Transmit Diversity Vs Beamforming for Multi-User OFDM Systems

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***Abstract*— In an Orthogonal Frequency Division Multiplexing (OFDM) system, downlink beamforming can be implemented either before IDFT (frequency domain) or after IDFT (time domain) module in a base station transmitter. We denote the former scheme as Pre-IDFT downlink beamforming, and the latter as Post-IDFT downlink beamforming. In this work, we have compared Pre-IDFT downlink beamforming with Space-Time Block coded and Space-Frequency block coded transmit diversity schemes for 4×1 downlink multi-user OFDM (OFDM-TDMA and OFDMA) systems. The study is performed for indoor micro and pico cells and urban macro cells. Regardless of the multiple access scheme, it is found that beamforming always performs better in outdoor environment, where angular spread is lower, thus spatial correlation is higher. Similarly, indoor environment (high angular spread and low spatial correlation) suggests that transmit diversity schemes performs better than beamforming strategies.**

***Keywords*— Multi-user OFDM, Beamforming, Transmit Diversity**

I. Introduction

Wireless systems which operate at high data rate, providing higher multi-user capabilities, are always impaired by harsh wireless channel. Multi-antenna techniques can be used to overcome these unwanted situations, e.g. diversity techniques can be used to obtain reliable transmission systems or beamforming can be used to increase the signal strength towards a particular user, thus reducing interference to others. Traditionally spatial diversity is exploited involving multiple antennas in transmitter (Transmit Diversity) and/or receiver (Receive Diversity). Transmit diversity is a lucrative and reasonable choice for downlink (DL), i.e. BS-to-MS, especially for portable receivers where current drain and physical size are important constraints.

Space-Time Block Coding (STBC) [1] is an open loop transmit diversity scheme where the diversity is achieved at the receiver without the knowledge of the channel at the transmitter. A complementary to this kind of transmit diversity scheme is beamforming (BF) [2]. When the wireless channels between transmit and receive antennas are correlated to each other, then transmit diversity scheme is not expected to perform well, i.e. if independent fading among the antenna signals cannot be achieved, BF is preferred over transmit diversity. In BF we exploit the fact that the antenna elements are close together so that appreciable coherence between the antenna signals is present.

Orthogonal Frequency Division Multiplexing (OFDM) itself does not pose any built-in diversity, thus it is necessary to install some forms of diversity in an OFDM system for the purpose of achieving higher link quality and link availability without using any extra bandwidth. For example, channel coding and interleaving are used in IEEE 802.11a to obtain frequency diversity. Contrary to this, BF techniques can be used to achieve similar performance. In this work, we compare the usability of transmit diversity and BF for DL of OFDM based TDD (Time Division Duplex) cellular systems at indoor (micro and pico cells) and outdoor urban macrocell scenarios. In both approaches the configuration used is MISO (Multiple-Input-Single-Output), since it is supposed that multiple antennas are employed at the BS transmitter and a single antenna at the MS receiver. The target is to define the conditions in which one of the two techniques is preferred to the other for DL of MU-OFDM based. We compare the schemes based on Bit-Error-Rate (BER) performance, on various Angular Spread (AS) values and corresponding channel correlation status. In order to get enough array gain for BF, we should use at least 4 transmit antennas, so for reasonable comparison between the schemes, we have used 4 transmit antennas in all cases.

This paper consists of seven main sections. Following a brief overview of the multi-antenna techniques considered in this work, to be found in Section II, the way to employ DL-BF in multi-user OFDM systems is explained in Section III. Section IV explains how transmit diversity and beamforming can be compared in multi-user OFDM systems. Simulation related issues are presented in Section V. Section VI presents the results obtained from simulations, and final conclusions are drawn in Section VII.

