High-Performance WLAN Architectures Using MIMO Technology in Line-of-Sight

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***Abstract*—This paper investigates the Packet-Error-Rate (PER) and throughput performance of WLANs in Line-of-Sight (LoS) conditions. A novel antenna array architecture is proposed as a way of overcoming the problem of excessive correlation under these conditions. The performance of systems designed with the proposed method is assessed by means of link-level simulations using channels generated from an appropriate stochastic MIMO channel model. The results are validated using MIMO measurements at 5.2 GHz in an anechoic chamber and in an indoor office environment. Our study shows that a very substantial performance enhancement is possible, compared to conventional MIMO arrays, when the proposed architecture is employed. The difference between the modelled and measured cases was less than 0.5 dB at a PER of 10^{-2}.**

***Index Terms*—WLAN, MIMO,Line-of-Sight communications.**

I. Introduction

At present, Wireless Local Area Networks (WLANs) are being deployed around the world at an increasing rate. These networks follow the IEEE 802.11 group of standards with some of the most popular variants being 802.11a and 802.11g, which are based on Orthogonal Frequency Division Multiplexing (OFDM) [1]-[3]. Given the increasing demand for higher spectral efficiencies, Multiple-Input Multiple-Output (MIMO) technology is expected to be incorporated into these standards as a method for providing additional capacity.

In this paper, work performed under the framework of the IST ASTRALS project, considering the specific case of MIMO WLANs in Line-of-Sight (LoS) conditions is presented. All investigations are based on a Spatial Multiplexing (SM) scheme that relies on transmitting independent data streams from each transmit antenna. Under specific propagation conditions, the data-rate in a MIMO system employing this scheme increases linearly with the minimum number of transmit and receive antenna elements [4]. This enhancement is achieved by the utilization of a number of spatial sub-channels between each set of transmit and receive elements. One example where this increase can occur is a (non-LoS) rich-scattering environment, where a large number of independent communications paths exists between the transmit and receive antenna elements.

When a LoS signal is present in the environment however, the performance of SM-MIMO systems is limited due to the statistical correlation between the received signals [5], [6]. This correlation results in very small variations on the spatial signature of the received signals and thus limits the number of independent communication subchannels. One way to overcome this problem has been presented in previous work and involves specific antenna array architectures that preserve the orthogonality between the received signals [7], [8]. In this paper we present an investigation of the performance of such structures in the context of a WLAN system.

The physical layer performance of such systems is investigated for a number of measured and modelled MIMO channels by means of a WLAN physical layer simulator employing MIMO techniques [2], [6]. The results are presented in terms of the PER and throughput performance for a number of channel scenarios corresponding to different propagation conditions.

II. WLAN Physical Layer

The physical layers of 802.11a and 802.11g are based on the use of OFDM, which is used to combat frequency selective fading and to randomize the burst errors caused by a wideband-fading channel. OFDM is implemented by means of an inverse Fast Fourier Transform (FFT). In detail, 48 data symbols and 4 pilots are transmitted in parallel in the form of one OFDM symbol. In order to prevent Inter-Symbol Interference (ISI), a guard interval is implemented by means of a cyclic prefix. When the guard interval is longer than the excess delay of the radio channel, ISI is eliminated. The physical layer provides several modes, each with a different coding and modulation configuration (Mode1: BPSK ½ rate, Mode2: BPSK ¾ rate, Mode3: QPSK ½ rate, Mode4: QPSK ¾ rate, Mode5: 16QAM ½ rate, Mode6: 16QAM ¾ rate, Mode7: 64QAM ¾ rate). These are selected by a link adaptation scheme. Further physical layer details can be found in [1], [2].

III. System Model of SM-MIMO

Spatial multiplexing, also known as Bell Laboratories Layered Space Time Architecture (BLAST), represents a direct exploitation of the available space-time resources [4], [9]. Maximum likelihood detection (ML) is the optimal method for minimizing the Bit-Error-Rate (BER) in SM schemes. However the main drawback of this detection technique is its complexity, since the system must perform M^{N_t} vector searches per subcarrier, where M is the number of symbols in the constellation. To reduce the complexity of such a detector, suboptimal techniques that range in performance can be used. These techniques range from linear processing techniques, such as zero forcing (ZF) and minimum mean squared error (MMSE) methods, to nonlinear techniques such as ordered successive interference cancellation (OSIC). In this study, ZF detection algorithms were used.

