SSSMA for Multi-User MIMO Systems

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The proliferation of high-bit-rate wireless services such as multimedia and high-speed Internet access is driving the development of next-generation wireless communication systems to support much higher data rates than the current second-generation (2G) and the emerging third-generation (3G) systems. A 2G standard, such as IS-95, is capable of supporting 9.6 kb/s, while the 3G standards, such as CDMA 1xEV-DV and W-CDMA, are aiming to support a maximum rate ranging from 2–5 Mb/s. In the envisioned fourth-generation (4G) systems, further drive toward higher bit rate and spectral efficiency is expected. For other systems, such as wireless LANs and broadband wireless systems, such as IEEE 802.16, seamless interconnections at rates of tens of megabits per second are required. Figure 1 shows a technology roadmap for

some of these wireless systems, as well as the spectral efficiency (in terms of bits per second per hertz) being supported/expected over the course of technological evolution. It is clear that a multiple-fold increase in the spectral efficiency is a key requirement for the upcoming generations of wireless systems.

Among many cutting-edge wireless technologies, a new class of transmission techniques, known as the multiple-input-multiple-output (MIMO) technique, has emerged as an important technology, leading to promising link capacity gains of several-fold increase in spectral efficiency. While the use of MIMO techniques in the 3G standards is minimal, it is anticipated that these techniques will play an important role in the physical layer of fixed broadband and 4G wireless systems.

In a MIMO transmission link, an array of multiple antenna elements is employed at both the transmitter

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Figure 1. Roadmap from 1–4 G.

and receiver, as shown in Figure 2. As a result, multiple signal propagation paths exist between the different pairs of transmit/receive antenna elements. These paths result in the creation of a number of parallel *spatial channels*. Depending on the number of antenna elements and the degree of multipath propagation, MIMO systems may provide significant capacity gains over single-antenna systems while improving detection performance. Early studies from an information-theoretical perspective, such as [1], have laid the groundwork in the study of MIMO systems by predicting the ultimate achievable link capacity. Many novel MIMO transmission/detection schemes ([2]–[6] and references therein) achieve capacity gains that are close to these theoretical capacity limits.

Despite the large number of these sophisticated schemes for MIMO systems, past research has, for the most part, concentrated on single-user (point-to-point) systems, and the development of multi-user MIMO systems is still in its early stages. The diagram for a point-to-multipoint MIMO system that is considered in this article is depicted in Figure 3. In this system, transmissions from a base station to a number of independent mobile terminals occur simultaneously. The natur-

al approach taken in some of the previous research in multi-user MIMO systems is to employ a single-user MIMO scheme in conjunction with conventional multiple-access techniques, such as time-division multiple-access (TDMA), frequency-division multiple-access (FDMA), and code-division multiple-access (CDMA) (for example, see [8]). These traditional techniques utilize orthogonal channels in the time or frequency domain to separate different users so that the multiple-access-interference (MAI) is eliminated completely (see Figure 4). In other words, the multi-user MIMO system can be viewed as many self-contained single-user MIMO channels. It is then obvious that, while the performance of an individual user is improved greatly with MIMO, the number of user-channels depends on the available degrees of freedom in the time or frequency dimension that is the bandwidth of the system.

In this article, we present a new technique for a point-to-multipoint network (such as the forward link in a cellular system), which we refer to as spread space-spectrum multiple access (SSSMA). This scheme uses all the degrees of freedom in the frequency, time, and space dimensions for the transmission of each signal. SSSMA

is based on the transmission of spread space-spectrum signals, which are formed by modulating data signals from different user-channels with two-dimensional (2-D) space-time spreading sequences. These sequences do not create orthogonal channels in the time or frequency dimension but a set of channels overlapping in space, time, and frequency. This may result in supporting more user-channels than the single-antenna system and other multi-user MIMO systems, which rely on conventional multiple-access schemes that do not exploit the space dimension. Several other advantages of SSSMA will also be discussed in the article.