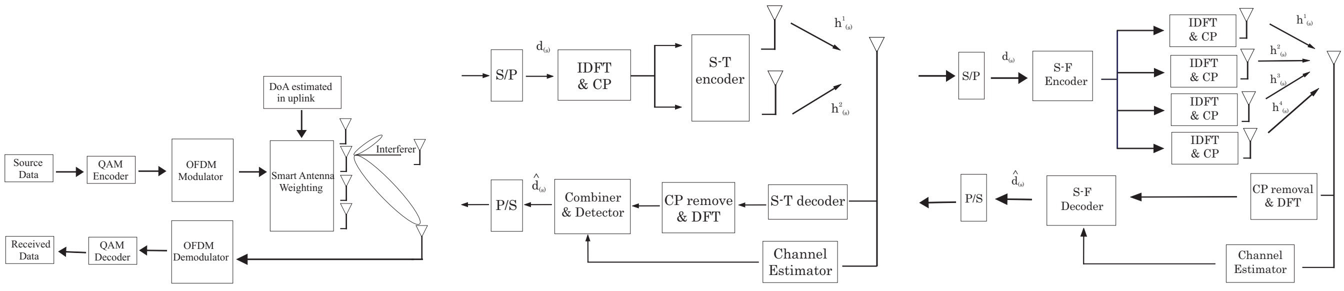
II. Multi-Antenna Techniques under Consideration

A. Beamforming

In a BF system, the weights to be multiplied with the signals have to be carefully chosen. From antenna theory, an array with P antenna elements has different excitation currents according to the angle of direction of the waves arriving or departing from each element of the array. Considering linear phase progression, the weights have a phase that increases the same amount from one element to the next. Defining as δ this increment, then for Uniform Spaced Linear Arrays (USLA), presumed to be used throughout this paper, the array factor becomes

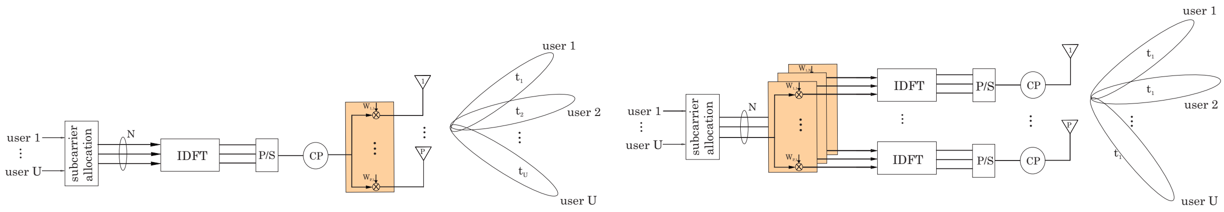
$$F(\theta) = \sum_{p=0}^{P-1} A_p e^{jp(kd \sin\theta + \delta)} \qquad (1)$$

Usually, BF is treated in literature as a method of increasing gain when receiving signals from a specific direction. Direction of Arrival (DoA) is the angle of the wave arriving to the antenna. However, in this study it is intended to analyse the DL case, placing the beamformer at the transmitter side, i.e. at the BS, since it is more feasible to have multiple antennas at the BS than at the MS. This will bring additional complications if it is assumed that there is complete channel knowledge at the receiver, but not at the transmitter. In order to solve this problem, the DL-BF technique to be employed in this analysis will extract the weights to be used in DL from the weights calculated in uplink (UL). This method can be used in TDD systems without losing performance. However, in Frequency Division Duplex (FDD) systems, as a consequence of the frequency dependent steering array response and uncorrelated fading, the UL weight reuse in DL degrades system's performance, since the frequency for UL is different from the one used to DL. In this work TDD systems will be considered for analysis. A block diagram showing the implementation of DL-BF in an OFDM transmitter is presented in Fig. 1(a). In order to cancel interference and increase gain from DoA, Minimum Mean Square Error (MMSE) criterion is used. A number of four antennas at the transmitter side was chosen from a trade-off between the fact that



(a) (b) (c)

Fig. 1. a) OFDM system with beamforming operation; b) Space-Time diversity in OFDM system; c) Space-Frequency diversity in OFDM system



(a) (b)

Fig. 2. a) Time-domain beamforming approach on an OFDMA system b) Frequency-domain beamforming approach on an OFDMA system

more antennas give more degrees of freedom and a small number of antennas keep the comparison with transmit diversity feasible, since the antennas need to have a large separation between them.