A. SM-MIMO Notation

In SM-MIMO systems the transmit vector **x** is usually expressed as:

$$\mathbf{x} = [x_1, x_2, \ldots, x_{N_t}]^T \tag{1}$$

where $(.)^T$ represents the transpose operation. In the case of OFDM, on a subcarrier by subcarrier basis, a multicarrier system can be considered analogous to a narrowband architecture and hence the transmit vector **x** applies per subcarrier. Assuming there are N_r receiving antennas, the received vector **r** can be expressed as:

$$\mathbf{r} = \mathbf{Hx} + \mathbf{n} \tag{2}$$

where **H** represents the channel matrix of size $N_r \times N_t$ and **n** represents an AWGN noise vector.

The channel matrix is given by:

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_t} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{bmatrix} \tag{3}$$

where $h_{i,j}$ are complex frequency responses in the case of OFDM. The ZF solution is then given by:

$$\hat{\mathbf{x}} = \left(\mathbf{H}^H \mathbf{H}\right)^{-1} \mathbf{H}^H \mathbf{r} \tag{4}$$

where $(.)^H$ represents the Hermitian transpose operation and **r** is the received signal vector.

B. Channel Model

A suitable channel model is required in order to investigate the performance of MIMO systems in LoS. For a LoS scenario it is common for the MIMO channel response matrix to be modelled as

$$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H}_{LOS} + \sqrt{\frac{1}{K+1}}\mathbf{H}_{NLOS} \tag{5}$$

where H_{LOS} is the matrix containing the free-space responses between all elements, H_{NLOS} accounts for the scattered signals and K (i.e. the Ricean K-factor) is equal to the ratio of the powers of the free-space and the scattered signals [10].

In free-space, the complex response between a transmit element q and a receive element p is equal to $e^{-jkd_{p,q}}/d_{p,q}$ (where k is the wavenumber (equal to $2\pi/\lambda$) and $d_{p,q}$ is the distance between the two elements) [11]. Assuming that the relative differences in path-loss are negligible, the normalized free-space channel response matrix of a MIMO system can be written as follows:

$$\mathbf{H}_{LOS} = \begin{bmatrix} e^{-jkd_{1,1}} & e^{-jkd_{1,2}} & \cdots & e^{-jkd_{1,N_t}} \\ \vdots & \ddots & & \\ & & & \\ e^{-jkd_{N_r,1}} & \cdots & \cdots & e^{-jkd_{N_r,N_t}} \end{bmatrix} \tag{6}$$

Thus, H_{LOS} is totally deterministic and depends only on the distances between each transmit and receive element.

On the other hand, the response of the scattered signals is not deterministic and is usually modelled as a stochastic process. In this study H_{NLOS} is modelled as a $\mathbf{C}^{N_r \times N_t}$ matrix with normally distributed, zero mean i.i.d. elements of unit variance [12].

IV. Full-Rank LoS Communications

As mentioned previously, the existence of a LoS signal in conventional MIMO systems is highly undesirable due to the excessive correlation between LoS signals. Contrary to these observations however, a number of studies have shown that the LoS response is not inherently correlated and that by using specifically designed antenna arrays the orthogonality of the received signals can be preserved. Under these conditions the signals arriving at each receive element are orthogonal and therefore, a number (equal to the minimum of the number of transmit and receive elements) of parallel and independent subchannels are effectively created between the transmit and receive arrays; thus realizing a full-rank H_{LOS} response. Under these conditions the capacity of the channel is higher than that of rich-scattering environments [13].

For the case of ULAs at both ends of a MIMO system a simple criterion has been derived that defines a number of array architectures with full-rank LoS responses [13], [14]. This is expressed by the following equation for a system with N_t transmit elements and N_r receive elements:

$$s_1 s_2 \approx \lambda\left(\frac{1}{N_t} + r\right)\frac{D}{\sin\omega \sin\theta}, r \in \mathbf{Z}^+ \tag{7}$$

In (7), $\mathbf{Z}^+$ corresponds to the set of positive integers and the angles ω and θ correspond to the geometry of Fig. 1.

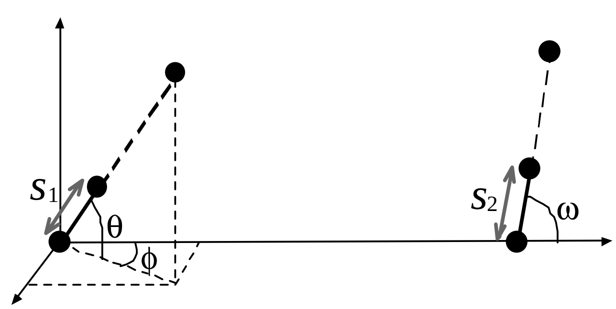

Figure 1 Uniform Linear Array orientations

Additionally, other work in this area has presented a derivation of a monotonous relationship between the BER in a ZF-MIMO system in LoS conditions and the determinant of H_{LOS}; thus showing that the criterion for full-rank H_{LOS} is equivalent to the criterion for minimum BER in a ZF-MIMO system in LoS [15]. Our contribution is the investigation of the physical layer performance of the proposed architectures in the context of WLANs.