Single-User MIMO

Prior to the detailed discussion of SSSMA, it is beneficial to start with the consideration of MIMO techniques from a perspective of a single-user system. Roughly speaking, single-user MIMO techniques exploit the multiple spatial channels with two types of objectives:

- 1) increase the spectral efficiency by supporting multiple data streams over the spatial channels
- 2) enhance the detection performance by exploiting the spatial diversity.

To achieve the first type of objective, multiple data streams or layers (a terminology used in [3]) are

Figure 2. MIMO system.

Figure 3. Multi-user MIMO system.

generated and mapped to different transmitting antennas in a predetermined fashion. At each of the receiver antenna elements a signal equal to a linear combination of the transmitted signals is received; i.e., the set of

The novelty of SSSMA stems from the exploitation of the space dimension for multiple access.

received signals is obtained from the transmitted signals through a matrix multiplication. The receiver then utilizes signal-processing techniques to recover each data stream. In essence, the received signal vector is

Figure 4. Multiple-access methods.

Figure 5. SSSMA versus TDMA-MIMO.

multiplied by a matrix to decouple the received signals. A novel approach, which performs all the tasks above based on multilayer processing, was suggested in [3], which also reveals the trade off one usually encounters in MIMO systems: diversity gain versus multiplexing gain. This trade-off arises from the fact that, due to the fixed number of antennas employed, only limited degrees of freedom in the space dimension are available, while they are responsible for both enhancing the performance of the target data stream (diversity gain) and supporting multiple layers (multiplexing gain).

To achieve the second type of objective, several groundbreaking techniques have been previously proposed, such as fading-resistant modulation [2] and space-time coding (STC) [4], which exploits the spatial diversity from a coding perspective. The invention of STC has sparked an explosion of research activities to find schemes that exploit the full benefit of spatial diversity. Unlike the multilayer approach, these techniques rely heavily on the elegant signaling structure employed at the transmitter. It also displays a similar trade-off as in the multilayer approach: high spectral efficiency versus diversity gain. That is, supporting a higher data rate will result in the degradation of detection performance and vice versa.

Based on the discussions above, we note that these techniques, which achieve either objective, possess advantages and disadvantages that may complement one another. Thus, an attempt has been taken to seek a joint optimization of both objectives, and a notable example is found in [7], where a threaded space-time architecture, which resembles a multilayer structure, is developed. Each thread inherits a unique STC structure that may potentially achieve diversity gain by adopting rotated signal constellations. Rotated signal constellations can be generated by linearly transforming the regular constellations, such as binary phase-shift keying (BPSK), quadrature amplitude modulation (QAM), and quaternary phase-shift keying (QPSK), based on orthogonal rotation in the signal space (modulation) domain.

Multi-User MIMO: SSSMA

In Figure 5, we compare a TDMA-MIMO system with an SSSMA system. In TDMA-MIMO, each user occupies only a distinct time interval in which all its code symbols are transmitted across space and time based on any single-user MIMO technique while no MAI is present. On the other hand, in SSSMA, code symbols from multiple user-channels are multiplexed over a single interval (called the spreading period), and this repeats for subsequent code symbols over the entire transmission interval. SSSMA utilizes all available degrees of freedom provided by the multiple transmit antennas for the objective of multiple access, thereby supporting a maximum of N symbols for N different user-channels over each time instance (N is the number of transmit antennas). In other words, the broad data

Figure 6. Transmitter structure of SSSMA.

pipe associated with a MIMO channel is evenly divided and allocated to multiple users, rather than to only one user at a given time. As a result, each user-channel has access to the space domain over the entire transmission interval and frequency bandwidth. One main novelty of SSSMA is that it is inherently a space-time multiple-access technique, which, contrary to traditional approaches, actually allows the existence of MAI (instead of using orthogonal channels) and, in turn, creates a large number of user-channels.

In the following, the SSSMA scheme is explained under the following assumptions. N antennas are deployed at the base station transmitter, while each user's receiver employs M ($M \geq N$) antennas. The spreading period spans an interval of duration equal to $G \cdot T_c$, where G , and T_c are the processing gain and the chip period, respectively. When the space dimension is fully utilized for multiple access, one may support N symbols per hertz per second by transmitting $N \cdot G$ unique space-time spreading sequences over the spreading period, each modulating one unique user's data/code symbol.

