitable when the user’s session is of a relatively short duration. When the network traffic is composed largely of such transaction type traffic, the delay and overhead associated with the connection procedure become significant and a connection-oriented method is no longer practical.

To accommodate the large variety of traffic expected in integrated wireless networks, a connection-free, random access, packet-switched architecture such as ALOHA has been suggested [2]. In the conventional, narrowband ALOHA protocol, all the terminals transmit to the base station over a common channel, which is accessed through contention. Since there is no coordination between the different terminals, in certain instances packets from two or more terminals may occupy the channel simultaneously and arrive overlapped in time at the base station. For each packet, the other packet transmissions are a source of multiple access interference. With narrowband signaling, the base station can capture (synchronize with and decode) one of the packets only if its signal-power-to-interference-power ratio (SIR) is much greater than one. This rules out the possibility of a packet succeeding when multiple packets of equal power arrive simultaneously at the receiver since each packet is corrupted by the interference from the other packets resulting in packet collisions. The collided packets have to be re-transmitted until they are successfully received at the base station.

To support delay sensitive and constant bit rate traffic within a connection-free, random access structure, protocols that permit reservation have been developed. An example is the Packet Reservation Multiple Access (PRMA) protocol. The PRMA protocol [3] is a combination of slotted ALOHA and Time Division Multiple Access (TDMA). The time axis is divided into slots within each of which only one packet can be transmitted from a terminal to the base station. As in TDMA, the slots are grouped into frames with each frame containing a fixed number of slots. The terminals classify the slots in each frame as being either reserved or available based on information broadcast by the base station on a feedback channel during the previous frame. As in conventional ALOHA, a terminal with new information must access the common channel through contention. However, in PRMA it may only do so during the available slots. If the terminal’s packet is successfully received during an available slot (i.e. there are no collisions), the
status of the slot changes to reserved. The new slot status as well as the identity of the successful terminal is broadcast on the feedback channel at the end of the slot. In the subsequent frames, the terminal that succeeded has exclusive use of that slot as long as it transmits a packet in each frame. If no packet is received in a reserved slot, its status reverts back to available in the subsequent frames.

A fundamental objective in packet-switched, random-access schemes is to maximize system throughput while channel access delays and packet bit-errors are kept to a minimum. In narrowband schemes such as ALOHA and PRMA, the throughput is limited by the fact that at most only one packet may be captured at a time. However, with the application of spread-spectrum techniques, packet capture in the presence of multiple access interference is possible due to the interference rejection capability of this signaling scheme. As a result, multiple packets can be captured at a time (multiple-packet capture).

In [4], a technique called spread ALOHA is presented which combines direct sequence spread spectrum (DSSS) and slotted ALOHA. The random access structure and the channel access protocol of this method are similar to the conventional slotted ALOHA protocol. The difference is that all terminals use a common non-repeating pseudonoise (PN) sequence to spread the packets prior to transmission. With DSSS, collisions do not necessarily occur when multiple packets occupy the same ALOHA slot. When the arrival of one packet precedes the arrival of the others by at least one spreading symbol (chip) period, the received signal of the first packet is pseudo-orthogonal to the signals of the others. Hence, the receiver is able to capture the first packet while the interference caused by others is rejected by a factor related to the processing gain of the spreading process. This is referred to as delay capture. However, when two or more packets arrive within one chip period, there is strong correlation over each data symbol of the received signals and, as in narrowband schemes, packet collisions result.

In another connection-less scheme called packet CDMA, spread spectrum in the form of CDMA is utilized. In this case, each terminal is assigned a separate spreading code from a set of short codes. The set has the property that the periodic cross-correlation function for any two codes in the set is uniformly small over all cyclic shifts of the codes (examples: Gold codes, Kasami codes). The random access structure can be either slotted [5] or unslotted [6]. With an unslotted structure, a terminal can transmit individual packets or a contiguous burst of packets.
Since each terminal uses a separate code no arrival time offset is required for capture. Hence, multiple packets from different terminals can occupy the channel simultaneously and can be successfully captured.

A fundamental problem with packet CDMA is receiver complexity [2]. Since each terminal utilizes a separate spreading code, the base station must have a multiplicity of receivers (i.e. matched filters) to demodulate the different codes and complexity becomes an issue when the number of terminals is large. In [7] and [8], receiver schemes are proposed for spread ALOHA which allow multiple-packet capture but without the complexity of packet CDMA. With spread ALOHA, the base station requires only one matched filter since all terminals utilize a common spreading code. Multiple-packet capture occurs when the arrival times of the different packets meet the delay capture criteria.

With spread spectrum, it is necessary to control the number of simultaneous transmissions. When there too many transmissions, the multiple access interference exceeds the interference rejection capability of the spreading process and the transmitted packets are corrupted. One method of controlling multiple access interference in packet CDMA is the joint CDMA/PRMA protocol [5]. This technique shares the same slot and frame structure as narrowband PRMA but with the difference that with CDMA each slot can support more than one packet. Also, unlike conventional PRMA, the slots are not classified as being either reserved or available. Rather, the initial access to a particular slot is controlled by a transmission permission probability that is broadcast by the base station. A channel access function at the base station determines the permission probability for each slot based on the level of traffic in the same slot during the previous frame. When a new terminal wishes to utilize a particular slot, it first performs a Bernoulli experiment with the permission probability of that slot as the parameter. It is only allowed to use the slot if the outcome of the experiment is positive. In this case, it may continue to use the slot (reservation) in the subsequent frames until the last packet of its current spurt is transmitted.

In designing a packet-switched, random access scheme for future wireless networks, provisions should be made for the following - a method of reservation in order to accommodate delay sensitive and constant bit rate traffic, the capability for multiple packet capture through the application of spread spectrum and a technique to control multiple access interference.
In this thesis, a receiver scheme is proposed which addresses the above three issues. It allows a form of reservation in that during each transmission, a terminal can send a contiguous sequence of packets - a packet-burst. The initial portion of the packet-burst which is required for capture is spread with codes that are common to all terminals. Multiple capture is achieved through the delay capture phenomena and since common codes are utilized, the complexity associated with packet CDMA is avoided. For the data portion of the packet-burst, each terminal utilizes a separate long spreading code. The long code is assigned to a terminal subsequent to the capture of its packet-burst and it is used only for the duration of that burst. To prevent excessive multiple-access interference, a busy tone signal is broadcast by the base station to block new transmissions when the number of on-going transmissions reaches the receiver’s full capacity. The chip rate (4 Mcps) and bit rate (250 Kbps) of the scheme are similar to those in third generation mobile communication systems. Antenna selection diversity is utilized to combat Rayleigh fading and RAKE receivers are used combine multipath components of the terminals’ transmissions. The terminals utilize a combination of open-loop and closed-loop power control.

A model of the receiver scheme is developed and simulated for a centralized system in which the terminal traffic is Poisson. The initial transmit power required, the maximum number of concurrent packet-burst transmissions (or receiver ports), the maximum traffic load, the effect of the number of paths (path diversity), the number of RAKE receiver fingers and the number of antennas required are examined. In addition, the effect of slow terminal motion is also considered.

1.1 THESIS OUTLINE

The thesis is organized as follows. Chapter two is a survey of the two common code multiple-packet capture receiver schemes proposed in [7] and [8]. In Chapter three, a model of the CDMA Multiple Packet-burst Capture Receiver Scheme is developed while Chapter four contains the simulation results for this model and related discussions. Finally, Chapter five summarizes the simulation results and suggests some topics for further research.
LITERATURE SURVEY OF COMMON CODE MULTIPLE-PACKET CAPTURE RECEIVER SCHEMES

In [7] and [8], receiver schemes for common code multiple-packet capture in a slotted ALOHA channel are presented. In both schemes, the packets are composed of an initial header bit sequence [7] or a preamble PN code [8], which is then followed by the data bits. In [7], all the bits of a packet are modulated by one period of a short, common spreading code. In [8], the preamble is one distinct PN code while the data bits are spread with a separate non-repeating code. Both the preamble and the spreading code are common to all terminals. Multiple-packet capture is achieved through the delay capture phenomena of the DSSS signaling used.

2.1 SHORT CODE METHOD

2.1.1 Signal Model

With PSK, the baseband signal of the $i$-th terminal is modeled as

$$x_i(t) = \sum_{n=0}^{L_p-1} \sqrt{2P}b_n^{(i)} c(t - nT_b) \exp(j\theta_i(t))$$  \hspace{1cm} (2.1)

and the transmitted signal corresponding to this is

$$y_i(t) = \text{Re}\{x_i(t) \exp(j\omega_c t)\}$$  \hspace{1cm} (2.2)

Each packet contains a total of $L_p$ bits denoted by $b_0^{(i)} ... b_{L_p-1}^{(i)}$. The first $L_H$ bits contain the common header sequence, $h_0 ... h_{L_H-1}$ while the remaining are the data bits. All bits have a duration of $T_h$ and a constant modulus of $|b_n^{(i)}| = 1$. $P$ is the signal power of
each terminal. \( M \) is the total number of terminals. \( \omega_c \) is the carrier frequency and \( \theta_i(t) \) is the slowly varying carrier phase of the \( i \)-th modulator. The common spreading code waveform is given by

\[
c(t) = \sum_{k=0}^{N-1} c_k p(t - kT_c) \tag{2.3}
\]

where \( \{c_k\} \) is the common PN code sequence, \( p(t) \) is the chip pulse and \( T_c \) is the time interval between consecutive chips. In the case of rectangular chip pulses,

\[
p(t) = \begin{cases} 
1 & (0 \leq t \leq T_c) \\
0 & \text{Otherwise} 
\end{cases} \tag{2.4}
\]

Each bit is modulated by one period of the PN code. Hence, the code period \( N \) which is related to the bit period and chip pulse interval by

\[
N = \frac{T_b}{T_c} \tag{2.5}
\]

is also the processing gain.

The signal received at the base station during a particular slot is modeled as

\[
r(t) = \sum_{i=1}^{K} y_i(t - \tau_i) \tag{2.6}
\]

\[
= \sum_{i=1}^{K} \text{Re} \left\{ \sum_{n=0}^{L_p-1} \sqrt{2} P b_n^{(i)} c(t - \tau_i - nT_b) \exp[j(\omega_c t + \phi_i(t))] \right\}
\]

where \( \tau_i \) is the arrival time of the packet from the \( i \)-th terminal within this slot, \( K \) is the number of active terminals during this slot and \( \phi_i(t) = \theta_i(t) - \omega_c \tau_i \). The terminals randomizes their packet transmission time such that the arrival times \( \{\tau_i\} \) are distributed over a small interval \([0, rT_b]\) (\( r << L_p \)) at the beginning of each slot.
2.1.2 **Multiple-Capture Receiver Model**

The receiver at the base station extracts the baseband complex envelope \( \tilde{r}(t) \) of the received signal

\[
r(t) = \text{Re}\{\tilde{r}(t)\exp(j\omega_c t)\}
\]  

\( (2.7) \)

![Diagram of the receiver scheme for the short code method](image)

Figure 2.1: Receiver Scheme for the Short Code Method

The complex envelope signal

\[
\tilde{r}(t) = \sum_{i=1}^{K} \sum_{n=0}^{L_p-1} \sqrt{2} P_b^{(i)} c(t - \tau_i - nT_b) \exp[j\phi_i(t)]
\]  

\( (2.8) \)
is passed through a filter that is matched to the spreading code waveform \( c(t) \), as shown in Figure 2.1. The impulse response of the filter is

\[
\tilde{h}(t) = \frac{1}{2} c(T_b - t)
\]  

(2.9)

and the output of the filter, \( z(t) \), is the correlation between the complex envelope and the spreading code waveform,

\[
z(t) = \int_{-\infty}^{\infty} \tilde{F}(v)\tilde{h}(t-v)dv
\]

\[
= \frac{1}{2} \int_{t-T_b}^{t} \tilde{F}(v)c(v + T_b - t)dv
\]

\[
= \sqrt{\frac{P}{2}} \sum_{i=1}^{K} \sum_{n=0}^{L_p-1} b^{(i)}_n \int_{t-T_b}^{t} c(v - \tau_1 - nT_b) \exp[j\phi_i(v)]c(v + T_b - t)dv
\]

For the case of \( K = 1 \) and a slowly varying carrier phase, Equation 2.10 may be written as

\[
\sqrt{\frac{P}{2}} \exp[j\phi(\tau)] \{ b_m \int_{t-T_b}^{(m+1)T_b + \tau} c(v - \tau - mT_b)c(v + T_b - t)dv +
\]

\[
\quad + b_{m+1} \int_{(m+1)T_b + \tau}^{t} c(v - \tau - (m+1)T_b)c(v + T_b - t)dv \}
\]

(2.11)

where \( m = \left\lfloor \frac{t - T_b}{T_b} \right\rfloor \). Since the filter has a finite impulse response only those bits in the received signal that occur within the interval \((t - T_b, t)\) affect the filter output at time \( t \).

Hence, the first term within the parenthesis of Equation 2.11 is the contribution of the \( m \)-th bit in the received signal while the second term is the effect of the subsequent bit.
This "sliding window" effect of the matched filter and its corresponding output is illustrated in Figure 2.2. At times $t = \tau + (j + 1)T_b$, $j = 0, 1, 2, \ldots, L_p - 1$, the matched filter output contains the correlation mainlobe peaks of the spreading code waveform $c(t)$ modulated by the packet bits $\{b_j\}$. The correlation mainlobe for each bit occurs over a period of $2T_c$ centered about its peak.

