Simple correlated channel model for ultrawideband multiple-input multiple-output systems

J. Adeane, W.Q. Malik, I.J. Wassell and D.J. Edwards

Abstract: A simple correlated channel model for ultrawideband (UWB) multiple-antenna systems is proposed. The authors show that a single numerical value of the spatial correlation coefficient is sufficient to accurately model the performance of UWB spatial multiplexing systems in an indoor environment. The appropriate value of the correlation coefficient is selected by ensuring a close match between the bit error rate results achieved on the proposed correlated channel and those on the measured indoor channel. The authors also experimentally confirm that the performance substantially degrades in the presence of high values of spatial correlation for a range of spatial multiplexing receivers, and quantify the relationship between this degradation and the value of the spatial correlation coefficient. Thus, a route for the development of the existing standards for single-antenna UWB channels to the multiple-antenna regime is provided here.

1 Introduction

The demand for high data rate, low cost and low power systems has brought to prominence research interest in ultrawideband (UWB) communications [1]. Aimed primarily for short-range and high-bandwidth data transmission in wireless personal area networks (WPAN), UWB complements other longer-range radio technologies such as Wi-Fi, WiMAX and cellular wide area communications. The ability of UWB systems to resolve multipath components opens the way to greater diversity, and consequently reduced small-scale fading. Recently, UWB technology has been adopted for WPAN and sensor networks by the IEEE 802.15.3a and 802.15.4 standards.

In complimentary work, multiple-input multiple-output (MIMO) systems have been developed with the aim of delivering high data rates or increasing the robustness without the use of additional power, bandwidth or time slots [2]. Narrowband MIMO technology has been incorporated in the IEEE 802.11n wireless local area network (WLAN) standards. Extending MIMO to the UWB regime in [3], we demonstrated a large gain in the channel capacity, robustness and coverage radius of UWB indoor communications systems with the use of multiple antennas. In [4], we proposed and analysed various detection techniques for UWB MIMO spatial multiplexing (SM) systems. The space–time coding implementation of MIMO was applied to UWB in [5], and significant performance improvement was reported.

Various channel models have been proposed for use in the single-input single-output (SISO) UWB environment (see [6] for a review). To extend the model to the MIMO environment, we primarily need to take into account the spatial correlation, since in many practical situations sparse scattering and insufficient spacing between adjacent antennas can cause correlation between the received signals. For example, in the narrowband transmission results presented in [7, 8], it is shown that spatial correlation degrades both capacity and bit error rate (BER) performance. Consequently, a tractable correlated MIMO UWB channel model is essential when developing multiple-antenna UWB systems in order to accurately predict their performance.

There have been numerous correlated channel models applicable for narrowband transmission reported in the literature. For example, the authors in [9] proposed a stochastic MIMO channel model for picocellular and microcellular environments, while in [10], the authors examined the spatial correlation in MIMO channels at 5.2 GHz in an office environment and compared the measurement data with the results generated using a stochastic MIMO channel model. It is also worth noting that a fixed, distance-independent correlation model was adopted in the IEEE 802.16 standard for fixed broadband wireless access [11].

In this paper, we propose a constant (i.e. distance-independent) spatial correlation model for MIMO UWB systems with linear array structures, and then examine the effect of channel correlation on the performance of various detection schemes. We select an appropriate value of correlation coefficient by ensuring close correspondence between the BER results on the proposed correlated channel model with those on the measured indoor channel. We also present BER results for various MIMO UWB systems using our proposed model for various values of the channel correlation coefficient. Although our results are based mainly on the analysis of system performance in the SM context, the proposed correlated channel model can be applied to MIMO UWB systems in general.