Figure 6 depicts the block diagram of a coded communication system based on SSSMA. The independent data streams from different users are first produced. The encoder then adds some redundancy to the incoming bits at a specified coding rate. The encoded message is sequentially delivered to the interleaver and then to the multiplexer, which combines all independent messages based on space-time spreading. The number of users K is assumed to be equal to $N \cdot G$. From Figure 6, it is clear that the SSSMA scheme adopts the multilayer approach for multi-user transmission, as each user-channel resembles a layer and distinct space-time spreading sequences are used to modulate these layers.

Space-Time Diagonal Spreading Sequence

Each symbol is modulated with a unique 2-D real spreading sequence (i.e., the chip's value is a function

of space and time). The 2-D sequence assigned for the i -th user is represented as follows,

$$\mathbf{S}_i = \begin{bmatrix} s_{1,1}^i & s_{1,2}^i & \cdots & s_{1,G}^i \\ s_{2,1}^i & s_{2,2}^i & \cdots & s_{2,G}^i \\ \vdots & \vdots & \ddots & \vdots \\ s_{N,1}^i & s_{N,2}^i & \cdots & s_{N,G}^i \end{bmatrix}$$

where $s_{n,t}^i \in \{0, \pm 1\}$ denotes the chip of the i -th sequence transmitted at antenna n during time index t . As each nonzero chip occupies one space-time slot, each code symbol is spread over multiple space-time slots through the multiplication with the spreading sequence.

The sequences employed in SSSMA are named space-time diagonal (STD) spreading sequences. To obtain full diversity gain, the STD sequence spreads the data symbol over a set of space-time slots corresponding to different transmitting antennas. This set of slots must reside in different time instances to avoid interference due to the same symbol. These multiple space-time slots constitute an STD. The chips of STD sequences outside the diagonal are zero. With N transmitting antennas, one can construct a set of N such STDs, each containing G slots (see Figure 7, for an example). To utilize all available degrees of freedom, the number of

Figure 7. Examples of STDs ($N = 4$, $G = 16$).

Figure 8. Examples of STD sequences ($N = 2$, $G = 2$).

Figure 9. Iterative (turbo) processing receiver.

sequences spreading to one diagonal is equal to G . The set of sequences using the same diagonal are taken from a $G \times G$ orthogonal matrix such as the Walsh-Hadamard matrix. Therefore, in total, $N \cdot G$ sequences can be generated. Figure 8 contains an example for the construction of STD sequences with $N = 2$ and $G = 2$.

Channel Coding and Interleaving

In SSSMA, the channel-coding scheme employed by each user-channel is of the single-input-single-output (SISO) type, which is equivalent to a single-antenna

coding scheme. After multiplexing, the SISO code words drawn from different user-channels will form a composite multi-user space-time code word, which can be expressed as follows:

$$C = \sum_{i=1}^K S_i \otimes c_i,$$

where c_i is the row-vector containing the SISO code word of i -th channel and $\otimes$ denotes the kronecker product. To obtain full diversity, the composite code

word must satisfy the following criterion [2]: the pairwise error matrix, $C - \hat{C}$, is full rank for all pairs of code word ($C, \hat{C}$). However, it can be shown that the STD sequences fail to achieve full rank for all pairs of multi-user code words. This motivates the use of interleaving, which permutes the symbols within each SISO code word. It is shown in [9] that it is possible to derive a set of user-unique optimal SISO interleavers, which can fulfill the diversity criterion for all STD-based multi-user code word pairs when $N = 2$. The novelty of this approach is that it applies to any SISO coding scheme (for full diversity, there is a limitation on the coding rate of each SISO code, see [9]) and no rotated signal constellations are required. While it may not be easy to obtain the optimal interleavers, we show by simulations (in the last section) that for both $N = 2, 4$, random interleaving is sufficient to provide significant performance improvement.