B. Space-Time Block Coding (STBC)

STBC consists of applying STC on blocks of data symbols instead of individual symbols. Its implementation in an OFDM system is shown in Fig. 1(b). A special case of STC is Alamouti's STBC [1], which can be applied in 2×1 transmit diversity systems. Alamouti proposed a full diversity and full rate STBC for 2×1 system. In this process, where two transmitter and one receiver antennas are used, at each time symbol two symbols are being transmitted through two transmitting antennas. Tarokh et al. [3] proved that full rate and full diversity is only achievable for 2×1 system. They proposed partial rate and full diversity codes for 4×1 space-time transmit diversity system.

Since Alamouti scheme addresses the problem of two transmit antennas and for the present analysis the scheme to be studied will have four transmit antennas, we use $\frac{1}{2}$ rate and fully orthogonal scheme for 4×1 system that [3] proposed. Using an orthogonal design, this proposal extended STBC usage to more than two antennas giving full diversity but losing bandwidth efficiency. The orthogonal transmitted symbol block design is described Tab. 1.

OFDM Symbol	Ant 1	Ant 2	Ant 3	Ant 4
T_n	s_n	s_{n+1}	s_{n+2}	s_{n+3}
T_n+1	$-s_{n+1}$	s_n	$-s_{n+3}$	s_{n+2}
T_n+2	$-s_{n+2}$	s_{n+3}	s_n	$-s_{n+1}$
T_n+3	$-s_{n+3}$	$-s_{n+2}$	s_{n+1}	s_n
T_n+4	s_n^*	s_{n+1}^*	s_{n+2}^*	s_{n+3}^*
T_n+5	$-s_{n+1}^*$	s_n^*	$-s_{n+3}^*$	s_{n+2}^*
T_n+6	$-s_{n+2}^*$	s_{n+3}^*	s_n^*	$-s_{n+1}^*$
T_n+7	$-s_{n+3}^*$	$-s_{n+2}^*$	s_{n+1}^*	s_n^*

Tab. 1. Tarokh's $\frac{1}{2}$ rate Space-Time Block Encoding Scheme; s_n denotes the transmitted symbol at n^{th} OFDM symbol duration.

By combining the received eight symbols and applying ML detector, the four transmitted symbols can be obtained [3]. The abstract transceiver structure of this scheme in an OFDM system is shown in Fig. 1(b).

C. Space-Frequency Block Coding (SFBC)

STBC algorithms can be implemented in OFDM systems with a condition that the channel is time-invariant for the duration of the orthogonal transmission block (i.e. coherence time, $T_c \geq PT_s$, where T_s is total OFDM symbol duration including the cyclic prefix). This can be a bottleneck for highly time-variant mobile environment. Besides, effectively the latency that the receiver incurs because of STBC algorithm is essentially equal to PT_s. This can also be unsatisfactory for some particular real-time services.

An alternative to STBC-OFDM system in this regard is SFBC-OFDM system. In SFBC-OFDM system, the orthogonal code blocks are designed across OFDM subcarriers. Thus, as long as neighbouring subcarriers have similar frequency response, there will be no problems with SFBC algorithms. It is worth noting here that SFBC-OFDM systems will not perform well in situations where $\Delta f \leq B_c \leq P\Delta f$. Here, Δf is the subcarrier spacing of the OFDM systems. For cases when P is small, e.g. ≤ 8, there should not be any problem with SFBC system. Even for the case of higher P, the degradation can be avoided with proper OFDM system design. Moreover, the orthogonal coding is not done across OFDM symbols, rather in one OFDM symbol, so as long as the channel remains static for one OFDM symbol duration (T_s), the coding should provide optimum diversity gain to the system [4]. Its implementation in OFDM system is shown in Fig. 1(c). The orthogonal space-frequency blocks can be defined in a similar fashion like Tab. 1.

III. Downlink Beamforming (DL-BF) in Multi-User OFDM Systems

A. DL-BF in OFDM-TDMA

In OFDM-TDMA, each OFDM symbol is being sent to one user at a time. Hence, during that period the beamformer acts to determine the best radiation pattern to send information to the user allocated to that time slot. The number of OFDM symbols per TDMA frame can be varied according to each user requests. Its main drawback is the increase of the latency when the number of users gets higher in the cell.

If the beamformer is placed before the IDFT, the problem is that the number of IDFTs must be equal to the number of transmitting antennas P, instead of only one as if the beamformer was placed after the IDFT. On the other hand, if the weights are calculated after the IDFT, only one IDFT is necessary. It is better to allocate the beamformer after the IDFT, in fact in this case the complexity of the system is lower (one IDFT is needed instead of P).