V. Simulation Method and Results

Our study focuses on the investigation of the physical layer performance of the proposed architectures in comparison with standard array architectures. For this purpose, a WLAN physical layer simulator employing SM-MIMO techniques is used to evaluate the PER and throughput performance of a 2x2 MIMO WLAN in LoS. Two array architectures are employed in this study; the first corresponds to a system designed with the minimum BER criterion of (7) and has an inter-element spacing of 38cm, while the second corresponds to a conventional system with array spacing of half-wavelength. For both systems the distance between the Tx and Rx arrays is 5 m and the orientations of the arrays correspond to $\omega = 90^0$, $\varphi = 0^0$ and $\theta = 90^0$ of Fig .1. PER and throughput results have been produced for a number of different values of the *K*-factor. All channel response matrices have been generated using the combined stochastic and deterministic channel model of Section III-B.

A. PER Performance of proposed and standard systems

The PER performance of the proposed and standard methods for a number of values of *K*-factor are shown in Fig.2-3.

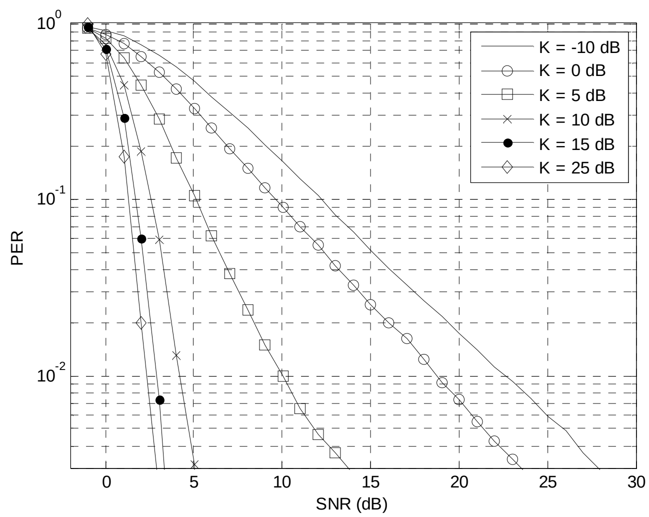

Figure 2 PER vs SNR for the proposed system as a function of the Rician *K*-factor (802.11a - mode 3)

From Fig.2-3 it is obvious that when a strong LoS signal exists (i.e. for large values of *K*-factor) there is a huge performance enhancement associated with arrays designed following the proposed architecture over conventional systems. For example, in the case of the *K*-factor being equal to 15 dB the difference in the required SNR at a PER of 10^{-2} is more than 30 dB.

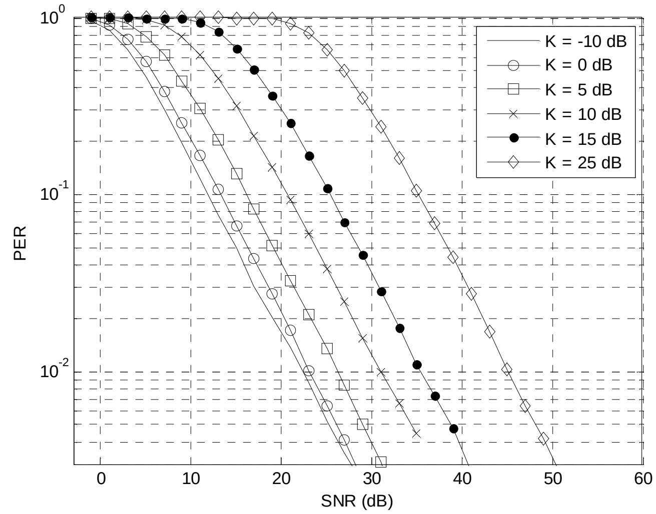

Figure 3 PER vs SNR for the standard system as a function of the Rician *K*-factor (802.11a - mode 3)

On the extreme of a very low *K*-factor the channel approaches the i.i.d. Rayleigh model that corresponds to a rich-scattering environment. Under these conditions the performance of both architectures converges.

B. Throughput of proposed and standard systems

Our second investigation involves the evaluation of the throughput performances of the proposed and standard methods for all the WLAN modes discussed in Section II. The results are shown in Fig. 4-5.