Iterative (Turbo) Processing Receiver

It is assumed that each user will detect its own signals as well as those from the interferers. The receiver will operate on multi-user detection (MUD) and decoding technique in order to minimize the effect of MAI. The proposed receiver (employed at each user's terminal) based on MUD and iterative processing is depicted in Figure 9. It consists of two main elements:

- 1) a MUD detector based on a linear minimum-mean-square-error (MMSE) filter with parallel interference cancellation (IC) processing
- 2) a bank of SISO decoders, one for each coded user-channel.

For 1), the linear MMSE filter is used to filter out the interfering signals and noise while the IC processing performs a pre-emptive removal of the interference, which was detected in previous iterations. For 2), the decoders exploit the redundancy and structure of the code words to extract the required code bit information. As in any iterative receiver, these two elements alternatively calculate the log a-posterior probability (APP) of the required code bit. The log-APP is a piece of information that aids the receiver in making the right decision regarding the unknown code bit. This information can be decomposed into two parts, namely the extrinsic information and the intrinsic information, the latter being provided by either the detector or decoders in the previous iteration if the information is currently processed by the decoders or detector, respectively. Likewise, the extrinsic information is delivered to the detector or decoders as the new intrinsic information. As the iteration proceeds, the information is transferred back and forth between the detector and decoders so that it can be further polished before it is used to make the final decision regarding the unknown bit. More detail in relation to the structure of the iterative receiver can be found in [9]. This type of iterative receiver,

based on the well-known turbo principle, has been widely acknowledged as a powerful detection scheme approaching the optimal performance. Although the price of high complexity has to be paid, the success of SSSMA relies heavily on the use of MUD receivers, due to the fact that SSSMA may exploit the spatial MAI effectively for good performance.

It is anticipated that SSSMA would be a strong candidate as a standard multiple-access scheme in future generations of MIMO systems, due to its many remarkable attributes.

Advantages of SSSMA

As mentioned previously, a key advantage of SSSMA is that the number of user-channels can be increased beyond the limit imposed by the time/frequency dimension. In the following, we summarize and raise a few more issues in which the advantages of SSSMA may be unveiled.

Advantages of Spread Spectrum

Since SSSMA is inherently a spread spectrum technique, many benign features possessed by CDMA in single-antenna systems are also available in SSSMA. Some notable features are multipath diversity (frequency diversity), interference/jamming rejection ability, and unity frequency-reuse factor.

Spatial Diversity with SISO Channel Coding

SSSMA seeks to achieve both objectives of collecting multiplexing gain and diversity gain. It facilitates multi-layer transmission with full spatial diversity (based on BPSK and QPSK modulation), but unlike the threaded space-time architecture, a rotated constellation is not required. Hence, any SISO channel coding scheme designed for single-antenna systems can be effectively incorporated into SSSMA. Finally, we note that, as user-channels may alternatively be identified as different data streams due to the same user, SSSMA is well applicable for both single-user and multi-user transmission.

Optimality of STD Spreading Sequences

The STD spreading sequences can be shown to be optimal in terms of minimizing the average probability of detection error at the output of a linear MMSE receiver [9]. Furthermore, data symbols modulated with distinct STD sequences will be subject to the same signal-to-interference-plus-noise ratio (SINR) at the output of the MMSE receiver. This is the SINR-averaging effect exhibited by the STD sequences [9]. Thus, unlike other conventional multilayer approaches, each user-channel

Figure 10. Comparison between SSSMA and other multi-user MIMO techniques (each user, 1, 2, 3, 4, is sending four symbols a, b, c, d).

may employ the same sequence without the need to hop to other sequences at other time instances.

Time-Varying Fading Channel

When the MIMO channel is undergoing time-varying fading, SSSMA is particularly advantageous as user-channels may exploit a larger temporal dimension due to the fact that multiple users are sharing the MIMO channel at each time instant. Figure 10 illustrates this situation and compares the SSSMA ($N = 2, G = 2$), with a TDMA-MIMO and a CDMA-MIMO with the same processing gain ($G = 2$). There are four users in the system, and each user needs to transmit four symbols. [Note: the CDMA-MIMO is actually a hybrid, as it needs to support four users and the processing gain is only two. One may argue that a processing gain of four should be used instead. If this is the case, then the comparison with SSSMA would become unfair. This is because SSSMA may also increase the processing gain to four, and the number of users is no longer four but

eight ($2 \cdot 4$).]. It is clear that SSSMA, by allowing users to share the space dimension, results in continuous transmission for each user-channel over the entire transmission interval. This, in turn, facilitates the exploitation of time diversity if the channel undergoes different levels of fading at different time instances.