2 System model

The general concept of an MIMO system is illustrated by Fig. 1. The MIMO UWB channel can be represented as $\boldsymbol{H}^{(\mathrm{UWB})} \in \mathbb{C}^{N\times M\times F}$, where M, N and F are the number of

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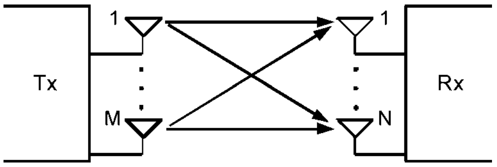

Fig. 1 *MIMO system block diagram*

transmit antennas, receive antennas and frequency components, respectively, following the approach in [3]. $\boldsymbol{H}^{(\mathrm{UWB})}$ can be seen as a frequency-domain row vector, each of whose elements is the flat-channel (i.e. narrowband) MIMO matrix, $\boldsymbol{H}^{(f)}$, at frequency $f \in \{f_l, \ldots, f_h\}$, where f_l and f_h define the lower- and upper-end frequencies of the channel transfer function, considering a discrete frequency representation. By applying the concept of multicarrier MIMO systems, also widely known as MIMO-OFDM, we can reduce the UWB channel into a set of parallel flat channels, each centered at a given frequency component. Using this approach, for a given f, the $M \times N$ system can be written as

$$\boldsymbol{y}^{(f)} = \boldsymbol{H}^{(f)}\boldsymbol{x}^{(f)} + \boldsymbol{n}^{(f)} \tag{1}$$

where $\boldsymbol{x}^{(f)} = \left[x_1^{(f)}, x_2^{(f)}, \ldots, x_M^{(f)}\right]$ and $\boldsymbol{y}^{(f)} = \left[y_1^{(f)}, y_2^{(f)}, \ldots, y_N^{(f)}\right]$ are the transmitted and received signal vectors at f, respectively, $\boldsymbol{n}^{(f)} = [n_1^{(f)}, n_2^{(f)}, \ldots, n_N^{(f)}]$ is the zero-mean complex Gaussian noise vector with unit variance, and $\boldsymbol{H}^{(f)}$ is the spatial channel matrix comprising the flat-fading coefficients. The channel in the above expression is normalised so that each underlying flat SISO channel has unit power [3]. Also note that in this SM system, $x_m^{(f)}$, $m = 1, \ldots, M$, are the data bits originating from the transmit antennas. To make the comparison fair, we keep the total transmit power the same in all the cases considered.

3 Spatial correlation model

We model the correlation between MIMO sub-channels within the framework of the separable correlation model, that is with the assumption that the correlation among the receive antennas is independent of the correlation between the transmit antennas. This can be justified by considering that only the immediate surroundings of the antenna array contribute to the correlation between array elements, and have no impact on correlations observed between the elements of the array at the other end of the link, which is a reasonable assumption for an indoor propagation environment. In our treatment, the effect of antenna coupling is neglected, and we focus only on the spatial correlation. We can include the correlation into the MIMO UWB channel model by introducing fixed transmit and receive correlation matrices following the well-known Kronecker model, so that [2]

$$\boldsymbol{H}^{(f)} = \boldsymbol{R}_{rx}^{1/2}\boldsymbol{H}_w^f\boldsymbol{R}_{tx}^{1/2} \tag{2}$$

where $\boldsymbol{H}_w^{(f)}$ is a stochastic $N \times M$ matrix with independent, identically distributed complex Gaussian entries with zero mean and unit variance. The matrices $\boldsymbol{R}_{tx}$ and $\boldsymbol{R}_{rx}$ are the transmit and receive correlation matrices with dimensions $M \times M$ and $N \times N$, respectively. With $\boldsymbol{h}_n$denoting the nth row of $\boldsymbol{H}^{(f)}$ and $\boldsymbol{h}_m$ the mth column of $\boldsymbol{H}^{(f)}$, the correlation matrices in (2) can be evaluated as $\boldsymbol{R}_{tx} = \boldsymbol{h}_n^H\,\boldsymbol{h}_n$ for $n = 1, \ldots, N$ and $\boldsymbol{R}_{rx} = \boldsymbol{h}_m\,\boldsymbol{h}_m^H$, for $m = 1, \ldots, M$.

One way to compute spatial correlation is by gathering a large amount of MIMO measurement data in the target propagation environment. A disadvantage of this approach, beside the fact that it may be very time-consuming, is that it may be necessary to estimate a large number of correlation coefficients: in an $M \times N$ MIMO systems, there are MN spatial sub-channels, and correlating each pair of them would give rise to $(MN)^2$ correlation values.