The matched filter output is sampled at a rate of $S$ samples per chip period $T_c$, and the samples are cyclically fed to $SN$ different data sequence channels ($S = 1$ in Figure 2.1). Since $T_b = NT_c$, samples taken one bit time apart get fed to the same data sequence channel. The samples of each channel are correlated with the common header sequence in the tapped-delay line header correlator, and the correlator output is compared to a detection threshold $|W_t|$. 

When a packet arrives, the matched filter output produces a sequence of correlation mainlobes modulated by the packet bits (Figure 2.2). Since these occur one bit time apart, samples of the mainlobe sequence are fed to the same data sequence channel. The first $L_H$
mainlobes are modulated by the header bits \( h_0, \ldots, h_{L_H - 1} \) and when their samples are read by the header correlator, there is high correlation and the correlator output exceeds the detection threshold. This triggers the "packet data decoder," which begins to decode the data bits of the packet.

When more than one packet occupies a slot (\( K > 1 \) in Equation 2.10), the matched filter output will contain correlation mainlobes due to all the packets. As an example, the case of \( K = 3 \) is shown in Figure 2.3. When the mainlobes of the different packets do not overlap (Figure 2.3a), multiple-capture is possible since the samples of the mainlobes for each packet are dependent mainly on the bits of that packet while the other packets appear as multiple
access noise. In Figure 2.3b, the mainlobes for two packets are coincident. In this case, the samples of the mainlobes are dependent on the bits of both packets (denoted “$b_k^2 + b_k^3$”) and as a result, the data bits of both packets are corrupted (“collided packets”). In certain instances, multiple-capture can occur even when the mainlobes partially overlap, if the samples taken fall in the region of the mainlobes that does not overlap (Figure 2.3c). Hence, the likelihood of multiple-capture for “partially collision-free” packets is related to the sampling rate employed by the receiver scheme.

2.2 PREAMBLE PN CODE METHOD

In [8], a different technique for multiple-packet capture with common codes is presented. In this method, the header sequence of [7] is replaced with a single PN code (preamble) while the information portion of a packet is spread with a separate non-repeating PN code (Figure 2.4). Both the preamble and the spreading code are common to all terminals. The receiver scheme is shown in Figure 2.5.

The received signal is correlated with the preamble PN code in the matched filter. When a packet transmission occurs, the preamble waveform in the received signal produces a correlation peak in the matched filter output that is detected by the threshold detector. At this point, the receiver has in effect acquired code synchronization with the received signal. Then, the logic circuitry activates one of the decoders which begins to track and demodulate the data portion of packet.

As in the short code method, terminals randomize their transmission time within a slot. Multiple-capture is possible when the arrival times of concurrent packet transmissions are separated by at least one chip period. Then, in the decoder of one packet, the interference from the other packets appears as wideband noise.
Figure 2.4: Packet Structure for the Preamble PN Code Method

Figure 2.5: Receiver Scheme for the Preamble PN Code Method
3

THE CDMA MULTIPLE PACKET-BURST CAPTURE RECEIVER SCHEME

3.1. OVERVIEW

The receiver scheme is implemented at a cell site's base station (Figure 3.1). The cell can be isolated (single cell) or it can exist within a cellular environment, surrounded by other cells. In either case, each cell is assumed to contain a fixed and equal number of mobile terminals requiring service (equally loaded cells). Once a terminal completes service, it leaves the system, and is immediately replaced by a new terminal requiring service. The terminals are modeled as being either stationary or slow moving during their service time.

The forward (base station to terminal) and reverse (terminal to base station) links are implemented in two separate frequency channels (Frequency Division Duplex). The forward link, which could be implemented as a broadcast channel, is assumed to transmit information to the terminals without error and with negligible delay. The reverse link is a common channel that the terminals access through contention.

Figure 3.1: Receiver scheme at a cell site
3.2. TERMINAL TRAFFIC MODEL

When a new terminal enters the system, it is required to establish a session at the base station in order to receive service. During its session, the terminal periodically transmits messages (data) to the base station, and the session terminates when the last message has been successfully transmitted. Message arrival at each terminal is Poisson with rate $\lambda_M$. New messages are buffered if the current message is still in the transmission stage. The number of messages that originate at a terminal during its session is a geometric random variable with mean $K_M$.

The transmissions in the reverse channel occur in the form of a contiguous sequence of packets called packet-bursts. For the initial session establishment, a terminal transmits a session-initiate burst while the subsequent messages are transmitted in the form of message bursts. The session-initiate bursts contain a fixed number of packets (5) while the number of packets in each message burst is a geometric random variable with mean $K_B$.

3.3 PACKET-BURST STRUCTURE

A packet-burst is composed of two segments: the probe and the payload (Figure 3.2). The probe consists of a preamble, a header and an ACK interval (acknowledgment interval) while the payload carries the data packets. The probe is transmitted every time a terminal attempts to contact the base station. The payload follows only if the preceding probe is successfully received and acknowledged by the base station. Otherwise, the terminal ceases the transmission after the probe segment.

![Packet Burst Structure](image)

**Figure 3.2: Packet Burst Structure**

**PREAMBLE:** A PN code of length $N_p$ that is common to all terminals. It enables the base station to detect the start of the packet-burst transmission and to acquire code...
synchronization with the received signal. The preamble has a duration of $T_p$ given by $N_p/R_C$, where $R_C$ is the chip rate.

**HEADER:** This segment carries 16 bits, which contain the identity of the transmitting terminal as well as a CRC. The source terminal's identity allows the base station to send an acknowledgment back to that terminal. The CRC is used to check the validity of the demodulated header bits. The header is spread with a common, non-repeating spreading code. This segment has a duration of $T_H$ and a processing gain of $N_H/16$, where $N_H = T_H R_C$.

**ACK Interval:** During this 1 millisecond interval, the base station sends an acknowledgment to the source terminal if it was able to detect the packet-burst transmission and correctly demodulate the header. In this case, the terminal is assigned a long spreading code for the subsequent data packets. In addition, the terminal also performs closed-loop power control which is assumed to be complete at the end of this interval (Section 3.6.4.2). However, if no acknowledgment is sent to the terminal, the terminal ceases the transmission at the end of the ACK interval (or probe).

The probe segment has a duration of $T_{Prb} = T_p + T_H + T_A$ where $T_A$, which is the duration of the ACK interval, is 1 millisecond.

**DATA:** When the packet-burst's probe is successfully received and acknowledged by the base station, the terminal transmits the payload, which contains the data packets. Each packet has the size of an ATM Cell (424 bits) and is composed of data bits, a CRC and forward error correcting (FEC) code bits. The packet bits are spread using the code assigned to the terminal during the preceding ACK interval. The processing gain is $R_C/R_D$, where $R_D$ is the packet bit rate.

While both the session-initiate bursts and the message bursts have the structure shown in Figure 3.2, they differ in two aspects. Firstly, the session-initiate burst probe is transmitted with open-loop power control and hence, its received power is a random variable (Section 3.6.4.1). In
the case of a message burst probe, its received power is a deterministic value since it is transmitted after the closed-loop power control procedure of the previous message burst or the session-initiate burst, (assuming the terminal remained stationary subsequent to that procedure). Secondly, the session-initiate burst payload always contains a fixed number of packets (5) which is the session initiation overhead while the size of the message burst payload is a geometric random variable.

3.4 REVERSE LINK MULTIPATH MODEL

The packet-burst transmissions from the terminals arrive at the base station through multiple multipath components. Adjacent multipath components can be resolved if the separation between their arrival times is at least one chip period $T_C = 1/R_C$. The number of resolvable multipath components (or echoes) associated with a terminal is modeled as a random variable uniformly distributed between 1 and $K_E$, where $K_E$ is the maximum number of echoes observed anywhere in the system. All the echoes associated with a packet-burst transmission arrive at the base station within an interval called the delay-spread period $T_D$ (Figure 3.3). The arrival time offset of the second and higher echoes (if any) with respect to the first echo is modeled as a random variable uniformly distributed within the delay-spread period. The number of echoes and the arrival time offsets are assumed to remain constant during a terminal’s session since these are related to macroscopic phenomena which will not change appreciably for stationary or slow-moving terminals.

![Diagram of Min. separation of $T_C$ for resolvability of adjacent echoes](image)

*Figure 3.3: Multipath Echoes & the Delay-spread Period*
The received power of the \( i \)-th multipath component \( P^{(i)} \), is modeled as

\[
P^{(i)} = P L G Y_i \quad (1 \leq i \leq K_E)
\]  

\( P \) is the transmit power used by the terminal. \( G \) is a log-normal random variable with a mean of 1 and \( \sigma = 7 \) dB which models shadow fading effects. \( Y_i \) is an exponential random variable with a mean of 1 which models Rayleigh fading effects. \( L \) is the propagation path loss factor which is given by

\[
L = R^{-\gamma}
\]  

where \( R \) is the distance between the terminal and the base station and \( \gamma \) is the path loss exponent which is taken as 4 [9].

The path loss and shadow fading terms are the same for all echoes associated with a transmission, and since these phenomena are only affected by large variations in the terminal’s position, they are modeled as being constant during a terminal’s session. In addition, the path loss and shadow fading are also frequency independent. Hence, their effect on the forward and the reverse links is modeled as being the same. This is utilized in performing open-loop power control (Section 3.6.4.1).

Each echo has independent Rayleigh fading characteristics. Therefore, the term \( Y_i \) is modeled as an independent exponential random variable for each index \( i \). Rayleigh fading is affected by small-scale variations in position. In the case where the terminals are stationary, the Rayleigh fading terms will remain constant during a session. The effect of slow terminal motion is considered in Section 3.9.
3.5 TRANSMIT - RECEIVE SIGNAL MODEL

The baseband signal of a packet-burst transmission is modeled as

\[ S_B(t) = \sqrt{2P_p} X_p(t) + \sqrt{2P_H} X_H(t - T_p) + \sqrt{2P_A} X_A(t - T_p - T_H) + \sqrt{2P_D} X_D(t - T_{Prb}) \]  

(3.3)

where the \( P_p \), \( P_H \), \( P_A \) and \( P_D \) are the terminal’s transmit power and \( X_p(t) \), \( X_H(t) \), \( X_A(t) \) and \( X_D(t) \) are the signal waveforms during the preamble, header, ACK interval and payload segments, respectively. In each segment, the signal waveform is the direct sequence spreading code waveform of that segment modulated by the information bits of that segment.

With BPSK, the transmitted signal corresponding to Equation 3.3, is

\[ S_T(t) = \cos(\omega_c t + \theta(t)) S_B(t) \]  

(3.4)

where \( \omega_c \) is the carrier frequency and \( \theta(t) \) is the slowly varying phase of the terminal’s modulator.

The received signal at the base station is composed of multiple echoes of the transmitted signal due to multipath. Let

\[ r_i(t) = \sqrt{2P_p^{(i)}} X_p(t) + \sqrt{2P_H^{(i)}} X_H(t - T_p) + \sqrt{2P_A^{(i)}} X_A(t - T_p - T_H) + \sqrt{2P_D^{(i)}} X_D(t - T_{Prb}) \]  

(3.5)

where \( P_p^{(i)} \), \( P_H^{(i)} \), \( P_A^{(i)} \) and \( P_D^{(i)} \) are the received power of the \( i \)-th echo during the preamble, header, ACK interval and payload segments, respectively. The received power of an echo during a particular segment is related to the terminal’s transmit power during the same segment by Equation 3.1. The received signal corresponding to Equation 3.4 is then given by
where \( m \) \((m \leq K_E)\) is the number of echoes associated with the packet-burst transmission and \( \tau_i \) is the arrival time of the \( i \)-th echo which has a phase \( \phi_i(t) \) given by

\[
\phi_i(t) = \theta(t) - \omega_c \tau_i
\]  

(3.7)

In general, the received signal at the base station is a composite of multiple concurrent packet-burst transmissions from different terminals and hence, Equation 3.6 becomes

\[
r(t) = \sum_{i=1}^{m} r_i(t - \tau_i) \cos(\omega_c t + \phi_i(t))
\]

(3.6)

where \( K \) is the number of active terminals at time \( t \), and the index \( j \) indicates the terminal to which the expressions or arguments apply.

---

**Figure 3.4: Single-Antenna Receiver System**
3.6 RECEIVER SYSTEM MODEL

The single-antenna receiver system as shown in Figure 3.4 consists of one antenna, a filter matched to the preamble PN code, a threshold detector, logic circuitry and a number of receiver ports. Each port is a RAKE receiver with a number of fingers.

The matched filter correlates the received signal with the preamble PN code and produces a correlation mainlobe whenever the preamble waveform is detected in the received signal. When a packet-burst transmission arrives at the base station, a correlation mainlobe is produced for each resolvable echo in that transmission. If an echo has sufficient signal strength, its correlation mainlobe is detected by the threshold detector, which triggers the logic circuitry. The logic circuitry in turn activates one of the fingers of a port (or RAKE receiver). The port maximally combines the detected echoes to enhance the signal-power-to-interference-power ratio (SIR) during the demodulation of the header and the data packets of the transmission.