SSSMA in Power-Controlled Cellular Networks

In a cellular network or metropolitan area network (MAN), due to large scale attenuation such as path-loss and shadowing (see Figures 2 and 3), the received signal power among different users' terminals varies in a larger scale. To ensure equal quality of service among these users, power control may be employed, and it is often shown to be critical for interference-limited systems. In this section, we discuss another advantage of SSSMA, which arises when power control is employed in a cellular network or MAN. First, we note that power control is commonly utilized to compensate the

signal attenuation due to path-loss and shadowing effect, while recovering loss due to multipath fading is rather difficult as it changes more rapidly and is harder to be tracked. It is, therefore, assumed that the base station acquires a perfect knowledge of the path-loss and shadowing coefficient but not the multipath fading coefficient. Traditionally, the intracell interference is assumed to be negligible due to the utilization of orthogonal channels for separating users in the downlink (e.g., IS-95). This is also the case for any multi-user MIMO system based on conventional multiple access. Therefore, power control is used to ensure equal quality of service received by different users' channels, which may take the form of signal-to-noise (SNR) ratio defined as follows,

$$SNR_i = \frac{P_i \gamma_i}{\eta_i}$$

where P_i and γ_i are the total transmitted power for the i -th user and the associated channel gain (including path-loss and shadowing components only), respectively. The background noise power at the i -th user's terminal is given by η_i . Although MAI is present in SSSMA, the power level allocated to each user-channel can also be calculated based on SNR. Therefore, the total power required in SSSMA is the same as in any conventional multiple-access scheme where the MAI is absent.

In other multi-user MIMO schemes, due to the absence of MAI, the multi-user system resem-

bles a single-user system, and the power variation among other users is irrelevant from any target user's standpoint. On the other hand, SSSMA displays a

Figure 11. Comparison of SSSMA and single-user MIMO techniques used in multi-user transmission. ($N = 2$, $G = 2$, 2 b/s/Hz, QPSK, multipath fading.)

Figure 12. Performance of SSSMA ($N = 4$, $G = 4$, 4 b/s/Hz, QPSK, multipath fading).

Figure 13. Comparison of SSSMA and TDMA-MIMO in a power-controlled system ($N = 2$, $G = 2$, 4 bps/Hz, 8-PSK, path-loss, shadowing, multipath fading).

unique feature when power control is applied, as the receiver may exploit the power variation among the interfering user-channels to its advantage. When a user is located near the base station, less power is allocated to it, and the interference it causes to others is small, especially to the users who are further away. Hence, the user at the cell boundary picks up negligible interference and may exploit the additional degrees of freedom in the space dimension freed up by the interfering user. The receiver may use these degrees of freedom to improve the diversity performance instead of eliminating interference (a principle used in D-BLAST [4]). Note that this is impossible for any conventional multiple-access scheme, in which the entire space dimension is dedicated to one user over a single time/frequency/code slot. Now, if we consider the performance of the users who are closer to the base station, the near-far effect may occur as the strong interference may swamp the desired signal. Yet, the interference-canceling detector is known to be near-far resistance as the strong interfering signals are estimated and then subtracted from the received signal. Thus, the overall effect of power variations among the interferers has a positive impact on the link performance, and we name this unique advantage offered by SSSMA as the *space-interferers diversity*.