B. DL-BF in OFDMA

In an OFDMA system, subcarriers are shared among users according to a certain allocation procedure. BS allocates the available subcarriers to users while transmitting in the DL. After that IDFT modulation is performed on frequency domain data. After IDFT modulation, time-domain sampled data is transmitted towards the user. It is obvious that based on the CSI of each user, we can apply the BF weights either before IDFT modulation, or after IDFT modulation. These are called Post-IDFT Beamforming and Pre-IDFT Beamforming respectively.

1) Post-IDFT Downlink Beamforming: A block diagram of an implementation of Post-IDFT BF technique in an OFDMA system is shown in Fig. 2(a). After the IDFT operation in the transmitter, the signal is wideband and time-domain signal, so any wideband BF technique can be used. A multi-tap beamformer can be used for this purpose. The wideband OFDM signal is frequency selective, thus the weight vectors are required for each user which can be used to steer the signal towards the user. The BF problem can be expressed as [5]

$$\frac{\mathbf{w}_u^H \mathbf{R}_u \mathbf{w}_u}{\sum_{l=1;l\neq u}^{U} \mathbf{w}_l^H \mathbf{R}_u \mathbf{w}_l + \sigma_u^2} \geq \gamma_u, \qquad u = 1, 2, \ldots, U \tag{2}$$

Here, $\mathbf{R}$ denotes the co-variance matrix as it is shown in Section V. γ_u, $\mathbf{w}_u$ and σ_u^2 denote the required SNR, beamformer tap weights and additive white gaussian noise variance of u^{th} user respectively. Solving this problem with algorithm proposed by [5] will give us the beamformer weights $\mathbf{w}_u$ for all users.

For this purpose, the channel needs to be estimated in time domain. Once the beamformer weights are decided, then the received signal at the MS, $\tilde{y}_s$, can be written as

$$\tilde{y}_s = \mathbf{w}_u * \tilde{x}_s \tag{3}$$

2) Pre-IDFT Downlink Beamforming: Before applying the IDFT, the BF can be implemented across OFDM subcarriers, as shown in Fig. 2 (b). Subcarriers poses narrowband frequencies and thus, any narrowband scheme can be used in this case. Similar to (2), we can write

$$\frac{w_{u,k}^H \mathbf{R}_{u,k} w_{u,k}}{\sum_{l=1;l\neq u}^{U} w_{l,k}^H \mathbf{R}_u w_{l,k} + \sigma_u^2} \geq \gamma_u^k,$$
$$u = 1, 2, \ldots, U \ \& \ k = 0, \ldots, N-1 \tag{4}$$

Here, the number of subcarriers is identified by N and γ_u^k defines required SNR for u^{th} user's N^{th} subcarrier.

C. DL-BF in Clustered OFDMA

Both the Pre- and Post-IDFT BF schemes clearly show that the user data is not separated before steering the beams to user's location, rather all the OFDM modulated signal is sent towards all users. In this way, it is made sure that the users receive the transmitted data with higher SNR, but they also receive other users' data at the same time. In a sense, it can be said that using these kind of BF schemes, it is not possible to obtain all the goals of BF.

In order to reduce the power inefficiency of BF in OFDMA, in the way that user individual highly directive beams are carrying data from all users in the cell, we take another approach which partially solve this issue. If using a number of IDFTs equal to the number of antennas, the BS can transmit through that same number of beams to groups of users. So, what we do is to create clusters of users who are co-located. This means grouping the users spatially, i.e. define clusters of users that are close to each other, each beam can be set to acquire a shape that covers the users in that set and protects them from interference coming from other user sets in the cell. The process of grouping users into clusters, shall be undertaken by the BS using an algorithm that identifies DoA from the Channel State Information (CSI) and organizes the transmission radiation pattern according to an error criterion like MMSE. This clustering beamforming approach is employed in our studies.