The successful reception of a packet-burst transmission requires four events: the detection of the packet-burst transmission, the availability of a free port to receive it, the correct demodulation of its header and finally, the correct decoding of its data packets. When the first three events occur, the packet-burst’s probe is said to have been captured. A packet-burst transmission is detected when at least one of its echoes is detected.

![Diagram](Figure 3.5: Digital Matched Filter for Non-coherent Preamble Detection)
3.6.1 Preamble Matched Filter Model

The matched filter first recovers the in-phase component \( I(t) \) and quadrature component \( Q(t) \) of the received signal (Figure 3.5). Both these signals are sampled at the chip rate \( R_C \), the samples are quantized and then clocked through the preamble correlators. In the correlators, the samples are correlated with the preamble PN code sequence \( \{C_n\} \). The output of the two correlators are squared and combined to form the matched filter output. At any instance, the preamble correlators contain \( N_p \) samples of the received signal collected over the previous \( N_p \cdot T_C \) or \( T_p \) period of time. Let the samples in the in-phase and quadrature branch correlators be denoted as \( \{I_1, I_2, \ldots, I_{N_p}\} \) and \( \{Q_1, Q_2, \ldots, Q_{N_p}\} \) with \( I_1 \) & \( Q_1 \) being the most recent samples and \( I_{N_p} \) & \( Q_{N_p} \) being the oldest samples. Then, the matched filter output can be written as

\[
Z = \left( \sum_{n=1}^{N_p} C_{N_p-n} \cdot I_n \right)^2 + \left( \sum_{n=1}^{N_p} C_{N_p-n} \cdot Q_n \right)^2 \quad (3.9)
\]

where the two terms on the RHS of the equation are the square of the in-phase and quadrature branch preamble correlator outputs, respectively. The output of each correlator is the weighted sum of its \( N_p \) samples with the weights being the elements of the preamble PN code sequence \( \{C_{N_p-1}, C_{N_p-2}, \ldots, C_0\} \), which are applied to the samples in this order.

Consider first the case when there is only one active terminal whose transmitted signal arrives through a single echo (i.e. \( K = 1 \) & \( m = 1 \) in Equation 3.8). The in-phase and quadrature components of the received signal are

\[
I(t) = \frac{1}{2} r_{1,1}(t - \tau) \cos\{\phi(t)\} \quad (3.10)
\]

\[
Q(t) = \frac{1}{2} r_{1,1}(t - \tau) \sin\{\phi(t)\} \quad (3.11)
\]
Prior to the arrival of the packet-burst (i.e. for \( t < \tau \)), the received signal is zero and hence, the matched filter output is also zero. During \( \tau < t < \tau + T_p \), the received signal contains the preamble waveform which is sampled and clocked into the preamble correlators of the matched filter. At time \( t_0 = \tau + T_p \), the samples in the correlators are

\[
\langle I_1, I_2, \ldots, I_{N_p} \rangle = \sqrt{\frac{P_p}{2}} \cos\{\phi(t)\}\langle C_{N_p-1}, C_{N_p-2}, \ldots, C_0 \rangle
\]

(3.12)

\[
\langle Q_1, Q_2, \ldots, Q_{N_p} \rangle = \sqrt{\frac{P_p}{2}} \sin\{\phi(t)\}\langle C_{N_p-1}, C_{N_p-2}, \ldots, C_0 \rangle
\]

(3.13)

with \( P_p \) being the received power during the preamble segment. The matched filter output from Equation 3.9 is

\[
z(t_0) = \left\{ \sqrt{\frac{P_p}{2}} \cos(\phi(t_0)) \sum_{n=1}^{N_p} (C_{N_p-n})^2 \right\}^2 + \left\{ \sqrt{\frac{P_p}{2}} \sin(\phi(t_0)) \sum_{n=1}^{N_p} (C_{N_p-n})^2 \right\}^2
\]

\[
= \frac{1}{2} P_p N_p^2
\]

(3.14)

where the second equality is due to the fact that elements of the preamble PN code \( \{C_n\} \) take on values of +1 or -1 and thus \( (C_n)^2 \) is identically equal to 1. This is the correlation mainlobe of the preamble. When \( \tau < t < \tau + 2T_p \) \& \( t \neq \tau + T_p \), only some of the samples in the correlators are from the preamble waveform. During this interval, the matched filter output is said to contain the correlation sidelobes of the preamble.

When the matched filter output does not contain the mainlobe (i.e. \( t \neq \tau + T_p \)), the contents of the preamble correlators are modeled as a random sequence
\[
\begin{align*}
\langle I_1, I_2, \ldots, I_{N_p} \rangle &= \sqrt{\frac{P}{2}} \cos\{\phi(t)\} \langle s_1, s_2, \ldots, s_{N_p} \rangle \\
\langle Q_1, Q_2, \ldots, Q_{N_p} \rangle &= \sqrt{\frac{P}{2}} \sin\{\phi(t)\} \langle s_1, s_2, \ldots, s_{N_p} \rangle
\end{align*}
\] (3.15) (3.16)

where the elements \( s_n \) can take on values of +1 or -1 with equi-probability. The signal power is modeled conservatively by \( P \) which is the largest received signal power during the previous \( T_p \) period of time. In this case, the matched filter output as formulated in Equation 3.9, is

\[
z(t) = \left[ \sqrt{\frac{P}{2}} \sum_{n=1}^{N_p} (C_{N_p-n} \cdot s_n) \right]^2
\] (3.17)

\[
\equiv (X)^2
\] (3.18)

Since typically \( N_p \gg 1 \), the Central Limit Theorem is applied and Equation 3.17 is approximated by Equation 3.18, where \( X \) is a Gaussian random variable with

\[
E[X] = 0
\] (3.19)

\[
\sigma_X^2 = \frac{1}{2} PN_p
\]

In general, a packet-burst transmission will arrive at the base station through multiple echoes and in the presence of transmissions from other terminals (i.e. \( K \geq 1 \) and \( m \geq 1 \) in Equation 3.8). The correlation mainlobe for the \( i \)-th echo from terminal \( j \) occurs at time \( t = \tau_{i,j} + T_p \). In modeling the matched filter output at this time, the worst case for the interfering signals is considered, that is all interfering signals are assumed to be in phase with the signal of the desired echo. The matched filter output is then

\[
z(t) = (W_{i,j} + X)^2
\] (3.20)
$W_{i,j}$ is the mainlobe component of the output and it is given by

$$W_{i,j} = \sqrt{\frac{1}{2} P_{p}^{(i,j)} N_p} \tag{3.21}$$

where $P_{p}^{(i,j)}$ is the received power of the echo during the preamble segment. $X$ is the contribution of interference from all the other echoes of terminal $j$ and from all other transmissions (i.e. interpath & multiple access interference). $X$ is modeled as a zero mean Gaussian random variable with a variance

$$\sigma_X^2 = \frac{1}{2} \left( \sum_{u=1}^{K} \sum_{v=1}^{m_u} P^{(v,u)} - P_{p}^{(i,j)} \right) N_p \tag{3.22}$$

where $P^{(v,u)}$ is the largest received power of the $v$-th echo from terminal $u$ during the previous $T_p$ period of time. When the matched filter output does not contain the mainlobe of any of the echoes, (i.e. $t \neq \tau_{i,j} + T_p$; $1 \leq j \leq K$ & $1 \leq i \leq m_j$), it is modeled as the square of a zero mean Gaussian random variable $X$

$$z(t) = (X)^2 \tag{3.23}$$

where the variance of $X$ is related to the total interference at the base station by

$$\sigma_X^2 = N_p \cdot \frac{1}{2} \sum_{u=1}^{K} \sum_{v=1}^{m_u} P^{(v,u)} \tag{3.24}$$

In the threshold detector, the matched filter output is compared to a preamble detection threshold ($\gamma_p$) every chip period. If the output is greater than or equal to this threshold, the detector triggers the logic circuitry indicating the arrival of an echo. The successful detection of an echo requires that the matched filter output during its mainlobe be
no less than the detection threshold. Hence, the detection decision for the \( i \)-th echo from terminal \( j \) is

\[
(W_{i,j} + X)^2 \geq \gamma_p^2
\]

\[
= |W_{i,j} + X| \geq \gamma_p
\]  

In certain instances, excessive background interference can cause the matched filter output (as given in Equation 3.23) to exceed the detection threshold even though the matched filter output does not contain a correlation mainlobe. Such events are called false alarms, and their occurrence is modeled in Section 3.6.5.1.

### 3.6.2 Receiver Port (RAKE Receiver) Model

Each port in the receiver system is a RAKE receiver, which allows the echoes of a packet-burst transmission to be combined to enhance SIR during demodulation. As described in Section 3.4, all echoes associated with a packet-burst transmission are modeled as arriving at the base station within an interval called the delay-spread period after the first echo. Hence, all echoes that are detected by the matched filter within a one delay-spread period are processed by the fingers of the same port. However, if the number of detected echoes within this period exceeds the number of fingers in the port (\( K_F \)), then only the first \( K_F \) of the echoes will be processed.

Each activated finger demodulates one of the detected echoes, and the results of the fingers are maximally combined. The signal-to-interference power ratio required for this method is estimated from the detected echo, and the estimation is assumed to be perfect. The SIR of the \( i \)-th echo from terminal \( j \) (assuming it is detected) is given by

\[
SIR_{i,j} = \frac{P^{(i,j)} N}{\Psi\left(\sum_{u=1}^{K_F} \sum_{v=1}^{m_u} P^{(v,u)} - P^{(i,j)}\right)}
\]  

\[
(3.26)
\]
where $P^{(v,u)}$ is the received power of the $v$-th echo from terminal $u$. $N$ is the processing gain of the segment being demodulated, which could be either the header or a data packet.

$\Psi$ is the chip pulse shaping factor, which for rectangular pulses is $\frac{2}{3}$. When the detected echoes are combined, the resultant SIR is the sum of the SIR’s of the individual echoes. Hence, the SIR for the transmission from terminal $j$ is

$$SIR_{\text{Resultant}} = \sum_{\text{all detected echoes } i \text{ of terminal } j} SIR_{i,j} \quad (3.27)$$

### 3.6.2.1 SIR Threshold Model

A SIR threshold model is used to determine the outcome of the demodulation/decoding process for the header and data packets.

In the case of the header, the model is as follows

$$SIR_{\text{Resultant}} < \Psi_{\text{SIR}} \quad \text{Header CRC fails with probability 1}$$

(for any period of time)

Otherwise \quad \text{Header CRC succeeds with probability 1}

An erasure occurs (i.e. the header’s CRC fails) if the terminal’s SIR is less than SIR threshold $\Psi_{\text{SIR}}$ at any time during the header’s demodulation. Otherwise, the demodulated results are valid with probability one.

In the case of the data packets, each packet has FEC code in addition to a CRC. The FEC code is able to correct bit errors so long as the number of errors does not exceed its error correcting capability. This is incorporated into the SIR threshold model as follows:
\[ SIR_{\text{Resultant}} < \gamma SIR \]

(for more than the "Error Burst Length Period")

Otherwise

Packet's CRC fails with Probability 1

\[ \text{Packet's CRC succeeds with Probability 1} \]

The error burst length period (EBLP) is a fraction of the total duration of a data packet, for example 10%. A packet erasure occurs (i.e. the packet's CRC fails) only if the total period of time that the SIR is below threshold exceeds the EBLP.

An ARQ scheme can be implemented to resolve packet erasures. With an ARQ scheme, the base station requests the re-transmission of packets for which the CRC fails and the terminal re-transmits these packets in a separate packet-burst transmission, shortly after the original packet-burst transmission.

![Diagram](image_url)

Figure 3.6: Receiver System with Antenna Selection Diversity
3.6.3 Antenna Selection Diversity

When a Rayleigh fading signal is received through multiple antennas and the separation between them is on the order of a few carrier wavelengths, the signal at each antenna has independent Rayleigh fading characteristics. With independent fading, if the received signal from a terminal is in deep fade at one antenna, there is a possibility that the signal is stronger at the other antennas. Hence, antenna diversity may be used to enhance packet-burst reception.

Antenna diversity is implemented in the receiver system as shown in Figure 3.6. Since the separation between the antennas is in the order of a few wavelengths, the arrival of a packet-burst transmission at each antenna is practically simultaneous. The signal from each of the antennas ($K_A$ antennas in total) is processed by a separate preamble matched filter.

With antenna diversity, the multipath model given in Equation 3.1 becomes

$$P_k^{(i)} = PLGY_{i,k} \quad (1 \leq i \leq K_E) \quad (1 \leq k \leq K_A)$$

(3.28)

where $P_k^{(i)}$ is the received power of the $i$-th echo at the $k$-th antenna. The attenuation in the received power of an echo due to path loss ($L$) and shadow fading ($G$) are the same at all the antennas. However, $Y_{i,k}$, which represents the Rayleigh fading in the echo at the $k$-th antenna, is an independent exponential random variable for each index value $k$.

When the same echo is detected at more than one antenna, the echo’s signal at the different antennas can be maximally combined to enhance SIR since the interference at the different antennas is uncorrelated. A second possibility is that for each such echo, the antenna where its received signal is the strongest is selected when the echo is demodulated (antenna selection diversity) and the echo is maximally combined with other detected echoes of the packet-burst transmission. The latter method is utilized in this receiver scheme.
Let the antenna selected for the $i$-th echo from terminal $j$ be denoted by $a_i$. Then, the SIR for this echo is given by

$$SNR_{i,j} = \frac{p^{(i,j)}_{a_i} N}{\Psi(\sum_{u=1}^{K} \sum_{v=1}^{m_u} p^{(v,u)}_{a_i} - p^{(i,j)}_{a_i})} \tag{3.29}$$

where $p^{(v,u)}_{a_i}$ is the received power of the $u$-th echo from terminal $v$ at the $a_i$-th antenna.