Performance

In order to provide a fair comparison between the proposed SSSMA and other multi-user MIMO techniques, this section contains some simulation results for the individual link performance over a point-to-multipoint network (which can be LAN or MAN). For simplicity, the channel fading is assumed to be static, and the number of resolvable multipaths is equal to one. As all links have identical and independent fading statistics, the average individual link performance represents the average performance over all links. When SSSMA is compared with other multi-user MIMO schemes, it is assumed that the number of users is the same. The performance measure is based on the outage probability (i.e., frame error rate), given a fixed spectral efficiency R , which is defined as the total transmission rates (b/s/Hz) of all user-channels. One may then refer to Figure 1 for a comparison between our results and the current technologies in terms of the spectral efficiency. Note that the results obtained here only serve as a motivation for employing MIMO/SSSMA technology, and it is obvious that there is room for improvement by adding more antennas beyond those used in our simulations. Lastly, we remark that the simulation results would be compared with the Shannon outage capacity bound, which gives the best achievable outage perfor-

mance given the above system parameters.

Now, a small-scale environment, such as wireless LAN, is considered (with multipath fading only). In SSSMA, we use the 32-state rate-1/2 convolutional code [octal generators (53, 75)] for each user. In the simulations, a block of 255 information symbols is generated for each user-channel. The output code symbols are interleaved, then modulated based on QPSK with Gray mapping. The set of interleavers are randomly and uniformly chosen from the permutation {1, 2,..., 512}. With $N = 2$, $G = 128$, the spectral efficiency is 2 b/s/Hz. Figure 11 depicts the results in terms of average outage probability under independent fading. With the same per-user transmit energy and bandwidth constraint, we include the performance of a single-user 32-state space-time-code (STC-32) with the same data rate (2 b/s/Hz) provided in [4], and the single-user 64-state multilayer system with turbo receiver in [5] (wherein this is named LST-II, which is shown to be the best scheme for $N = 2$ in [5]). Note that these single-user schemes can be employed in any orthogonal TDMA/FDMA/CDMA-MIMO system, thereby allowing a fair comparison with SSSMA. The SSSMA system outperforms all the above. Furthermore, it is shown that the SSSMA approaches the capacity bound within 2 dB. Next, we study the performance for $N = 4$, $G = 128$. The same rate-1/2 coding schemes are used for all users, and the spectral efficiency becomes 4 b/s/Hz. In Figure 12, the average outage performance is shown, and it is found that the SSSMA is only 1.5 dB away from the theoretic outage capacity bound.

Next, a power-controlled single-cell system or MAN (with path-loss, shadowing and multipath fading) is considered. We consider $N = 2$, $G = 2$, and four users. The users are uniformly distributed within a distance of 10–210 m from the base station in a single-cell. The path-loss exponent and the standard deviation of log-normal shadowing are taken to be 3.7 and 6 dB, respectively. Unlike the LAN scenario, a higher spectral efficiency is attempted by employing a rate 2/3 bit-interleaved-coded-modulation scheme for each user with a 64-states generator (236, 155, 337). Using 8-PSK modulation, the resulting spectral efficiency is 4 b/s/Hz. In this case, the space-interferers diversity helps combat the MAI, and the result is depicted in Figure 13. It is clear that the SSSMA is 4-dB close to the outage capacity bound. Note that orthogonal multiple-access schemes (TDMA, FDMA, and CDMA) cannot exploit the space-interferers diversity. For illustration, we include the results of a TDMA multilayered MIMO scheme, which has zero MAI, and all layers (channels) are shared by a single user over a given

time interval. The performance is very poor. It is clear that SSSMA outperforms the conventional multiple-access schemes significantly in a power-controlled cellular/MAN network, especially for heavily-loaded systems with high spectral efficiency. We can then conclude that our simulation results have justified the use of MIMO techniques and SSSMA in future wireless technologies, which require a significant growth in the spectral efficiency.

Summary

In this article, a new multiple-access scheme suitable for the forward link transmission in a multi-user MIMO system, namely SSSMA, is presented. The novelty of SSSMA stems from the exploitation of the space dimension for multiple access. As a result, the number of user-channels sharing the MIMO system increases, and it becomes a function of the available degrees of freedom in the time and frequency dimension, as well as the number of transmit antennas employed. SSSMA displays various advantages that cannot be found in conventional multiple-access schemes, and this article has provided an overview of these advantages. While many technical aspects in SSSMA have yet to be explored, it is anticipated that SSSMA would be a strong candidate as a standard multiple-access scheme in future generations of MIMO systems, due to its many remarkable attributes.

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