Hence in this paper, we propose a simpler modelling approach that is shown to be sufficiently realistic to reflect the UWB MIMO channel statistics. To satisfy these requirements, we propose a fixed correlation matrix for the UWB MIMO channel similar to that proposed for the fixed broadband wireless channel [11]. Under this model, the correlation matrices in (2) are given by

$$\boldsymbol{R}_{tx} = \begin{bmatrix} 1 & r_{12}^{tx} & \cdots & r_{1M}^{tx} \\ r_{12}^{tx*} & 1 & \ddots & \\ \vdots & & \ddots & r_{12}^{tx} \\ r_{1M}^{tx*} & r_{1M-1}^{tx*} & \cdots & 1 \end{bmatrix} \quad \text{and}$$

$$\boldsymbol{R}_{rx} = \begin{bmatrix} 1 & r_{12}^{rx} & \cdots & r_{1M}^{rx} \\ r_{12}^{rx*} & 1 & \ddots & \\ \vdots & & \ddots & r_{12}^{rx} \\ r_{1M}^{rx*} & r_{1M-1}^{rx*} & \cdots & 1 \end{bmatrix} \tag{3}$$

where $(\cdot)^*$ denotes the conjugate operation. An alternative to the fixed correlation matrices is to use the distance-dependant correlation function as is proposed in [12] in the context of narrowband MIMO systems. Using an approximation function to calculate the fading correlation between two adjacent antenna elements, it can be shown that the correlation coefficients decay exponentially with the square of the inter-element distance [13]. The correlation matrices under the distance-dependent model are devised as follows [14]

$$\boldsymbol{R}_{tx} = \begin{bmatrix} 1 & (r_{12}^{tx})^4 & \cdots & (r_{1M}^{tx})^{(M-1)^2} \\ r_{12}^{tx*} & 1 & \ddots & \\ \vdots & & \ddots & r_{12}^{tx} \\ (r_{1M}^{tx*})^{(M-1)^2} & (r_{1M-1}^{tx*})^{(M-2)^2} & \cdots & 1 \end{bmatrix} \quad \text{and}$$

$$\boldsymbol{R}_{rx} = \begin{bmatrix} 1 & (r_{12}^{rx})^4 & \cdots & (r_{1|N}^{rx})^{(N-1)^2} \\ r_{12}^{rx*} & 1 & \ddots & \\ \vdots & & \ddots & r_{12}^{rx} \\ (r_{1M}^{rx*})^{(N-1)^2} & (r_{1N-1}^{rx*})^{(N-2)^2} & \cdots & 1 \end{bmatrix} \tag{4}$$

The fixed correlation matrices $\boldsymbol{R}_{tx}$ and $\boldsymbol{R}_{rx}$ appropriate for a particular environment can be determined by selecting the numerical values of r^{tx} and r^{rx}, such that a close match is obtained to the BER results achieved when conducting the system simulation using the measured indoor channel. The advantage of the fixed correlation model is its simplicity and its immediate application to the existing IEEE 802.15.3a standard, which specifies a modified Saleh-Valenzuela SISO channel model [6]. Note that our proposed model is considerably simpler than that put forward for the WPAN standard IEEE 802.11n [14], since in the latter case, the complex correlation coefficients are calculated for each resolvable tap based on an assumed power angular spectrum.