The resultant SIR, when different echoes of a transmission are combined, is the sum of the SIR's of the individual echoes, each of which may be received through a different antenna.

### 3.6.4 Power Control

#### 3.6.4.1 Open Loop Power Control

When a terminal transmits a session-initiate burst probe for the first time, it employs open-loop power control. In this method, the terminal estimates the path loss ($L$) and shadow fading ($G$) in the forward link by measuring the attenuation of the signal from the base station. The terminal makes several such measurements to average out the Rayleigh fading in the base station’s signal. The estimation of path loss and shadow fading is assumed to be perfect. Since the signal attenuation due to these phenomena is the same in the reverse link (Section 3.4), the terminal adjusts its transmit power to compensate for these losses. For example, if the session-initiate probe is to be received at the base station with a power of $\overline{P}_0$ (the target received power), the terminal utilizes a transmit power of

$$P = \frac{\overline{P}_0}{LG} \tag{3.30}$$

All segments of the session-initiate burst probe are transmitted with this power. That is, in Equation 3.3

$$P_P = P_H = P_A = P \tag{3.31}$$

30
At the base station, the received power of the $i$-th echo of the transmission is given by Equation 3.1

$$P^{(i)} = PLGY_i \quad (1 \leq i \leq K_E)$$

That is, the power of each echo is an exponential random variable with mean equal to the target received power $P_0$.

If the session-initiate burst probe is not captured and acknowledged by the base station, the terminal increases its transmit power at the next transmission attempt (Section 3.7).

3.6.4.2 Closed-Loop Power Control

A terminal and the base station engage in closed-loop power control during the ACK interval. The objective of this procedure is to ensure that during the payload segment, the total received power in all the detected echoes from the terminal is a constant $P_C$. To achieve this, the base station measures the total power in the detected echoes from the source terminal:

$$\text{Total Detected Power from Terminal } j = \sum_{all \ detected \ echoes \ i \ of \ terminal \ j} P^{(i,j)}$$

and instructs that terminal to change its transmit power as follows

$$P_T' = \frac{P_C}{\sum_{all \ detected \ echoes \ i \ of \ terminal \ j} P^{(i,j)}} P_T$$

(3.34)
Power control is assumed to be complete at the end of the ACK interval. During the
ACK interval itself, the total detected power is modeled as being the same as during the
preceding header segment.

3.6.5 Impediments to Probe Capture

After a packet-burst transmission is detected, two additional events are required for
capture: the availability of a free port to receive the transmission and the correct
demodulation of its header (i.e. the header CRC succeeds). In addition to the possibility of
interference corrupting the header CRC, there are two other mechanisms that can impede
capture: false alarms and collisions.

3.6.5.1 False Alarms

False alarms occur when high interference levels cause the matched filter output
to exceed the detection threshold even though the matched filter output does not contain
a correlation mainlobe. The high interference may be due to other on-going
transmissions and/or due to the correlation sidelobes of a packet-burst transmission that
is received with excessively high power. The logic circuitry interprets the false alarm as
an echo of a packet-burst transmission and assigns a receiver port to demodulate it. The
false alarm is only identified when the header CRC fails. Hence, there is a penalty
period of $T_H$ when the assigned port is busy with the false alarm and is unavailable to
service a legitimate packet-burst transmission.

The output of a matched filter is tested against the detection threshold every chip
interval (i.e. at the chip rate $R_C$). At each such instance, the probability that a false
alarm occurs $P_{FA}(\sigma_X)$, is given by

$$P_{FA}(\sigma_X) = \text{probability}\{|X| \geq \gamma_P\}$$

$$= \text{erfc}\left(-\frac{\gamma_P}{\sqrt{2}\sigma_X}\right)$$  \hspace{1cm} (3.35)
where \( X \) and \( \sigma_X \) are defined by Equation 3.23 and 3.24, respectively. The occurrence of false alarms is approximated by a Poisson process with an “arrival rate”

\[
\lambda_{FA}(\sigma_X) = P_{FA}(\sigma_X)R_C
\]  

(3.36)

Equivalently, the “inter-arrival” time between the false alarms is an exponential random variable with mean \( \lambda_{FA}(\sigma_X)^{-1} \). The arrival time of the next false alarm is valid so long as the interference level remains constant until its arrival. Otherwise, a new inter-arrival time is determined at the time that the interference level changes [10].

3.6.5.2 Collisions

When combining echoes within a port, the logic circuitry assumes that the echoes which are detected within a one delay-spread period originate from the same packet-burst transmission. This assumption is valid so long as only one transmission occurs within this period. When two or more transmissions arrive within a one delay-spread period (Figure 3.7), echoes from different terminals may be combined within the same port resulting in the failure of the header CRC. This is referred to as a collision. As in the case of false alarms, there is a penalty period of \( T_H \) required for a collision to be identified.

Collisions between packet-burst transmissions are modeled as follows. A collision is assumed to occur when at least two packet-burst transmissions arrive at the base station within a one delay-spread period and if at least two of them are detected. The model assumes that the collision results in all the involved packet-burst transmissions being lost. Collisions are avoided when the arrival times of concurrent transmissions are separated by at least one delay-spread period.
3.6.6 Busy Tone Signal

Since packet-burst transmission capture requires the availability of a free port, transmissions that occur when all ports are engaged only create unnecessary multiple access interference. To reduce this type of interference, a busy tone signal is implemented in the forward channel. This signal has two states: busy to indicate that all ports are occupied and free to indicate otherwise. A terminal transmits a packet-burst only if the busy tone signal is free. At the end of a busy period, several terminals may wish to transmit. Hence, to avoid collisions and enhance multiple packet-burst capture, terminals randomize their transmit time at the end of a busy period.

3.7 GENERAL MEDIUM ACCESS RULES

Before transmitting a packet-burst, a terminal monitors the busy tone signal. The transmission is carried out only if the busy tone signal is free. Otherwise, the terminal waits until the end of the busy period. At the end of a busy period, it waits an additional random period of time $W$, checks the busy tone signal and then proceeds with the transmission. If the busy tone signal is again busy, this procedure is repeated at the end of the next busy period.

When a terminal does transmit a packet-burst, it expects an acknowledgment from the base station at the end of the transmitted probe. If none is received, the transmission ceases at the end of the probe. After each such failed transmission attempt, the terminal increases its
transmit power by a factor $I$, waits a random period of time $W$, and then re-transmits the packet-burst if the busy tone signal is free.

The waiting time $W$ at the $n$-th transmission attempt is a random variable with a uniform distribution as given below

$$f_W(w) = \begin{cases} \sqrt{\frac{1}{nT_R}} & 0 \leq w \leq nT_R \\ 0 & \text{Otherwise} \end{cases}$$

(3.37)

where $T_R$ is the smallest waiting time randomization interval. After every failed transmission attempt, the terminal increases its randomization interval by $T_R$ to reduce the likelihood of collisions at the subsequent attempts.

3.8 INTERCELL INTERFERENCE

When the receiver scheme is implemented in a cellular environment, the total interference at a base station has two components: intracell and intercell. The intracell interference is due to on-going transmissions within the cell while the intercell interference is due to transmissions in neighboring cells.

With intercell interference, Equation 3.29 for the SIR of an echo becomes

$$SIR_{i,j} = \frac{P^{(i,j)} N}{\Psi \left( \sum_{u=1}^{K} \sum_{v=1}^{m_u} P^{(v,u)} - P^{(i,j)} + P_{\text{InterCell}} \right)}$$

(3.38)

where $P_{\text{InterCell}}$ is the intercell interference power. When all cells are equally loaded and fading effects are neglected, the average intercell interference can be approximated as 50% of the average intracell interference [11].

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3.9 SLOW TERMINAL MOTION

The terminals are assumed to shift periodically between their message bursts. The occurrence of these shifts is modeled as a Poisson process with rate $\lambda_S$. The path loss and shadow fading are unaffected by the movement. However, the Rayleigh fading after a shift is modeled as being independent of the fading prior to the shift. Hence, if the received power of an echo is initially

$$P^{(i)} = PLGY_i$$

then its power after the terminal moves is

$$P'^{(i)} = PLGY'_i$$

where $Y_i$ and $Y'_i$ are independent exponential random variables with mean 1.
4

SIMULATION RESULTS & DISCUSSION

The simulation results and related discussions of the receiver scheme model developed in Chapter 3 are presented in the following order. In Section 4.1, a single-antenna receiver system in a single cell environment with single multipath echo transmission is considered. In Section 4.2, the effect of intercell interference, when the receiver scheme is implemented in a cellular environment, is examined. Path diversity (multiple multipath echo transmission) and antenna selection diversity are investigated in Sections 4.3 and 4.4, respectively. In all these cases, the terminals are assumed to be stationary during their sessions. In Section 4.5, the effect of slow terminal motion is considered.

The model parameter values utilized in the simulation are listed in appendix A. They are also listed below the graphs in this Chapter when their value is different from that in the appendix.

4.1 SINGLE-ANTENNA RECEIVER SYSTEM, SINGLE CELL ENVIRONMENT & SINGLE MULTIPATH COMPONENT TRANSMISSION

The single-antenna receiver system is shown in Figure 3.4. All packet-burst transmissions are captured and received through a single matched filter - antenna combination. No intercell interference exists since a single cell environment is considered. The transmissions in the reverse link arrive at the base station through a single multipath echo. In addition, the terminals are assumed to be stationary during their sessions.

4.1.1 Probe Capture

A terminal transmits an entire packet-burst only if the packet-burst’s probe is captured at the base station. Probe capture requires the detection of the packet-burst transmission, the availability of a free port to receive it and the correct demodulation of the
probe's header. If any of these conditions is not met, capture does not occur and the source terminal does not receive an acknowledgment from the base station. The terminal then increases its transmit power and re-transmits the probe until it is successfully captured. Since the unsuccessful attempts introduce additional access delays, it is desirable to minimize the average number of attempts required for capture.

With single echo transmission, a packet-burst is detected when its single echo is detected. The echo detection decision is given by Equation 3.25

\[ |W + X| > \gamma_p \]  

(4.1)

where

\[ W = \sqrt{\frac{1}{2} P_P N_P} \]  

(4.2)

is the echo's preamble correlation mainlobe component (Equation 3.21), \( X \) is the effect of interference (Equation 3.22) and \( \gamma_p \) is the preamble detection threshold. In all the analysis and simulation results that follow, the preamble detection threshold is set as

\[ \gamma_p = \frac{N_P}{\sqrt{2}} \]  

(4.3)

This is the value of an echo's mainlobe component \( W \), when its received power during the preamble segment \( P_P \) is 1. All subsequent power levels are given relative to this nominal threshold power value.

4.1.1.1 Session-Initiate-Burst Probe

The session-initiate burst enables a terminal to establish a session at the base station. At the first transmission attempt of a session-initiate burst, a terminal utilizes open-loop power control to determine the transmit power. The transmit power is set
such that the received power at the base station is $\bar{P}_0$ (the target received power value). However, due to Rayleigh fading in the reverse channel, the actual received power of the session-initiate burst probe is an exponential random variable with mean equal to $\bar{P}_0$ (Equation 3.32). If the received power is too low due to signal fade, the probe is missed by the base station. After each failed attempt, the terminal increases its transmit power by a factor $I$ and re-transmits probe. As long as the fading conditions remain the same between re-transmissions (which is the case when the terminals are stationary), the received power of the probe also increases by the factor $I$. The received power at the $k$-th transmission attempt is then

$$P_k = I^{k-1} P_0, \quad k = 1, 2, \ldots$$

(4.4)

where $P_0$ is an exponential random variable with mean equal to the target received power $\bar{P}_0$.

i. Detection & False Alarms without Background Interference

With the detection threshold set as in Equation 4.3, the session-initiate burst detection decision at the $k$-th attempt is

$$\left| \sqrt{P_k} + \frac{\sqrt{2}}{N_p} X \right| \geq \frac{1}{\triangle}$$

(4.5)

Since a single cell environment with single echo transmission is considered, no intercell or interpath interference exists. In addition, if there is only one terminal in the cell, then multiple access interference is also non-existent. In this case, the detection decision becomes

$$P_k \geq \frac{1}{\triangle}$$

(4.6)
the probability of detection at the \( k \)-th attempt is

\[
\text{Prob}[k]_{\text{SDetect}} = \exp(-1/\overline{P}_0) \quad k = 1
\]

\[
\exp(-I^{1-k}/\overline{P}_0) - \exp(-I^{2-k}/\overline{P}_0) \quad k > 1
\]

and the number of transmission attempts required on average for the detection of the session-initiate burst is

\[
E[k]_{\text{SDetect}} = \sum_{k=1}^{\infty} k \exp(-I^{1-k}/\overline{P}_0) - \sum_{k=2}^{\infty} k \exp(-I^{2-k}/\overline{P}_0)
\]

(4.8)

In Figure 4.1, \( E[k]_{\text{SDetect}} \) is plotted as a function of the target received power \( \overline{P}_0 \), for two power increments factors \( I \). By utilizing a higher target received power, the terminals can reduce the average number of transmission attempts required for detection.