IV. Transmit Diversity Vs Beamforming in DL Multi-User OFDM Systems

A. OFDM-TDMA System

In an OFDM-TDMA system, one complete OFDM symbol at a certain time is allocated to a user [6]. If there are U users in the system and if all users require same bit rate services, we can assign every $(lU+1)^{\text{th}}$ OFDM symbol to U^{th} user ($l = 0, 1, \ldots$). Keeping in mind that STBC algorithm requires more than one consecutive OFDM symbols for orthogonal transmission (to be exact, P number of consecutive OFDM symbols for $P \times 1$ STBC-OFDM-TDMA system), it is clear that STBC orthogonal blocks need to be implemented with data from different users. This will mean that though an OFDM symbol slot is not allocated to any user, that particular user has to receive the data in that slot to decode STBC blocks. This is not desired, so we propose to use SFBC algorithms in OFDM-TDMA systems for transmit diversity purposes. In this case, only one user at a time is involved in the transmission process and so the benefits of OFDM-TDMA is preserved.

It is fairly easy to implement beamforming algorithms in OFDM-TDMA systems. Because the data carried by one whole OFDM symbol is intended for one single user, it is possible to direct the transmitted signal at that symbol duration to the direction of respective user. So, the goals of beamforming is preserved, i.e. only the involved user's data is directed to concerned user and interference to other users is reduced.

B. OFDMA System

In OFDMA system, users are separated across subcarriers. So, if the subcarrier allocation is kept static for at least μP number of OFDM symbols (or even if it is dynamic allocation via subcarrier hopping for each OFDM symbol), then the creation and transmission of orthogonal transmit block is done simply by implementing the algorithm across OFDM symbols. Here, we denote transmit diversity coding rate as μ. As usual, it will not change any OFDMA properties, only that it will increase the latency of detection process (which is typical to any STBC algorithm). Similar to this, SFBC can also be used in OFDMA system, satisfying the condition that the users are allocated contiguous subcarriers and the number of subcarriers assigned to one user, $\eta = l\mu P$, where $l \in [1, \ldots, \lfloor \frac{N}{\mu P} \rfloor - 1]$.

As it is discussed in the previous section, traditional beamforming can be applied in OFDMA system, only to increase the range, but not to decrease the multi-user interference. It is also worth noting here that if the users are homogeneously distributed over the whole cell area, then DL BF in OFDMA system will not bring any extra benefit to the system.

V. Simulations

A. Channel Model

Indoor (micro and pico cells) and outdoor (macro cells) wireless channels for low and high user mobility are considered at 5GHz carrier frequency. For indoor channel delay profiles, we use HiperLan/2 channel model A, corresponding to a typical office environment for NLOS conditions and 50 ns average rms delay spread [7]. For outdoor delay profiles, we use typical urban 12-path channel model [8, Appendix-E].

B. Angular Spread and Spatial Correlation

Angular spread (AS) is a measure of the angular dispersiveness of DoAs. AS is usually higher in indoor scenario, whereas it is smaller in urban macro scenario.

This characteristic makes it difficult to get the most out of angle diversity in outdoor channels, hence BF could be an interesting option to follow. On the other hand, in indoor channels, due to a broader AS, the multipath signals have low correlation between them, therefore angle diversity can be effectively exploited. Furthermore, BF may not be suitable for indoor scenarios, since there is no narrow beam to increase SNR and separate from neighbouring interferers.

The rays departing from BS are spread over a certain AS. The spatial covariance matrix is characterised on the geometry relevant to a certain Direction of Departure (DoD) profile which is represented by (5) [9].

$$\mathbf{R} = \sum_{l=1}^{L} \mathbf{a}^H(\theta_l)\mathbf{a}(\theta_l) \quad (5)$$

$$\mathbf{a}(\theta_l) = [1, \exp(-j\alpha_l), ..., \exp(-j(P-1)\alpha_l)] \quad (6)$$

$$\alpha_l = \frac{2\pi}{\lambda} d \sin\theta_l \quad (7)$$

where L is the number of rays emitted from the BS, $\mathbf{a}(\theta_l)$ is the directional vector dependent on azimuth direction θ_l of the l^{th} ray and P is the number of transmit antennas.