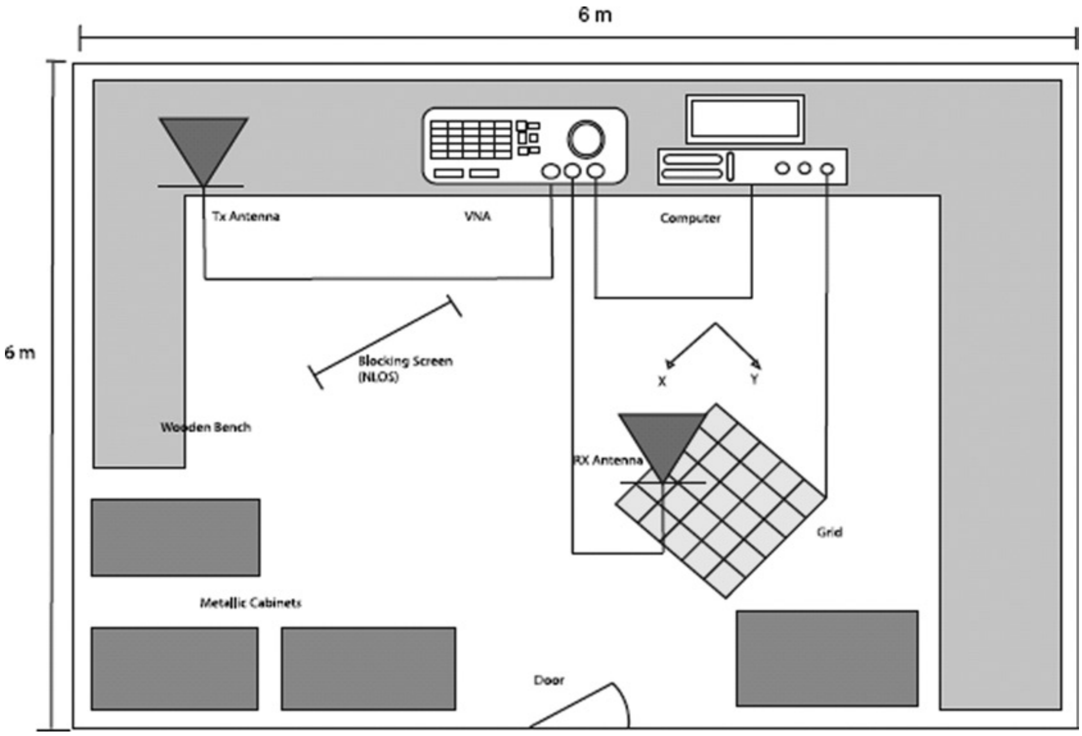

Fig. 2 *Indoor MIMO channel measurement environment*

4 UWB SM in correlated channels

4.1 Channel description and measurement setup

In this paper, we characterise the system performance using the BER as the metric. We employ two MIMO detectors, namely the zero forcing (ZF) linear receiver and the maximum likelihood (ML) nonlinear receiver [2]. The channel realisations are generated for comparison using both the proposed correlated channel model and those obtained from indoor measurements. Performance results follow a description of the channel models.

We modify the channel model in the IEEE 802.15.3a standard [6], which is formulated for SISO UWB. The standard describes four typical indoor operating environments, referred to as channel models 1–4 (CM1–CM4). We concentrate on the short-range indoor environment, both short-range line-of-sight (LOS) and non-line-of-sight (NLOS), as that is likely to be a common scenario in a small office or home environment for applications such as wireless USB. These scenarios are referred to as CM1 (for LOS) and CM2 (for NLOS) in the IEEE 802.15.3a UWB channel model [6]. We thus generate the time-domain channel impulse response using the CM1 and CM2 models and use the discrete Fourier transform to obtain the frequency-domain UWB channel transfer function, $\boldsymbol{H}_w$. For each OFDM sub-carrier, f, the narrowband channel $\boldsymbol{H}_w^{(f)}$ is considered to be flat.

The indoor channels are measured with the use of a vector network analyser (VNA) operating in the UWB frequency band, 3.1–10.6 GHz, in an indoor office setting. The details of the measurement configuration can be found in Fig. 2. We measure the complex response at 1601 frequency points across the 7.5 GHz bandwidth of the UWB channel. The transmitter and receiver arrays are synthesised, each with up to three omni-directional antenna elements, using an automated positioning grid. The adjacent antennas are separated by 6 cm and the mean separation between transmitter and receiver antennas is kept at 4.5 m. The arrays are orientated to each other's broadside direction. In total, 960 spatial channel realisations are measured in an area of 1 m^2. For the LOS measurement, we maintain the LOS path throughout the measurement, to correspond to the CM1 model. For the NLOS measurement, we block the LOS path by a screen of RF absorbent material, to correspond to the CM2 model. Further details of the LOS and NLOS MIMO channel measurements can be found in [3].