![Figure 4.1: Session-initiate burst detection](image-url)
While higher received power levels enhance detection, the effect on the overall capture process is quite different. When a session-initiate burst probe is received with excessive power, its preamble correlation sidelobes can cause false alarms (the threshold detector is prematurely triggered), which tie up free receiver ports and hinder the second condition for successful capture. The occurrence of the false alarms is modeled as a Poisson process with an “arrival rate” given by Equation 3.36. In the case of only a single user and no background interference, the arrival rate when the matched filter contains the correlation sidelobes is given by

$$\lambda_{FA} = \text{erfc}(\sqrt{\frac{N_p}{2P_k}}) \cdot R_C$$

(4.9)

The effect of false alarms on $E[k]_{SCapture}$, the average number of transmission attempts required for session-initiate burst capture, is illustrated in Figure 4.2 for probes with varying preamble lengths $N_p$. A receiver system with a single port is considered. In this case, the session-initiate bursts are more likely to be blocked by the false alarms since there is only one port available.

![Figure 4.2: Session-initiate burst capture with no background interference (One terminal, single port receiver system)](image-url)
The "128 NFA" curve represents $E[k]_{\text{SCapture}}$ as a function of target received power $\bar{P}_0$ when the preamble length $N_p = 128$ chips and with the false alarm process disabled. It is identical to the "$I = 1$ dB" session-initiate burst detection curve of Figure 4.1 since without the hindrance of false alarms, capture and detection are synonymous. In contrast, the "128 FA", "256 FA" and the "512 FA" curves of Figure 4.2 show $E[k]_{\text{SCapture}}$ with the false alarm process enabled and with the preamble length equal to 128 chips, 256 chips and 512 chips, respectively.

Increasing the target received power initially assists capture since the detection of the packet-bursts is improved. However, there is also an increase in the incidence of false alarms and eventually their blocking effect offsets the gain in detection. If a longer preamble is utilized, the onset of the false alarms occurs at an even higher target received power level and as a result, the overall capture process is enhanced.

ii. Detection & False Alarms with Background Interference

In general, the session-initiate bursts are transmitted in the presence of transmissions from other terminals and so, the effect of multiple access interference must be included in the analysis of capture. The multiple access interference is a function of the offered traffic load in the cell, which is measured as follows

$$\text{offered traffic load} = K_T \cdot \text{duty cycle per terminal}$$

$$= K_T \cdot \lambda_M \left( T_{Prb} + \frac{K_B N_B}{R_D} \right)$$

(4.10)

where $\lambda_M$ is the message arrival rate at the terminals, $T_{Prb}$ is the duration of the probes, $K_B$ is the average number of packets in the message bursts, $N_B$ is the number of bits per packet and $R_D$ is the packet bit rate. The offered traffic load has units of Erlang.

With multiple access interference, the session-initiate burst detection decision is as given in Equation 4.5. If $P_0$, the received power of the session-initiate burst probe at
the first transmission attempt, is fixed, then the conditional probability of detection at the \( k \)-th attempt is given by

\[
\text{Prob}[k|P_0]_{SDet} = \frac{1}{2} \text{erfc}\left[\frac{N_p}{2\sigma_X} (1 - \sqrt{I^{k-1}P_0})\right] + \frac{1}{2} \text{erfc}\left[\frac{N_p}{2\sigma_X} (1 + \sqrt{I^{k-1}P_0})\right]
\]

(4.11)

where \( \sigma_X \) is related to the interference power at the \( k \)-th attempt by Equation 3.22. Since \( P_0 \) has an exponential distribution with mean \( \overline{P}_0 \), the conditioning in Equation 4.11 can be removed as follows

\[
\text{Prob}[k]_{SDet} = \int_0^\infty \text{Prob}\{k|P_0\} \frac{1}{\overline{P}_0} \exp\left(-\frac{P_0}{\overline{P}_0}\right) dP_0
\]

(4.12)

The false alarm arrival rate at any instance is

\[
\lambda_{FA}(\sigma_X) = \text{erfc}\left(\frac{N_p}{2\sigma_X}\right)
\]

(4.13)

where \( \sigma_X \) is related to the total interference power by Equation 3.24.

The relationship between \( E[k]_{SCapture} \) and the target received power \( \overline{P}_0 \) is illustrated in Figure 4.3 for the case where the capture occurs in the presence of other terminal traffic. Four levels of offered traffic loads are considered. In Figure 4.4, the difference in \( E[k]_{SCapture} \) (or Delta \( E[k]_{SCapture} \)) with and without the false alarms process enabled is shown under the conditions considered in Figure 4.3. A receiver system with 5 ports is considered and the preamble length is 512 chips.
At a given level of traffic, the effect of the target received power value $P_0$ on session-initiate burst capture is the same as in the case when there is no background interference (Figure 4.2). However, at higher traffic loads, the increase in $E[k]_{SCapture}$ due to false alarms is more pronounced. This is due to two reasons. Firstly, at a higher traffic load, there is an increased level of interference which results in a higher incidence of false alarms. Secondly, with more traffic there are fewer free ports available on average and hence, the session-initiate bursts are more likely to be blocked by false alarms that originate from their preamble correlation sidelobes.

Figure 4.3: Session-initiate burst capture with background interference (Traffic per terminal: 0.023 Erlangs, $\lambda_M = 4$ Msgs/Min.)
iii. Increased Packet Erasure Rate Penalty

The session-initiate burst probes are a source of multiple access interference to other on-going transmissions. Therefore, when the target received power $P_0$ is increased, it results in additional packet erasures. The occurrence of the packet erasures is measured by the packet erasure rate (PER), which is defined as follows

$$\text{PER} = \lim_{t \to \infty} \frac{\text{# of packets received up to time } t \text{ for which the CRC's have failed}}{\text{Total # of packets received up to time } t}$$

(4.14)

This is illustrated in Figure 4.5, where the PER is graphed as a function of $P_0$. The change in the packet erasure rate with respect to the target received power is dependent on how frequently the session-initiate bursts occur. Since the session-initiate bursts get transmitted at the beginning of a session, their frequency of occurrence is inversely proportional to the average session duration. Hence, the increase in the packet erasure rate is more prominent when the session are relatively short ("0.5 minutes/session" curve) than when the sessions are five times longer ("2.5 minutes/session" curve).
Figure 4.5: The increase in the packet erasure rate with higher target received power levels
(Offered traffic load: 150 Terminals x 0.023 Erlangs/Terminal, \( \lambda_M = 4 \) Msgs/Min,
\( K_M = 2, 5 \& 10 \) Msgs)

4.1.1.2. Message Burst Probe

Once a terminal has established a session it utilizes the message bursts to send messages to the base station. Since each message burst occurs after the closed-loop power control procedure of the previous message burst or the session-initiate burst, its received power at the base station is a deterministic quantity.

Detection

Let the received power during the preamble segment of the message burst be denoted by \( P_p \). Then, the message burst detection decision at the first transmission attempt is

\[
\left| \sqrt{P_p} + \frac{\sqrt{2}}{N_p} X \right| \geq \frac{1}{1}
\]  

(4.15)
and the detection probability is given by

\[
\text{Prob}_{MD\text{detect}} \equiv \frac{1}{2} \text{erfc}\left[\frac{N_p}{2\sigma_X}(1 - \sqrt{P_p})\right]
\] (4.16)

where \(X\) and \(\sigma_X\) are related to the interference power by Equation 3.22. When the received power \(P_p\) is 1, the detection probability is also 1 if there is no interference (\(\sigma_X = 0\)) and \(\frac{1}{2}\), if there is some interference (\(\sigma_X > 0\)). At a given level of interference, the detection probability can be enhanced by increasing the received power. However, with a longer preamble, the same improvement can be achieved with a smaller increase in power since the interference term in the detection decision (i.e. its variance) is inversely proportional to the preamble length \(N_p\).

If the interference is assumed to originate from five on-going payload transmissions, then

\[
\sigma_X^2 = \frac{1}{2} N_p \cdot 5 \cdot P_C
\]

\[
= \frac{5}{2} N_p
\] (4.17)

when \(P_C\), the received power during the payload segment, is 1. In this case, a message burst detection probability greater than 0.99 can be achieved with a preamble segment power \(P_p\) of about 2 using a preamble of length 512 chips.

4.1.1.3 **Probe Header**

The third and final requirement for the successful capture of either a message burst or session-initiate burst probe is the correct demodulation of the header segment (i.e. its CRC succeeds). The header CRC can fail for two reasons: collisions between packet-burst transmissions or a low SIR (signal-power-to-interference-power ratio) during demodulation.
i. **Collisions**

Collisions occur when packet-burst transmissions from two or more terminals arrive within a one delay-spread period at the base station and echoes from the different transmissions are combined within the same port (Section 3.6.5.2). The transmissions that are involved in collisions could be new packet-bursts that are being transmitted for the first time or previously unsuccessful packet-bursts that are being re-transmitted. Hence, the frequency with which collisions occur is a function of the aggregate arrival rate of new packet-burst transmissions at the base-station as well as the re-transmission rate of the unsuccessful packet-bursts.

The aggregate arrival rate for new packet-burst transmissions can be approximated by the product of the number of terminals in the cell and the terminal message arrival rate. The re-transmission rate or how quickly terminals re-transmit unsuccessful packet-burst transmissions is inversely proportional to the waiting time randomization interval described in Section 3.7. In Figure 4.6, the relationship between the frequency of collisions and the number of terminals is illustrated for the case where the message arrival rate at the terminals is constant. In Figure 4.7, the effect of the smallest waiting time randomization interval $T_R$ on the collision frequency is shown. In both cases, the frequency of collision is measured by the collision ratio, which is the proportion of header CRC's that fail due to collisions.
Figure 4.6: The frequency of collisions versus the number of terminals 
(0.02 Erlangs/Terminal)

Figure 4.7: The frequency of collisions versus the re-transmission randomization interval 
(Offered traffic load: 200 terminals x 0.02 Erlangs/terminal)
ii. **Low SIR**

The second reason for the failure of the header CRC is a low SIR during demodulation (Section 3.6.2.1). The SIR during the header segment is given by

\[
SIR = \frac{P_H N_H}{16 \cdot \Psi(\sum_{u=1}^{K} P^u - P_H)}
\]  

where \( P_H \) is the received power of the desired signal, \( P^u \) is the received power of the \( u \)-th active terminal and \( K \) is the number of active terminals. \( N_H \) is the number of chips in the header segment and \( \frac{N_H}{16} \) is the header processing gain.

For a given level of multiple access interference \( \sum_{u=1}^{K} P^u - P_H \) in Equation 4.18, the SIR can be enhanced either by increasing the received power \( P_H \) or by increasing \( N_H \). In Figure 4.8, the message burst header erasure rate which is the proportion of message burst header CRC's that fail due to low SIR, is plotted as a function of the offered traffic load for different values of \( P_H \) and \( N_H \). The “256-1” curve is the header erasure rate with \( N_H = 256 \) chips and \( P_H = 1 \). The other two curves show that the improvement in the header erasure rate is the same when the received power is doubled (“256-2” curve) and when the processing gain (or \( N_H \)) is doubled (“512-1” curve). In Figure 4.9, the packet erasure rate is shown for the cases considered in Figure 4.8. While doubling power and doubling the processing gain have the same effect on the header erasure rate, the impact on the packet erasures is quite different. The first case results in an increase in the incidence of packet erasures while the second case provides a moderate reduction in the packet erasure rate. Hence, adjusting the processing gain is a more desirable solution as far as packet erasures are concerned. However, it comes at the price of a higher transmission overhead associated with the longer duration of the probes.
4.1.2. Payload Transmission

The payload of a packet-burst transmission contains the data packets, which carry a terminal’s session initiation information and its messages. The payload is transmitted only when the packet-burst’s probe has been successfully captured. Since closed-loop power
control is performed after probe capture, the received power during the payload segment is $P_C$ (Section 3.6.4.2).

When $K$ payload transmissions occur concurrently, the SIR for a packet in any one of the packet-burst transmissions is given by

$$SIR = \frac{P_C N}{\Psi P_C (K - 1)} = \frac{N}{\Psi (K - 1)} \quad (4.19)$$

where the processing gain $N = R_C / R_D = 16$ and $\Psi = \frac{2}{3}$. This is tabulated in Table 4.1 for $1 \leq K \leq 5$.

The cumulative distribution function (CDF) of packet SIR determined through model simulation is shown in Figure 4.10 for different traffic loads and for receiver systems with 4 ports and 5 ports. The jumps in the CDF curves represent the proportion of packets whose lowest SIR (i.e. the lowest SIR value anytime during the packet's demodulation) is given by the corresponding abscissa SIR value. The jumps occur at the SIR values tabulated in Table 4.1.

The CDF curves provide two pieces of information. Firstly, it is a measure of the receiver port occupancy. For example, in the "1.7 Erlangs - 5 Ports" case, the CDF jumps by 0.1 near 7.8 dB. From Table 4.1, an SIR of 7.8 dB corresponds to 5 concurrent packet transmissions or equivalently 5 ports being occupied simultaneously. This indicates that for only 10% of the packets transmitted are all five ports occupied. However, at twice the traffic load ("3.4 Erlangs - 5 Ports"), 50% of the packets are transmitted with all 5 ports occupied.