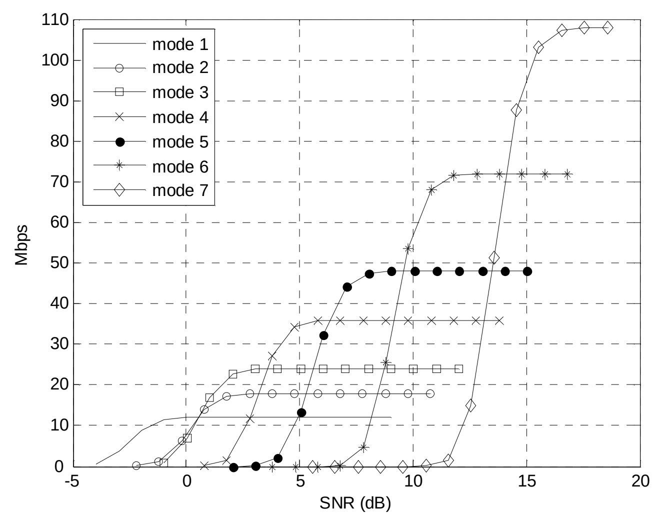

Figure 4 Throughput vs SNR for all modes in the proposed system (K = 15 dB)

Again, a very significant performance enhancement in the proposed system is observed. In detail, it was found that data-rates near the maximum limit of 108 Mbps where achieved at an SNR of 17 dB in the proposed system, whereas the same data-rate required an SNR of 50 dB in the standard system (a difference of 33 dB). A summary of the above results and the results for a *K*-factor of 5 dB are shown in Table 1.

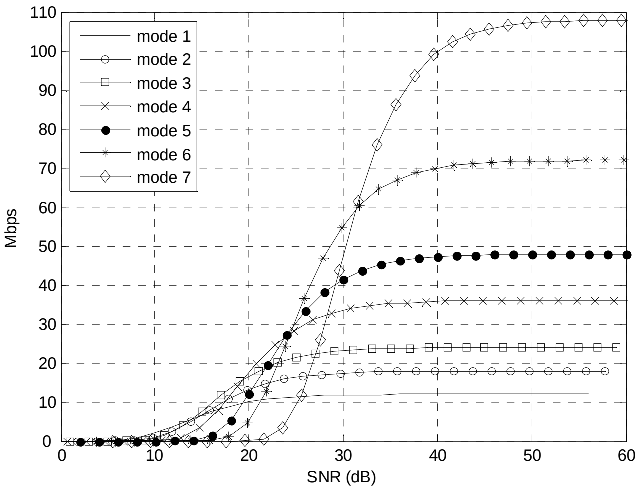

Figure 5 Throughput vs SNR for all modes in a standard system (K = 15 dB)

	SNR (dB)	**0**	**10**	**20**	**30**
K=5 dB	Standard (Mbps)	0.8	15.1	50.4	97.4
	Proposed (Mbps)	8.6	41.6	102.1	107.9
K=15 dB	Standard (Mbps)	0.0	1.9	17.6	55.2
	Proposed (Mbps)	12.1	56.4	108.0	108.0

Table 1 Throughputs of the standard and proposed architectures for K = 5 dB and K = 15 dB

It is interesting to note that even for a relatively small value of *K*-factor (K = 5 dB), a significant throughput enhancement in the order of a threefold and a twofold improvement (for SNR = 10 dB and 20 dB respectively) is possible using the proposed architecture.

VI. Measurement Results

In order to validate our theoretic investigation, two sets of measurements were performed at 5.2 GHz using a MEDAV RUSK BRI MIMO vector channel sounder (more details can be found in [16]). The first measurement set was taken in an anechoic chamber (Fig. 6a-b), whereas the second was taken in an indoor office environment (Fig. 6c-d). In the anechoic chamber measurements there is virtually no scattering and the channel response is expected to approximate the free-space response of (6) very closely. Thus, such a measurement could verify the fundamental validity of our proposed architecture. On the other hand, by performing a MIMO measurement in an indoor environment the practical performance of the proposed method could be evaluated.