4.2 Simulation results

The UWB system simulation results presented in this section are based on 2×2, 2×3, and 3×3 MIMO arrays. We use QPSK modulation and uncoded transmission over both the proposed correlated MIMO channel and the measured MIMO channel. The OFDM cyclic prefix is longer than the length of the multipath channel in order to avoid inter-symbol interference. We do not implement time–frequency interleaving.

Fig. 3 shows the BER results for $M = N = 2$, that is (2×2) for the systems operating in the modified CM1 channel with correlation coefficients $r^{tx} = r^{rx} = 0.4$ and also in the measured UWB LOS channel. The value of correlation coefficient that matches the measurement result is found by exhaustive search and is then rounded to one decimal place. It can be seen that the selected value of $r^{tx} = r^{rx} = 0.4$ gives BER results, which closely match those given by the measured channels. Note that the correlation value of 0.4 is specific to a particular measurement setting. However, the method is general and for any scenario, we can find a correlation value that matches the measurement results. For the measurement data used in this paper, the exact correlation coefficients have been reported in [3], where the mean correlation values are close to 0.4. Fig. 4 presents the BER performance results for a 2×2 MIMO system operating in an NLOS propagation environment. A similar trend as in the LOS case is observed, showing that the correlation model proposed is applicable to both LOS and NLOS indoor UWB environments.

Fig. 5 shows the performance of the proposed fixed and distance-based correlation model in a 3×3 system

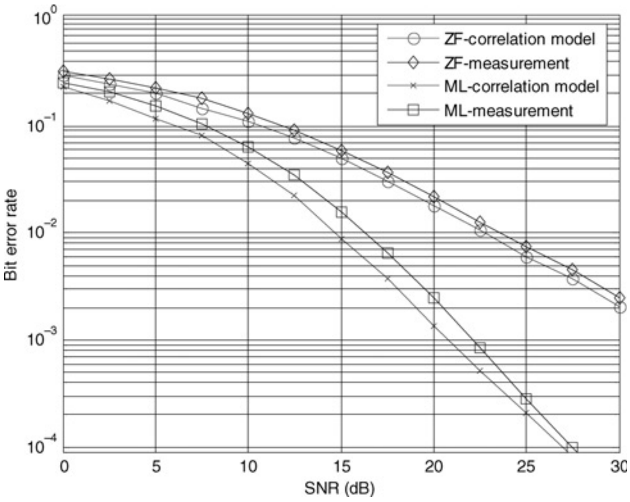

Fig. 3 *BER performance of 2 × 2 MIMO-UWB systems for various detection algorithms in the LOS indoor channel model (CM1) with $r^{tx} = r^{rx} = 0.4$ and for the measured LOS channel*

operating in the LOS environment. It can be seen that for a small array, the fixed correlation model closely approximates the performance achieved in the measured channel and does not differ appreciably from the performance of the distance-based model.

To see the effect of high correlation on the BER performance, we simulate the CM1 model with correlation coefficients $r^{tx} = r^{rx} = 0.8$. It can be seen from Fig. 6 that although the spatial correlation does not significantly affect the diversity order, it introduces a large SNR penalty, as is expected from wideband antenna diversity theory [1]. We note that the ZF receiver is particularly sensitive to spatial correlation, and a correlation coefficient of 0.8 degrades its performance by approximately 12 dB. On the other hand, the ML receiver suffers a penalty of 7.5 dB. These results demonstrate that it is essential to take spatial correlation into account when determining the performance of MIMO UWB systems, as it drastically impacts the achievable performance levels.