Secondly, the CDF curves show the minimum SIR value (i.e. the smallest SIR value at which the CDF contains a jump) is directly related to the number of ports in the receiver system. When the system has 5 ports ("3.4 Erlang - 5 ports" curve), the minimum SIR is 7.8 dB, which corresponds to 5 simultaneous packet transmissions. With only 4 ports ("3.4
Erlang - 4 ports" curve), the maximum number of concurrent transmissions is limited to 4 and as a result, the CDF curve no longer contains a jump at 7.8 dB. The minimum SIR becomes 9 dB.

<table>
<thead>
<tr>
<th>$K$</th>
<th>Packet SIR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\infty$</td>
</tr>
<tr>
<td>2</td>
<td>13.8</td>
</tr>
<tr>
<td>3</td>
<td>10.8</td>
</tr>
<tr>
<td>4</td>
<td>9.0</td>
</tr>
<tr>
<td>5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Table 4.1: Tabulation of Equation 4.19 for packet SIR

To avoid bit errors during the demodulation of the packets, the SIR must be greater than or equal to the SIR threshold (Section 3.6.2.1). The minimum SIR as shown in Figure 4.10, is determined by the number of ports $K_P$ in the receiver system. Hence, the maximum number of ports the receiver scheme can support is limited by the required SIR threshold $\gamma_{SIR}$. In particular, Equation 4.19 requires that

$$K_P \leq \frac{N}{\Psi \gamma_{SIR}} + 1 \quad (4.20)$$
If $\gamma_{SIR} = 7$ dB, the number of ports can be no greater than 5. Otherwise, the multiple access interference and the packet erasure rate become excessive (Figure 4.14).

4.1.3. **Throughput, Average Message Burst Access Delay & PER**

The objective of the Multiple Packet-burst Capture Receiver Scheme is to maximize the number of packets received per unit time while keeping access delays and packet erasures to a minimum. Three parameters that measure the performance of the receiver scheme are the packet throughput, the average message-burst access delay and the packet erasure rate.

The throughput is defined as the number of packets correctly received by the receiver system per unit time (i.e. packets for which the CRC's succeed) normalized by the maximum number packets that can be received by one port per unit time

$$
\text{throughput} = \lim_{t \to \infty} \frac{\# \text{of correctly received packets up to time } t}{\text{time } t} \cdot \frac{N_B}{R_D}
$$

(4.21)

Its magnitude is limited by the number of ports in the receiver system

$$
0 \leq \text{throughput} \leq K_p
$$

(4.22)

and it has units of Erlang.

The message burst access delay is the amount of time that elapses between when a terminal first attempts to transmit a message burst and when the message burst is finally captured. Hence, it takes into account the re-transmission delays when probe capture does not occur and also delays due to busy periods in the busy tone signal.

In Figure 4.11 through Figure 4.14, the three parameters are graphed as functions of the offered traffic loads for receiver systems with varying number of ports. The SIR threshold $\gamma_{SIR}$ is 7 dB. As the number of ports is increased (up to 5), the receiver scheme
is able to support higher levels of throughput from larger traffic loads with a lower average delay. When the number of ports is 4 or less, the throughput is equal to the offered traffic load (neglecting the probe overhead). With five ports, the throughput is initially equal to the offered load, however near full capacity (offered load = 5 Erlangs), the curve begins to taper due to an increase in the packet erasure rate (Figure 4.13). With a SIR threshold of 7 dB, no more than 5 simultaneous packet transmissions can be supported. Therefore, with 6 ports, the throughput drops to zero with increasing traffic load as the packet erasure rate becomes excessive (Figure 4.14). In a receiver system with a few ports, the access delay is dominant while in a system with several ports the packet erasure rate is dominant.

Figure 4.11: Packet throughput versus the offered traffic load (No session-initiate bursts, 0.02 Erlangs/Terminal)
Figure 4.12: The average message burst access delay versus the offered traffic load (Same conditions as in Figure 4.11)

Figure 4.13: The packet erasure rate versus the offered traffic load for receiver systems with up to 5 ports (Same conditions as in Figure 4.11)
4.1.3.1. **The Effect of Traffic Statistics**

While the packet erasure rate and the average message burst access delay are functions of the total offered traffic load as demonstrated in Figure 4.12 through 4.14, these parameters are also dependent on the statistics of the traffic. A given level of offered traffic as defined in Equation 4.10 can be comprised of a large number of terminals with short packet-bursts (variable bit-rate traffic) or a relatively few terminals with relatively long packet-bursts (constant bit-rate traffic). In this Section, the effect of varying these traffic parameters is examined. In particular, the packet erasure rate and the average message burst access delay are found when the number of terminals $K_T$ and the average message burst size $K_B$ are varied inversely while the message arrival rate $\lambda_M$ is adjusted (relatively small adjustments) such that the total offered traffic remains a constant.

\[
\text{offered traffic load} = K_T \cdot \lambda_M \{ T_{Prb} + \frac{K_B N_B}{R_D} \} = \text{constant}
\]

(4.23)

$\lambda_M \equiv \text{constant}$

$K_T \propto \frac{1}{K_B}$
i. **Packet Erasures**

Traffic from a large number of terminals with short packet-bursts is more conducive to the occurrence of packet erasures than traffic from a relatively few terminals with long packet-bursts. This is shown in Figure 4.15 for two levels of offered traffic.

The packet erasure rate, which is a function of the level of multiple access interference, is dependent on effectiveness of the busy tone signal in controlling the number of concurrent packet-burst transmissions. The purpose of the busy tone signal is to block new transmissions when all ports ($K_p$) at the base station are being utilized (Section 3.6.6). Ideally, the busy tone signal should change to the busy state as soon as the last successful packet-burst transmission arrives at the base station. However, there is finite delay of $T_p$ (the duration of the preamble) between the arrival of the last successful transmission and when the last receiver port is assigned to it resulting in the change in the busy tone signal. Packet-burst transmissions that arrive during this period only serve to increase the multiple access interference and therefore the packet erasure rate.
If re-transmissions are neglected, then the average number of packet-burst transmissions at the start of the busy periods can be approximated by

\[ E[\# \text{ of transmissions}] \equiv K_p + T_p \lambda_M N_T \quad (4.24) \]

\( \lambda_M N_T \), which is an approximation of the arrival rate of packet-burst transmissions at the base station, is directly proportional to the number of terminals \( N_T \) in the cell. Hence, when the traffic from a large number of terminals, the busy tone signal becomes less effective in limiting the number of concurrent transmissions to the number of receiver ports \( K_p \). This is illustrated in Figure 4.16, which shows the distribution of the number of transmissions at the start of the busy periods when the traffic is from 38 terminals with an average message burst size of 400 packets and when the traffic is from 304 terminals with an average message burst size of 50 packets. These two cases form the two extreme points in the "4.5 Erlang" curve of Figure 4.15. The receiver system considered has \( K_p = 5 \) ports. With 304 terminals instead 38 terminals, the distribution's frequency drops near \( K_p \) while the distribution's tail extends well beyond \( K_p \).

![Figure 4.16: The distribution of the number of transmissions at the start of the busy periods. (\( \lambda_M = 10.3 \text{Msgs./Min} \))](image-url)
ii. **Average Message Burst Access Delay**

The average message burst access delay responds to variations in the traffic statistics in manner contrary to that of the packet erasure rate. Unlike the packet erasure rate, the average delay is smaller when the number of terminals is large and the packet-bursts are short than when the converse holds. This is illustrated in Figure 4.17 and 4.18. Figure 4.17 shows the relationship between the average access delay and the number of terminals $K_T$, while in Figure 4.18, the same delay data is plotted against the corresponding average packet-burst size $K_B$.

The message burst access delay has two components: delay due to packet-burst re-transmissions and delay due to busy periods in the busy tone signal. The re-transmission delay (or the "waiting time" in Section 3.7) is on the order of a few multiples of $T_R$, which has a value of 1.5 milliseconds. The second delay component is much larger and is related to the duration of the busy tone signal's busy periods. Since the size of the packet-bursts is a geometric random variable with mean $K_B$, the service time of a busy port can be approximated by an exponential random variable with mean

$$\mu = \frac{K_B \cdot P_B}{R_D} \quad (4.25)$$

Then, the duration of a busy period (i.e. when all $K_P$ ports are busy) is an exponential random variable with mean given by

$$\mu = \frac{K_B \cdot P_B}{R_D K_P} \quad (4.26)$$

The average duration of the busy periods is directly proportional to the average message burst size $K_B$. Therefore, the average access delay is directly proportional to the average message burst size and inversely proportional to the number of terminals due to Equation 4.23.
Figure 4.17: The average message burst access delay with different traffic statistics \( (\lambda_M = 8.3 \text{ Msgs./Min} & 10.3 \text{ Msgs./Min}) \)

Figure 4.18: Delay data from Figure 4.17 versus the average message burst size

4.1.3.2. Resolving Packet Errors

Each packet has FEC code to resolve bit errors. A packet erasure occurs (i.e. the packet’s CRC fails) when the number of errors exceeds the FEC code’s error correcting capability. The effect of an ARQ scheme to resolve packet erasures is also examined.
i. **FEC**

The error correcting capability of the FEC code is modeled by the error burst length period (EBLP), which is a fraction of the duration of one data packet. In order for a packet's CRC to fail, its SIR must be less than the SIR threshold for a period greater than the EBLP. Otherwise, the FEC code is able to correct the bit errors (Section 3.6.2.1).

The effect of the EBLP on the packet erasure rate is illustrated in Figure 4.19 for two SIR thresholds values: 7 dB and 8 dB. A receiver system with 5 ports is considered. When $\gamma_{SIR} = 7$ dB, the packet erasure rate decreases to zero as the EBLP approaches 100% but with $\gamma_{SIR} = 8$ dB, the EBLP has a minimal effect on occurrence of packet erasures. This is because with a threshold of 7 dB, there must be more than 5 concurrent transmissions for a packet's SIR to be less than the threshold. However, in the receiver system with 5 ports, this situation only occurs for short periods of time since a terminal that does not capture one of the five ports ceases transmission at the end of the probe. Therefore, as the EBLP is increased, the likelihood of this situation persisting over the entire EBLP diminishes. In the case of $\gamma_{SIR} = 8$ dB, no more than 4 payload transmissions can occur concurrently. For the packets that are transmitted when all 5 ports are being utilized, the SIR is less than the threshold over the entire packet and the EBLP has no effect on the erasure rate for these packets.

![Figure 4.19: The packet erasure rate versus the error burst length period](image)

(Offered traffic load: 300 terminals x 0.015 Erlangs/Terminal)
With an ARQ scheme, the base station requests the re-transmission of those packets whose bit errors cannot be resolved by the FEC code. The source terminal retransmits the packets in a separate message burst shortly after the original packet-burst transmission. The transmissions cause the terminals to persist in the reverse channel for a longer duration with the result that the effective traffic load seen by the base station is higher. The additional traffic load has the effect of increasing the average access delay as well as the packet erasure rate as illustrated in Figure 4.20 and Figure 4.21.

![Figure 4.20: The effect of an ARQ scheme on the average message burst access delay (0.02 Erlangs/Terminal)](image)

![Figure 4.21: The effect of an ARQ scheme on the packet erasure rate (0.02 Erlangs/Terminal)](image)
4.2. CELLULAR ENVIRONMENT, SINGLE-ANTENNA RECEIVER SYSTEM & SINGLE MULTIPATH COMPONENT TRANSMISSION

In a cellular environment, the interference at the base station is due to both intracell as well as intercell interference. When the cells are equally loaded, the average intercell interference can be modeled as 50% of the average intracell interference.

The average intracell interference can be approximated by

\[ E[P_{\text{intraCell}}] = \{TP_{rb} + \frac{K_B N_B}{R_D}P_c \lambda_M \} \]
\[ = P_c \cdot \text{(offered traffic load)} \]
\[ = \text{offered traffic load} \]

when \( P_c \) is 1.

With the intercell interference represented by its average value, the SIR for a packet when \( K \) payloads are transmitted concurrently is

\[ SIR = \frac{N}{\Psi(K - 1 + 0.5 \cdot \text{(offered traffic load)\})} \]

For a given SIR threshold \( \gamma_{SIR} \), Equation 4.28 requires that the number of concurrent transmissions and the traffic load in a cell be restricted as follows

\[ K + 0.5 \cdot \text{(offered traffic load)} \leq \frac{N}{\Psi \gamma_{SIR}} + 1 \]

In a receiver system, the number of concurrent transmissions and the offered traffic load are also bounded by the number of ports

\[ K \leq K_p \]
\[ \text{offered traffic load} \leq K_p \]
Hence, if $\gamma_{\text{SIR}} = 7 \text{ dB} & N = 16$, the receiver scheme can support a maximum of 4 ports and a maximum offered traffic load of approximately 3.6 Erlangs (less than the full capacity of 4 Erlangs). With no intercell interference (and $\gamma_{\text{SIR}} = 7 \text{ dB} & N = 16$), the maximum number of ports is 5 and the maximum traffic load is 5 Erlangs. Therefore, a cellular environment has the effect of further restricting the number of ports as well as the traffic load in a cell.