A. Array Architectures and Post-Processing

The antenna arrays employed in both measurements were two identical ULAs each composed of four dual-polarized patch elements separated by 38 cm. For the purposes of our investigation however, only a 2x2 subset (elements tx_2, tx_3 and rx_2, rx_3) from the full 4x4 configuration was considered. At this carrier frequency the aforementioned spacing corresponds to the first (i.e. for r = 0) solution of (7). Each measurement was performed at a T-R separation distance of 5 m with $\omega = 90^0$, $\varphi = 0^0$ and $\theta = 90^0$. The MIMO channel response matrix was recorded for 1024 time snapshots. In the post-processing stage the channel matrix was normalized so that the effect of the array architectures is studied independently of the path-loss. The normalization was performed using the following equation:

$$E\left\{\left\|\mathbf{H}\right\|_F^2\right\} = N_t N_r \qquad \textbf{(8)}$$

In the above expression $E\{\ \}$ corresponds to the expectation operation and $\|\ \|_F$ represents the Frobenius norm. In physical terms, this normalization corresponds to a system with perfect power control [17].

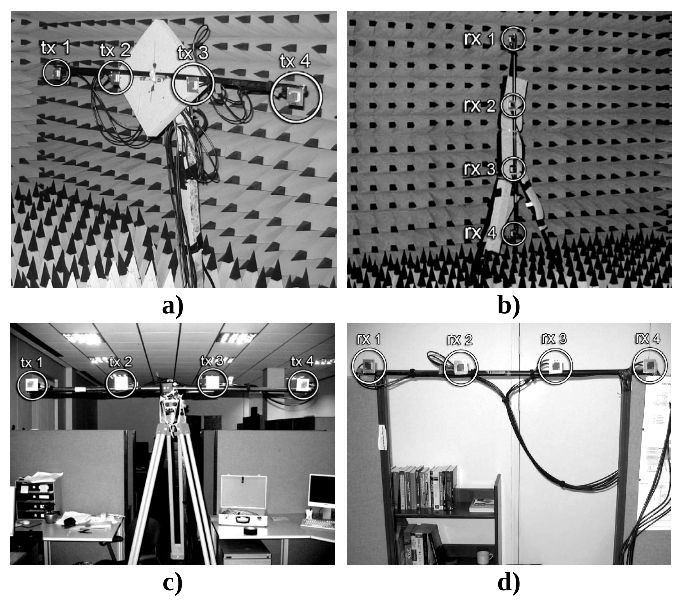

Figure 6 Array structures **a)** anechoic Tx **b)** anechoic Rx **c)** indoor Tx **d)** indoor Rx

The resulting PER performance from the indoor and anechoic chamber measurements are shown in Fig. 7. The *K*-factors were measured (using the method of [18]) in the anechoic and indoor environments and were found to be equal to 31.7 dB and 28.8 dB respectively.

Obviously, the measured PER performance shows close agreement with the results in Section V-A. It is very interesting to observe that the high *K*-factor in the indoor environment resulted in a performance very close to the (ideal) scenario of the anechoic chamber.

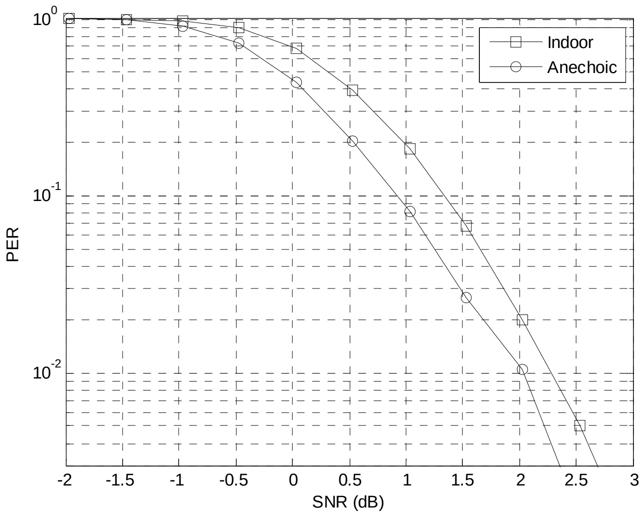

Figure 7 PER vs SNR for measured and modelled channels

VII. Conclusion

The performance of a novel architecture for MIMO communications is LoS conditions was assessed in the context of a WLAN system by means of stochastically modelled and measured MIMO channels using an appropriate WLAN physical layer simulator with SM-MIMO extensions. The performance of the proposed system showed a very significant performance improvement over conventional MIMO systems in LoS. Especially for high values of *K*-factor, the proposed system achieved a throughput which was several times higher than that from a conventional system. The theoretic predictions were validated from MIMO channel measurements where the expected results were recreated for a system designed with the proposed architecture. A difference of less than 0.5 dB was observed between the PER curve of the measured channels and that of the theoretic predictions.

Acknowledgment

This work was performed under the ASTRALS project for Mitsubishi Electric ITE-VIL. The authors would like to thank Dr. Paul Ratliff and Mr. Rob Heaton, in particular, for a number of stimulating technical discussions.

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