In Fig. 7, the proposed correlation model is applied to a 2 × 3 asymmetrical array configuration. Once again, it can be seen that the proposed model provides an accurate approximation of the measurement results. Comparing Figs. 3 and 7, it can be concluded that increasing the number of receive antennas in SM systems while keeping the number of transmit antennas fixed increases diversity, thus improving BER performance. On the other hand, Figs. 5 and 7 show that increasing the number of transmit antennas (up to N, the number of receive antennas) while keeping the number of receive antennas fixed increases the data rate at the expense of higher multi-stream interference, thus degrading the BER performance.

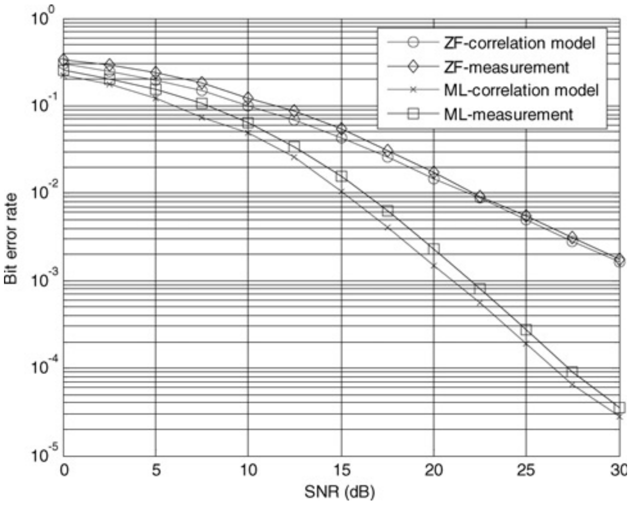

Fig. 4 *BER performance of 2 × 2 MIMO-UWB systems for various detection algorithms in the NLOS indoor channel model (CM2) with $r^{tx} = r^{rx} = 0.4$ and for the measured NLOS channel*

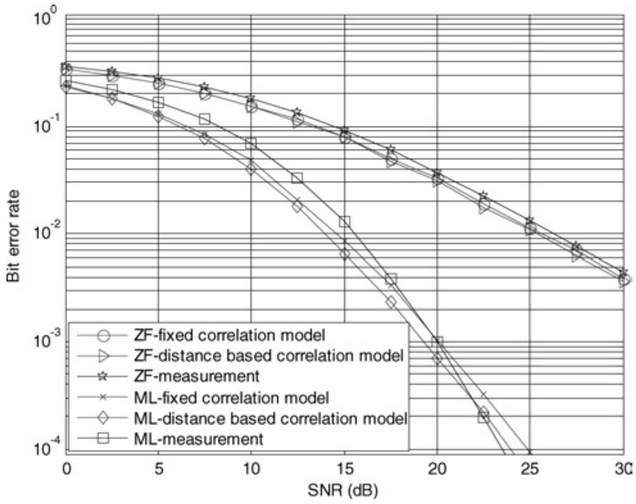

Fig. 5 *Comparison between BER performance of 3 × 3 MIMO-UWB systems for various detection algorithms in the LOS indoor channel model (CM1) with $r^{tx} = r^{rx} = 0.4$ and for the measured LOS channel*

Finally, Fig. 8 examines the case of a larger array size, that is 8 × 8. It can be seen that even for a reasonably large array size, the difference between the fixed and distance-dependent correlation models is less than 2 dB at high SNR. Thus, the performance prediction accuracy of the fixed spatial correlation model is maintained at large array sizes. For $r^{tx} = r^{rx} = 0.4$, there is a 7.5 dB difference between the BER results on the fixed correlated channel model and those on the independent channel. This observation emphasises the importance of taking correlation into account in devising a UWB spatial channel model.