![Packet throughput in the presence of intercell interference](image)

Figure 4.22: Packet throughput in the presence of intercell interference (0.02 Erlangs/Terminal)

In Figure 4.22, the throughput is given for a receiver system that is subjected to intercell interference as modeled in Equation 4.28. Receiver systems with 3, 4 and 5 ports are considered and $\gamma_{\text{SIR}} = 7 \text{ dB}$. In a receiver system with 3 ports, the intercell interference has a minimal effect on throughput. With 4 ports, the traffic must be limited to 3.6 Erlangs otherwise throughput drops off at larger traffic loads due to an increase in packet erasures. With 5 ports, the situation that arises is similar to the case of a six-port receiver system in a single cell environment (Section 4.1.3).

In practice, the intercell interference will fluctuate about its average value. To provide a SIR margin, the traffic load must be lower than 3.6 Erlangs in the receiver system with 4 ports.
4.3. MULTIPLE MULTIPATH COMPONENTS (Path Diversity),
SINGLE-ANTENNA RECEIVER SYSTEM
& SINGLE CELL ENVIRONMENT

The packet-burst transmissions arrive at the base station through multiple echoes. Each echo has independent Rayleigh fading characteristics.

4.3.1. Probe Capture

With path diversity, a probe is detected when at least one of the echoes of the transmission is detected.

4.3.1.1. Session-Initiate Burst Detection & False Alarms

When a session-initiate burst transmission arrives at the base station through multiple independently fading paths, each path offers an additional chance for the transmission to be detected. If the number of path is \( m \), then the received power of the \( i \)-th echo at the \( k \)-th transmission attempt of the packet-burst is given by

\[
P_{k}^{(i)} = I^{k-1} P_{0}^{(i)}, \quad k = 1, 2, \ldots \quad i = 1, 2, \ldots, m
\] (4.31)

where for each \( i \), \( P_{0}^{(i)} \) is an independent exponential random variable with mean equal to the target received power \( \bar{P}_{0} \) (Section 4.1.1.1). The detection decision for each echo is given by Equation 4.5. With path diversity, the interference term in the detection decision is a function of both the multiple access interference as well as the interpath interference (interference from the other paths of the same transmission). If the initial power of the echoes \( (P_{0}^{(1)}, P_{0}^{(2)}, \ldots, P_{0}^{(m)}) \) is fixed, then the conditional detection probability for the \( i \)-th echo at the \( k \)-th attempt is

\[
\frac{\text{Prob}[k | P_{0}^{(1)}, P_{0}^{(2)}, \ldots, P_{0}^{(m)}]}{N_{p}} \leq \frac{1}{2} \text{erfc}\left[ \frac{N_{p}}{2\sigma X} \left( 1 - \sqrt{I^{k-1} P_{0}^{(i)}} \right) \right] + \frac{1}{2} \text{erfc}\left[ \frac{N_{p}}{2\sigma X} (1 + \sqrt{I^{k-1} P_{0}^{(i)}}) \right]
\]

(4.32)
The conditional detection probability for the probe is the probability that at least one of the echoes is detected

\[ \text{Prob}[k|P_0^{(1)}, P_0^{(2)}, \ldots, P_0^{(m)}]_{SDetect} = 1 - \prod_{i=1}^{m} (1 - \text{Prob}[k|P_0^{(1)}, P_0^{(2)}, \ldots, P_0^{(m)}]) \]

(4.33)

Since \( P_0^{(1)}, P_0^{(2)}, \ldots, P_0^{(m)} \) are all exponentially distributed,

\[ \text{Prob}[k]_{SDetect} = \int_{0}^{\infty} \ldots \int_{0}^{\infty} \text{Prob}[k|P_0^{(1)}, \ldots, P_0^{(m)}]_{SDetect} \left( \frac{1}{P_0} \right)^m \exp\left(-\frac{P_0^{(1)} + \ldots + P_0^{(m)}}{P_0}\right)dP_0^{(1)} \ldots dP_0^{(m)} \]

(4.34)

The false alarm arrival rate is given by Equation 4.13 where \( \sigma_X \) is related to the multiple access and interpath interference by Equation 3.24.

In Figure 4.23, the average number of transmission attempts required for session-initiate burst capture \( E[k]_{\text{Capture}} \) is plotted as a function of the target received power for transmissions over one path ("m=1" curve) and over two paths. A cell with only a single terminal is considered and hence, background interference is non-existent. At low target received power levels, the transmissions over two paths require fewer transmission attempts since the two independently fading paths enhance detection. However, at larger target power levels, the additional interference due to the two paths results in a higher incidence of false alarms and in this case, the single path transmissions performs better.
Figure 4.23: Session-initiate burst capture with transmission over one and two paths (one terminal)

4.3.1.2. Message Burst Probe Detection

With single path transmission, the preamble segment power $P_P$ is supplied entirely by the one path. With path diversity, the preamble segment power is supplied by the multiple echoes of the transmission. As a result, the power of individual echoes $P_P^{(i)}$ is less than the total power $P_P$. Hence, a message burst transmission that arrives over multiple echoes requires a larger preamble segment power than a transmission over a single echo, if both are to be detected with the same probability.

If the number of paths is $m$, then the detection decision for the $i$-th echo is

$$\left| \sqrt{P_P^{(i)}} + \frac{\sqrt{2}}{N_P} X \right| \geq 1 \quad 1 \leq i \leq m$$

(4.35)

the echo detection probability is

$$\text{Prob}_i = \frac{1}{2} \text{erfc}[\frac{N_P}{2\sigma_X}(1 - \sqrt{P_P^{(i)}})] + \frac{1}{2} \text{erfc}[\frac{N_P}{2\sigma_X}(1 + \sqrt{P_P^{(i)}})]$$

(4.36)
and the message burst detection probability is the probability that at least one of the echoes is detected

\[
\text{Prob}_{\text{MDet}} = 1 - \prod_{i=1}^{m} (1 - \text{Prob}_i)
\]  

(4.37)

In Figure 4.24, the message burst detection probability is graphed as a function of the number of paths for different values of the preamble segment power \(P_p\). With single path transmission, a preamble segment power of 2 is sufficient to achieve a detection probability close to 1, but with more paths the preamble segment power must be increased to maintain the same detection probability.

![Figure 4.24: The message burst detection probability versus the number of paths (one terminal per cell)](image)

4.3.2. **Payload Transmission**

During closed-loop power control, a terminal adjusts its transmit power such that at the base station, the total power in its detected echoes is \(P_C\) (Section 3.6.4.2). In the case of single echo transmission, the total power must be supplied entirely by that one echo. With path diversity, the total power is derived from the multiple echoes and hence, a terminal can utilize a lower transmit power to achieve the required power level at the base station.
4.3.2.1 Inter-Path Interference

With path diversity, the resultant SIR is the sum of the SIR's of the echoes that are combined in a port (or RAKE receiver). When $K$ payloads transmission occur concurrently, the SIR of the $i$-th echo from terminal $j$ as given in Equation 3.26 can be written as

$$SIR_{(i,j)} = \frac{P(i,j)N}{\Psi(\sum_{u=1,u\neq j}^{K} \sum_{v=1}^{m_u} P^{(v,u)} + \sum_{v=1,v\neq i}^{m_j} P^{(v,j)})} \tag{4.38}$$

where $\sum_{u=1,u\neq j}^{K} \sum_{v=1}^{m_u} P^{(v,u)}$ is the multiple access interference from the other $K-1$ transmissions and $\sum_{v=1,v\neq i}^{m_j} P^{(v,j)}$ is the interpath interference. If all the echoes of all the packet-burst transmissions are detected and utilized in power control, the multiple access interference term becomes

$$\sum_{u=1,u\neq j}^{K} \sum_{v=1}^{m_u} P^{(v,u)} = (K-1)P_C \tag{4.39}$$

and the inter-path interference term becomes

$$\sum_{v=1,v\neq i}^{m_j} P^{(v,j)} = P_C - P(i,j) \tag{4.40}$$

$$\equiv P_C$$

where the approximation in Equation 4.40 holds when the number of echoes $m_j$ is large. The resultant SIR is then
Therefore, when the number of echoes is large, the interpath interference is equivalent to the interference from an additional concurrent packet-burst transmission. The additional interference results in an increased level of packet erasures. This is illustrated in Figure 4.25, where for each terminal, the number of echoes is modeled as a random variable uniformly distributed between 1 and a maximum value \( K_E \). A receiver system with 5 ports is considered.

The effect of interpath interference can be reduced by restricting the number of concurrent transmissions to compensate for the additional interpath interference. For a SIR threshold of 7 dB, Equation 4.41 requires that number of concurrent transmissions be limited to 4. In Figure 4.26, the packet erasure rate is graphed for a receiver system with 4 ports which is subjected to the same traffic load and path diversity conditions considered as in Figure 4.25. In this case, interpath interference only has a minimal effect on the packet erasure rate.

![Figure 4.25](image)

**Figure 4.25:** The effect of interpath interference on the packet erasure rate (Number of echoes is uniformly distributed between 1 & \( K_E \), all echoes are utilized in power control. 0.02 Erlangs/Terminal)
4.3.2.2 Interference due to Partial Message Burst Echo Detection

An assumption made in the derivation of Equation 4.41 is that all the echoes of the message burst transmissions are detected and utilized in closed-loop power control. However, since the echoes fade independently and since only one echo must be detected for message burst detection to occur, this assumption is not always valid. When only some of the echoes are detected, the SIR of \( i \)-th echo as given in Equation 4.38 becomes

\[
SIR_{(i,j)} = \frac{P^{(i,j)}N}{\Psi \left\{ (K-1)P_c + (P_c - P^{(i,j)}) + \sum_{u=1}^{K} \sum_{v: \text{all undetected echoes of terminal } u} P^{(v,u)} \right\}}
\]

(4.42)

The first two terms in the denominator represent the multiple access interference and the interpath interference, respectively. The last term is the interference due to the undetected echoes that are not utilized in power control. This interference can be reduced by increasing the proportion of message burst echoes that are detected.
The proportion of echoes detected which is measured as follows

\[ R_E = \lim_{t \to \infty} \frac{\text{# of echoes detected up to time } t}{\text{total # of echoes in the transmissions detected up to time } t} \] (4.43)

can be enhanced by increasing the preamble segment power \( P_p \). The relationship between proportion of echoes detected and the preamble segment power is illustrated in Figure 4.27, where the number of echoes for each terminal is modeled as a random variable uniformly distributed between 1 and 6. In Figure 4.28, the packet erasure rate is given for the cases considered in Figure 4.27. While a preamble segment power of 5 is sufficient to achieve a message burst detection probability close to 1 (Figure 4.24), a power of about 10 is required for the packet erasure rate approaches the case where all the echoes are detected ("100%" curve in Figure 4.28).

![Figure 4.27: The proportion of echoes detected with different preamble segment power levels](image)

(Number of echoes is uniformly distributed between 1 & 6, 0.02 Erlangs/Terminal, 4 port receiver system)
Offered Traffic Load (klangs)

Figure 4.28: The improvement in the packet erasure rate with higher preamble segment power (Same conditions as in Figure 4.27)

Figure 4.29: The packet erasure rate versus the number of fingers in the receiver ports (0.02 Erlangs/Terminal, 4 ports, preamble segment power = 10)

4.3.2.3. Number of Fingers in the Receiver Ports (Section 3.6.2)

When the number of echoes from the terminals can vary between 1 and some maximum value $K_E$, the number of fingers in the receiver ports need not be equal to the maximum value $K_E$. In Figure 4.29, the packet erasure rate is plotted as a function of number of fingers for the case where the number of echoes is a random variable
uniformly distributed between 1 and $K_E = 6$. As the number of fingers is increased up to 4, there is a significant reduction in the packet erasure rate but beyond this the improvement is negligible in comparison.

4.4. **MULTIPLE-ANTENNA RECEIVER SYSTEM (Antenna Selection Diversity), SINGLE CELL ENVIRONMENT**

The receiver system has multiple antenna - matched filter pairs as shown in Figure 3.6. The multipath echoes have independent Rayleigh fading characteristics at each antenna. When an echo is detected at more than one antenna, the antenna where its received signal is the strongest is selected when the echo is demodulated.

4.4.1. **Session-Initiate Burst Detection & False Alarms**

The echo detection decision at each antenna is given by Equation 4.5. Since the Rayleigh fading is independent at the different antennas, each antenna provides an additional chance for echo detection. At the same time, the matched filter at each antenna is a source of false alarms. While the false alarm arrival rate at each matched filter is given by Equation 4.13, the aggregate arrival rate for the receiver system is the sum of the arrival rates at the different filters. Therefore, at low target received power levels antenna diversity improves capture since detection is enhanced, but at higher power levels the effect of false alarms (from the correlation sidelobes) is more severe in a system with multiple antennas. This is illustrated in Figure 4.30.
4.4.2. **Payload Transmission**

Consider first the case of single echo transmission. In a single-antenna receiver system, all packet-burst transmissions must be received through the one antenna. When \( K \) payload transmissions occur concurrently, the multiple access interference encountered by one transmission is the received power of the other \( K-1 \) transmissions which is \((K-1)P_c\). With antenna selection diversity, each transmission is received through the antenna at which its received signal is the strongest. In this case, if a transmission is received with a power of \( P_c \) at its selected antenna, then its power at the other antennas is less than or equal to \( P_c \). Typically, the \( K \) concurrent packet-burst transmissions are received through different antennas and therefore, the multiple access interference encountered by one transmission is less than \((K-1)P_c\).

Similarly, with multiple echoes, each detected echo is received through the antenna at which its signal is the strongest and so the interference the echo creates at the other antennas is less than its power at the selected antenna.