The channel covariance matrix $\mathbf{R}$ can be decomposed into eigenvectors and eigenvalues; and the correlated channel vector for multiple transmit antennas and single receive antenna can now be written as [9]:

$$\mathbf{g}_p^R = \mathbf{Q}\mathbf{\Sigma}^{1/2}\mathbf{g}_p \quad (8)$$

where $\mathbf{g}_p$ and $\mathbf{g}_p^R$ are independent channel impulse response vector and correlated impulse response vector for p^{th} transmit path respectively. $\mathbf{Q}$ stands for the matrix which is composed with eigenvectors and $\mathbf{\Sigma}$ contains eigenvalues in diagonal locations for covariance matrix.

C. Simulation Parameters

Indoor micro-cell and outdoor macro-cell scenarios are considered for DL in our simulations. Simulations are performed for a single cell system to simplify the analysis. Obviously this means that no Co-Channel Interference (CCI) is present in the system. The simulation parameters are listed in Tab. 2.

In both transmit diversity approaches, STBC and SFBC, the antenna spacing has to be such that low correlation between signals is achieved at MS, hence it was chosen to use $d = 5\lambda$, since at the BS there are no space constraints as at the MS. However, since the performance of STBC and SFBC does not change much, to undertake this comparison, it has only been taken STBC into account. Regarding BF, in order to obtain a narrow beam, the antenna elements must be placed closely, hence the spacing chosen was $d = \lambda/4$.

	Indoor	Outdoor
Max delay spread [10]	≤0.5μs	5μs
Max angular spread [10]	360^o	20^o
System bandwidth	20MHz	
Carrier frequency	5.0GHz	
OFDM subcarriers, N	64	1024
Data subcarriers	52	832
Null subcarriers	12	192
Subcarrier spacing, kHz	312.5	19.53125
CP length, N_g	16	200
OFDM Symbol Duration, $T_s = T_u + T_g$, μs	4	61.2
Useful data period, T_u, μs	3.2	51.2
CP period, T_g, μs	0.8	10
Sampling duration, T, ns	50	50
Symbol mapping	QAM	QAM
Channel coding	$\frac{1}{2}$-rate Convolutional coding	
Data rate, Mbps	13	14.2
User velocity, kmph	3	50
Doppler spread, Hz	13.9	231.5
Coherence time, T_c, ms	30.5	1.8

Tab. 2. OFDM Simulation Parameters

VI. Performance Analysis and Comparison

STBC and BF applied to the multi-access schemes OFDM-TDMA and OFDMA are compared regarding their performance and implementation complexity. We assume that the synchronization requirement of the OFDM receiver is perfectly met and perfect Channel State Information (CSI) is present at the receiver.

Based on [10], AS was chosen for indoor channel as $[120^o, 240^o, 360^o]$. On the other hand, for outdoor channel, the AS was made to vary within $[5^o, 10^o, 20^o]$.

For these different values of AS, BER curves for STBC-OFDM system are presented in Fig. 3. The STBC was implemented with four antennas using Tarokh orthogonal code with half-rate. By analyzing the graph in that same figure, it can be seen that for indoor scenarios (higher AS) the performance is generally better than for outdoor scenarios (lower AS). This means that the advantage that can be taken out of the use of STBC is bigger in indoor environments than in outdoor scenarios, due to higher AS that makes the arriving signals from different spatial location less correlated. Hence, more reliability is achieved by combining those different sources of data.

The simulations were performed in an analogous way also for BF-OFDM system and the results are shown in Fig. 4. Unlike the previous case, it can now be seen that for BF, a smaller AS results in better performance of the system.

In order to compare which method better fits to each environment, the results presented in both previous figures were rearranged, showing in separate graphs the simulations for OFDM systems in outdoor and indoor case, Fig. 5 and Fig. 6, respectively.

From the results obtained in this work, it can be highlighted that in outdoor scenarios, BF performs better than transmit diversity in multi-user OFDM systems. It was confirmed that transmit diversity increases reliability of the received signals with the increase of AS. It has been noticed that in an outdoor environment, targeting a value for SNR of 6 dB in an environment with 20^o of AS, the use of an OFDM system with BF decreases the BER by more than 10^{-4} when compared to the performance of the same system using transmit diversity. Although the complexity of employing BF is much higher than the one for transmit diversity, it can be said that for outdoor environments, it is worthy.