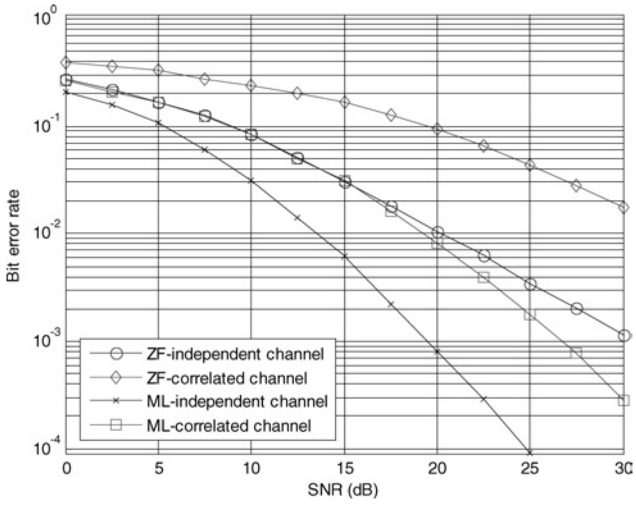

Fig. 6 *Comparison between BER performance of 2 × 2 MIMO-UWB systems for various detection algorithms in the LOS indoor channel model (CM1) with $r^{tx} = r^{rx} = 0$ (independent channels) and $r^{tx} = r^{rx} = 0.8$ (highly correlated channels)*

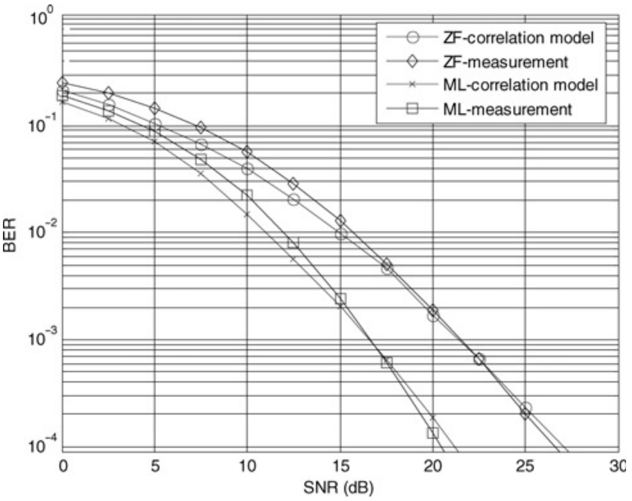

Fig. 7 *Comparison between BER performance of 2 × 3 MIMO-UWB systems for various detection algorithms in the LOS indoor channel model (CM1) with $r^{tx} = r^{rx} = 0.4$ and for the LOS measured channel*

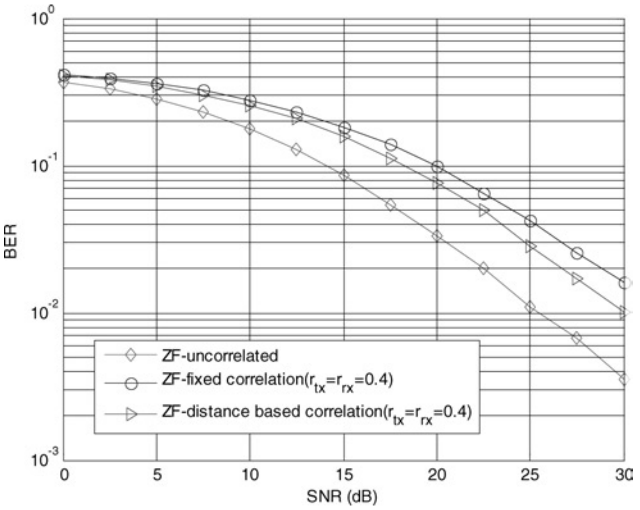

Fig. 8 *Comparison between BER performance of 8 × 8 MIMO-UWB systems in the LOS indoor channel model (CM1) generated by simulation based on fixed correlation and distance-based models*

From the results presented in this paper, it can be seen that MIMO spatial correlation is a significant factor in determining the BER performance, and our simple correlation model correctly predicts the performance of indoor multiple-antenna UWB systems.