The reduction in interference with antenna selection diversity is illustrated in Figure 4.31, where the average intracell interference as measured at one antenna is graphed as a
function of the offered traffic load for receiver systems with 1, 2, 4 and 5 antennas. In Figure 4.32, the packet erasure rate corresponding to the cases considered in Figure 4.31 is given. As the number of antennas is increased, the average interference and hence, the packet erasure rate is reduced. However, with more than 4 antennas, the change in the packet erasure rate is negligible in comparison.

![Graph showing packet erasure rate vs. traffic load with different numbers of antennas.](image1)

**Figure 4.31:** The reduction in intracell interference with antenna selection diversity (0.02 Erlangs/Terminal)

![Graph showing packet erasure rate vs. traffic load with different numbers of antennas.](image2)

**Figure 4.32:** The improvement in the packet erasure rate with antenna selection diversity (same conditions as in Figure 4.31)
4.5. Effect of Slow Terminal Motion

The terminals are assumed to shift periodically between their message bursts. The occurrence of the shifts is modeled as a Poisson process with rate $\lambda_S$. With each shift, the Rayleigh fading conditions are assumed to change. In addition, the fading before and after the shift are assumed to be independent (Section 3.9).

The received power of a message burst that is transmitted immediately after its source terminal shifts could be lower, higher or relatively unchanged when compared to the case where the terminals are stationary. If the power is too low, then the message burst is not detected and the terminal must re-transmit the probe until it is captured. If the received power is too high, the probe causes additional packet erasures in other on-going transmissions.

The effect of terminal motion on the average number of transmission attempts required for message burst capture ($E[k]_{\text{Max}}$) and on the packet erasure rate is illustrated in Figure 4.33 and 4.34. The terminal movement rate $\lambda_S$ is normalized by the terminal message arrival rate $\lambda_M$. In both Figures, transmissions over a single path and over multiple paths (number of paths is uniformly distributed between 1 & 6) are considered.

With single path transmission, the terminal motion results in a significant increase in the number of transmission attempts while the effect on packet erasures is relatively minimal. With path diversity, the converse is true. This is because with multiple independently fading echoes, there is a higher probability that the message burst is detected after each shift. On the other hand, since the Rayleigh fading for each of the echoes changes with terminal motion, the effect on the packet erasures is more severe.
Figure 4.33: The effect of terminal motion on message burst capture
(Number of echoes is uniformly distributed between 1 & 6 for "Random" case,
$\lambda_M = 3.5$ Msgs./Min)

Figure 4.34: The effect of terminal motion of the packet erasure rate
(same conditions as in Figure 4.33)
SUMMARY & CONCLUSIONS

In this thesis, a CDMA Multiple Packet-burst Capture Receiver Scheme is proposed. The scheme permits a form of reservation in that during each transmission, a terminal can send a contiguous sequence of packets - a packet-burst. The initial portion of the packet-burst which is necessary for capture is spread with codes that are common to all terminals. To spread the data portion of the packet-burst, each terminal utilizes a separate long code. The long code is assigned to a terminal subsequent to packet-burst capture and it is used only for the duration of that packet-burst. To prevent excessive multiple access interference, a busy tone signal is broadcast by the base station which blocks new transmissions when the number of transmissions being serviced by the base station is at its maximum. The bit and chip rate of the receiver scheme are similar to those in third generation mobile communication systems.

The simulation and analysis were primarily carried out for a single-antenna receiver system in a single cell environment where the reverse link transmissions occur over a single path and where the terminals are stationary during their sessions. Subsequently, the effects of intercell interference (in a cellular environment), path diversity, antenna diversity and slow terminal motion were also examined.

Capture

The successful capture of a packet-burst at the base station requires three events: the detection of the packet-burst, the availability of a free receiver port to receive the packet-burst and the correct demodulation of the packet-burst's header. If any of these conditions is not met, capture does not occur and the source terminal must re-transmit the packet-burst.

The terminals utilize the session-initiate bursts to establish a session at the base station. The session-initiate bursts are transmitted with open-loop power control, which compensates for path loss and shadow fading in the reverse channel. However, due to Rayleigh fading, in certain instances the session-initiate bursts are missed by the base station. The occurrence of these
events is reduced if the terminals utilize a higher transmit power. While increased power helps detection, it also results in a higher incidence of false alarms which originate from the correlation sidelobes of the packet-burst's preamble. The false alarms tie up free receiver ports and hinder the second condition required for capture. Hence, the session-initiate burst capture process initially improves with increased power but eventually the blocking effect of the false alarms offsets the gain in detection. If the length of the packet-burst's preamble is increased, the onset of the false alarms occurs at an even higher power level and therefore, the overall capture process is enhanced. A second penalty that is incurred when larger power levels are utilized is an increase in the number of packet erasures in the other on-going transmissions.

When the transmissions in the reverse channel occur over multiple paths (path diversity), session-initiate burst detection is enhanced. This is because each path has independent Rayleigh fading characteristics and hence, offers an additional chance for the detection of the transmission. Similarly, antenna diversity also improves detection since the received signal has independent Rayleigh fading characteristics at each antenna. However, at higher power levels the occurrence of false alarms is more pronounced with path diversity and with antenna diversity. In case of path diversity, this is due to the increased interference from the additional paths. Whereas with antenna diversity, it is because the matched filter at each additional antenna is a source of false alarms.

Once a terminal has established a session, it utilizes the message-bursts to send messages to the base station. Since each message burst is transmitted after the closed-loop power control procedure of the previous message burst or the session-initiate burst, its received power is a deterministic quantity. The message burst detection probability can be improved by utilizing a larger power for the preamble segment. However, if a longer preamble is used, the effect of interference is reduced and same detection probability can be achieved with a smaller increase in power.

The final condition required for packet-burst capture is the correct demodulation of the header. There are two events that prevent this: collisions and a low signal-power-to-interference ratio (SIR). A collision occurs when transmissions from different terminals arrive closely in time at the base station and the receiver system combines multipath components from different terminals within the same RAKE receiver. The transmissions that are involved in a collision can
either be new packet-bursts being transmitted for the first time or the re-transmissions of previously unsuccessful packet-bursts. Therefore, the frequency of collisions is function of the aggregate arrival rate of new transmissions at the base station as well as how quickly terminals re-transmit the unsuccessful packet-bursts. The SIR during the demodulation of the header can be enhanced either by increasing the received power or by increasing the processing gain of the header. The first solution has an adverse effect on the number of packet erasures in the other ongoing transmissions, while the second solution results in a greater transmission overhead due to the longer duration of the header.

Packet Transmission

The objective of the Multiple Packet-burst Capture Receiver Scheme is to maximize the number of packets received per unit time while keeping access delays and the packet erasures to a minimum. Hence, three parameters that are used to measure the performance of the receiver scheme are packet throughput, the average message burst access delay and the packet erasure rate. As the number of receiver ports is increased, the receiver system is able to support higher levels of throughput from larger traffic loads with lower access delays. However, the multiple access interference and hence, the number of packet erasures also increase. With even more ports, the packet erasure rate becomes excessive and throughput drops to zero with increasing traffic load. In a receiver system with few ports, the access delay is dominant while in a system with several ports the packet erasure rate is dominant.

The number of packet erasures and the average access delay, in addition to being functions of the offered traffic load (i.e. they increase with load), are also dependent on the statistics of the traffic. A given level of traffic can be composed of a large number of terminals with short packet-bursts or a relatively few terminals with relatively long packet-bursts. The first type of traffic is more conducive to the occurrence of packet erasures while the second type of traffic results in larger access delays. When the traffic is from a large number of terminals, the busy tone signal is less effective in controlling multiple access interference (i.e. in blocking new transmissions when all ports at the base station are busy). As a result, the packet erasure rate is higher for this type of traffic. When the packet-bursts are long, the duration of the busy periods of the busy tone signal increases and hence, the average access delay also increases.
**Cellular Environment**

In a cellular environment, the interference at the base station is due to both intercell as well as intracell interference. This requires that the number of receiver ports and the traffic load in the cells be further reduced to compensate for the additional interference.

**Path Diversity**

When the transmissions in the reverse link arrive over multiple paths, the base station combines the power in the different paths in the RAKE receiver. For each path, the other paths are a source of interference (interpath interference). When the number of paths is large, the interpath interference is equivalent to the interference from an additional concurrent packet-burst transmission. The effect of interpath interference can be mitigated by having one less port in the receiver system.

**Antenna Selection Diversity**

In a single-antenna receiver system, all transmissions must be received through the one antenna. With antenna selection diversity, each transmission is received through the antenna where its received signal is the strongest. As a result, the interference that a transmission creates at another antenna is less than its power at its selected antenna. When multiple packet-burst transmissions are received concurrently, typically they are received through different antennas. Therefore, the multiple access interference and the packet erasure rate encountered by a packet-burst transmission is lower in a receiver system which utilizes antenna selection diversity.

**Slow Terminal Motion**

The effect of terminal motion was investigated for reverse link transmissions with and without path diversity. In the case of single path transmission, terminal motion results in a significant increase in the average number of transmission attempts required for packet-burst capture. The effect on the packet erasure rate is relatively minimal. With path diversity, the opposite is true. There is a significant increase in the packet erasures while the capture process is relatively unaffected.
5.1 **FURTHER RESEARCH**

In the simulation of the receiver scheme, the following were assumed: all terminals produce the same type of traffic - either constant bit-rate (long packet-bursts) or variable bit rate traffic (short packet-bursts); the packets are delay insensitive; only one bit rate is available to the terminals and the same bit rate is used for the entire duration of each packet-burst.

In an integrated wireless network, the traffic will be from both constant and variable bit rate sources. Some services such as voice will be delay sensitive and packets will be lost if they excessively delayed. Also, to support multimedia services, the terminals will need a range of bit rates.

Hence, three items that must be further investigated are as follows. The performance of the receiver scheme under mixed (constant and variable bit rate) traffic conditions. The packet loss probability for delay sensitive traffic. The possibility of multiple bit-rates in the reverse channel and also the possibility of a terminal switching between bit rates during a packet-burst to take advantage of momentary periods of low traffic.
# Appendix A

The following is a list of the model parameter values utilized in the simulation of the Multiple Packet-Burst Capture Receiver Scheme. These values apply unless otherwise stated in Chapter Four, which contains the simulation results.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data packet bit rate</td>
<td>$R_D$</td>
<td>250 Kbps</td>
</tr>
<tr>
<td>Spreading (chip) rate</td>
<td>$R_C$</td>
<td>4 Mcps</td>
</tr>
<tr>
<td>Terminal message arrival rate</td>
<td>$\lambda_M$</td>
<td>3.5 messages/minute</td>
</tr>
<tr>
<td>Average number of messages per terminal per session</td>
<td>$K_M$</td>
<td>5 messages</td>
</tr>
<tr>
<td>Data packet size</td>
<td>$N_B$</td>
<td>424 bits</td>
</tr>
<tr>
<td>Session-initiate-burst size</td>
<td></td>
<td>5 packets</td>
</tr>
<tr>
<td>Average message-burst size</td>
<td>$K_B$</td>
<td>200 packets</td>
</tr>
<tr>
<td>Probe preamble length</td>
<td>$N_P$</td>
<td>512 chips</td>
</tr>
<tr>
<td>Number of probe header bits</td>
<td>$N_H$</td>
<td>16 bits</td>
</tr>
<tr>
<td>Probe header length</td>
<td>$N_H$</td>
<td>512 chips</td>
</tr>
<tr>
<td>Duration of ACK interval</td>
<td>$T_A$</td>
<td>1 millisecond (or 4000 chips)</td>
</tr>
<tr>
<td>Re-transmission transmit power increment</td>
<td>$I$</td>
<td>1 dB</td>
</tr>
<tr>
<td>Re-transmission waiting time randomization interval</td>
<td>$T_R$</td>
<td>1.5 milliseconds (or 6000 chips)</td>
</tr>
<tr>
<td>Parameter</td>
<td>Symbol</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>--------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Number of Antennas</td>
<td>$K_A$</td>
<td>1</td>
</tr>
<tr>
<td>Number of receiver ports</td>
<td>$K_P$</td>
<td>5 ports</td>
</tr>
<tr>
<td>Number of RAKE fingers</td>
<td>$K_F$</td>
<td>6 fingers</td>
</tr>
<tr>
<td>SIR Threshold</td>
<td>$\gamma_{SIR}$</td>
<td>7 dB</td>
</tr>
<tr>
<td>Error Burst Length Period</td>
<td>EBLP</td>
<td>10%</td>
</tr>
<tr>
<td>Delay-spread period</td>
<td>$T_D$</td>
<td>1.5 microseconds (or 60 chips)</td>
</tr>
<tr>
<td>Maximum number of multipath echoes</td>
<td>$K_E$</td>
<td>$\leq 6$</td>
</tr>
<tr>
<td>Echo detection threshold</td>
<td>$\gamma_P$</td>
<td>$\frac{N_P}{\sqrt{2}}$</td>
</tr>
<tr>
<td>Target received power</td>
<td>$P_0$</td>
<td>1</td>
</tr>
<tr>
<td>Total power in detected echoes after closed-loop power control</td>
<td>$P_C$</td>
<td>1</td>
</tr>
<tr>
<td>Terminal movement rate</td>
<td>$\lambda_S$</td>
<td>0</td>
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</table>
Bibliography