What concerns to indoor environments, it was seen that transmit

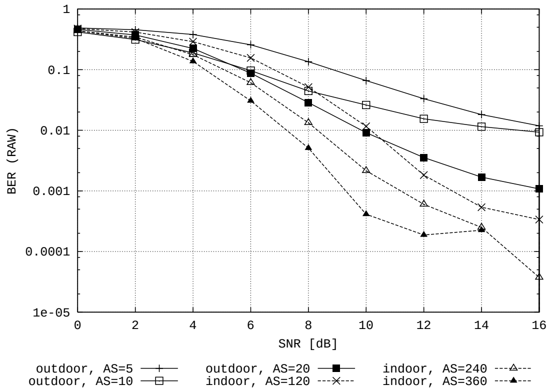


Fig. 3. BER performance for STBC/SFBC for different AS

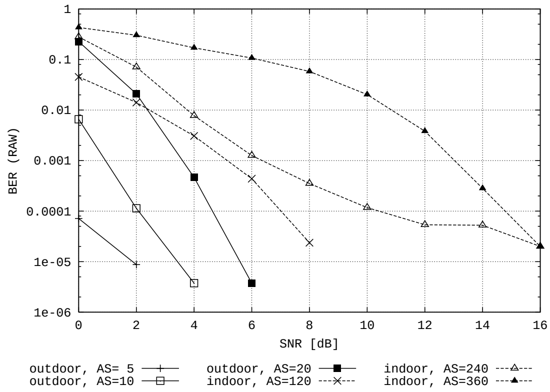


Fig. 4. BER performance for BF for different AS

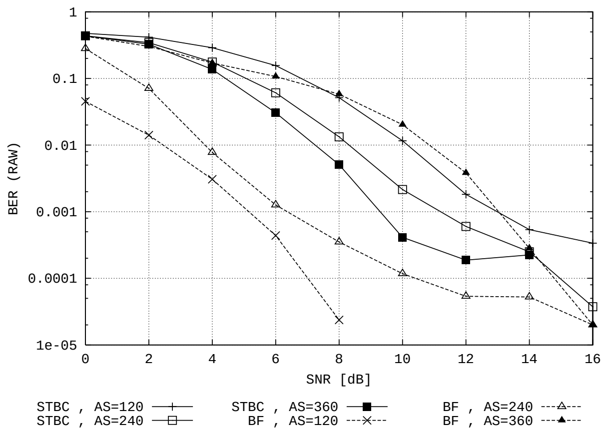


Fig. 5. BER comparison between BF and STBC for Indoor channel

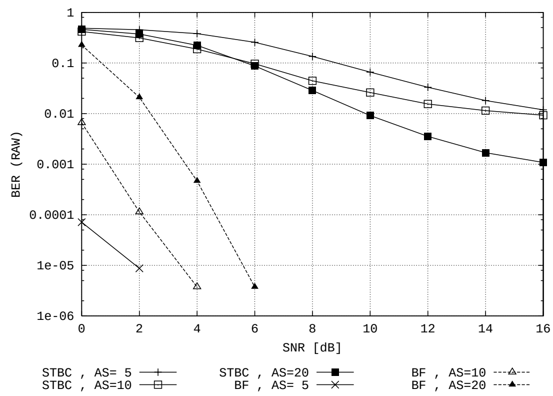


Fig. 6. BER comparison between BF and STBC for Outdoor channel

diversity not always performs better than BF. In some particular cases where the user is located in LOS in indoor environment, then BF certainly performs better than transmit diversity. But, one should keep in mind that when a strong LOS is present, then neither transmit diversity nor beamforming is actually required for system performance. However, even when it seems that employing BF would easily improve system's performance, one has to bear in mind that the complexity of this method is much higher than the simple transmit diversity scheme. Since the gain of employing BF in indoor scenarios is not so big as in outdoor, the strategy could pass for targeting a cheaper cost by employing transmit diversity. For instance, for a SNR of 12 dB and an AS of 240^o, the difference between techniques is around 10^{-1}, which may not justify the increase of cost and complexity.

VII. Conclusion

Regardless of the multiple access scheme, it is found that BF always performs better in outdoor environment, where AS is lower, thus spatial correlation is higher. Similarly, indoor environment (high AS and low spatial correlation) suggests that transmit diversity schemes are more suitable to employ than BF strategies.

Acknowledgements

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