5 Conclusion

We have proposed a fixed correlation model for the MIMO UWB channel and presented a comprehensive comparative analysis of this model with a distance-based spatial correlation model. A comparison between the BER results from measured channels and those based on our fixed correlation model show that the model can closely approximate the MIMO UWB indoor environment. It is found to be applicable to a variety of linear array configurations, specified by $M \times N$, for a range of values of M and N with $N \geq M$. In addition, the correlation coefficient in the proposed channel model is varied from 0 (independent channels) to 0.8 (highly correlated channel) in order to investigate the BER performance of the MIMO UWB receivers. When the correlation coefficient is increased from 0 to 0.8, it is observed that ML detector performance is degraded by 7.5 dB at BER $= 10^{-3}$. The BER performance of linear detectors is degraded even more severely due to spatial correlation, with an SNR penalty of 12 dB, and therefore it is important to take spatial correlation into account in practical UWB system design. Our proposed correlation model serves this purpose very well: it is simple enough with a single parameter to be estimated, yet it is accurate enough to correctly predict the MIMO UWB system BER performance in the indoor environment. Owing to its simplicity, our proposed correlated UWB MIMO channel model can be readily integrated with the existing IEEE 802.15.3a and other single-antenna UWB standards and channel models.

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7 References

1 Allen, B., Dohler, M., Okon, E.E., Malik, W.Q., Brown, A.K., and Edwards, D.J. (Eds.): 'Ultra-wideband antennas and propagation for communications, radar and imaging' (Wiley, London, UK, 2006)

2 Paulraj, A.J., Nabar, R., and Gore, D.: 'Introduction to Space-Time Wireless Communications' (Cambridge University Press, Cambridge, UK, 2003)

3 Malik, W.Q., Edwards, D.J., and Stevens, C.J.: 'Measured MIMO capacity and diversity gain with spatial and polar arrays in ultrawideband channels', *IEEE Trans. Commun.*, December 2007, **55**, (12)

4 Adeane, J., Wassell, I.J., and Malik, W.Q.: 'Error performance of ultrawideband MIMO spatial multiplexing systems'. Proc. IET UWB Symp. Joint with European UWB Radio Technology Workshop, Grenoble, France, May 2007

5 Yang, L., and Giannakis, G.B.: 'Analog space–time coding for multiantenna ultra-wideband transmissions', *IEEE Trans. Commun.*, 2004, **52**, (3), pp. 507–517

6 Molisch, A.F.: 'Ultrawideband propagation channels—theory, measurement, and modeling', *IEEE Trans. Veh. Technol.*, 2005, **54**, (5), pp. 1528–1545

7 Kyritsi, P., Cox, D.C., Valenzuela, R.A., and Wolniansky, P.W.: 'Correlation analysis based on MIMO channel measurements in an indoor environment', *IEEE J. Sel. Areas Commun.*, 2003, **21**, (5), pp. 713–720

8 Chiani, M., Win, M.Z., and Zanella, A.: 'On the capacity of spatially correlated MIMO Rayleigh-fading channels', *IEEE Trans. Info. Theory*, 2003, **49**, (10), pp. 2363–2371

9 Kermoal, J.P., Schumacher, L., Pedersen, K.I., Mogensen, P.E., and Frederiksen, F.: 'A stochastic MIMO radio channel model with experimental validation', *IEEE J. Sel. Areas Commun.*, 2002, **20**, (6), pp. 1211–1226

10 McNamara, D.P., Beach, M.A., and Fletcher, P.N.: 'Spatial correlation in indoor MIMO channels'. Proc. IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications, September 2002

11 Ercey, V., Hari, K.V.S., *et al.*: Channel models for fixed wireless applications' IEEE 802.16 Broadband Wireless, Access Working Group, June 2003

12 van Zelst, A., and Hemmerschmidt, J.S.: 'A single coefficient spatial correlation model for multiple-input multiple-output (MIMO) radio channels'. Proc. General Assembly of the Int. Union of Radio Science (URSI), Maastricht, The Netherlands, August 2002

13 Durgin, G.D., and Rappaport, T.S.: 'Effects of multipath angular spread on the spatial cross-correlation of received voltage envelopes'. Proc. IEEE Vehicular Technology Conf., Houston, TX, USA, May 1999

14 Erceg, V., Schumacher, L., Kyritsi, P., *et al.*: 'TGn channel models'. 'IEEE 802.11-03/940r2, January 2004