EUROPEAN COOPERATION
IN THE FIELD OF SCIENTIFIC
AND TECHNICAL RESEARCH

EURO-COST

COST 273 TD(05) 008
Bologna, Italy
January 20-21, 2005

SOURCE: Centre for Telecommunications Research
King's College London
Department of Engineering Science
University of Oxford

On the Spatial Correlation of MB-OFDM Ultra Wideband Transmissions

Junsheng Liu, Ben Allen, Wasim Malik and David Edwards
26-29 Drury Lane
London
WC2B 5RL
UK
Phone: +44 20 7848 2596
Fax: +44 20 7848 2664
Email: junsheng.liu, Ben.Alle@kcl.ac.uk; wasim.malik, david.edwards@eng.ox.ac.uk

On the Spatial Correlation of MB-OFDM Ultra Wideband Transmissions

Junsheng Liu, Ben Allen
Centre for Telecommunications Research, King's College London, London, UK
Wasim Q. Malik, David J. Edwards
Department of Engineering Science, University of Oxford, Parks Road, Oxford, UK

December 22, 2004

Abstract

Spatial diversity can be applied to Ultra Wideband (UWB) systems to achieve a higher bit rate. Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) breaks the UWB bandwidth into 13 sub-bands and the sub-bands into 128 narrow-band tones to achieve a high data rate from wide band systems. In this paper, the spatial correlation analysis is applied to a MB-OFDM system with one vertically polarized transmit antenna and two vertically polarized receive antennas. The analysis is supported by measurement results which show that an inter-sensor distance of 3cm is large enough to accomplish uncorrelated received signals for the given measurement environment.

1 Introduction

Since the Federal Communications Commission (FCC) assigned a bandwidth from 3.1GHz to 10.6 GHz for UWB usage, UWB signaling has become a candidate for high data rate transmission over short ranges. Applications of UWB wireless have been proposed with data rates from hundreds of Mbps to several Gbps over a range of 1 to 10m and even tens of meters [1], with a trade-off between range and data rate.

MB-OFDM is one of the two candidates proposed to the IEEE 802.15 task group 3a as a future signaling for UWB indoor transmission. The latest MB-OFDM proposal was released in September 2004. MB-OFDM provides a variety of data rates from 53.3 Mbps to 480 Mbps. Each MB-OFDM sub-band has 128 sub-carries and each sub-carrier occupies a bandwidth of 4.125MHz, which makes the channel appear much less frequency selective to these narrow-band signaling compared with the channel experienced by impulse radio UWB that occupies all of the available UWB spectrum.

Diversity combining has been developed over several decades as a means of increasing the wireless communication capacity. In [4], Brennan summarised the basic concepts and combination schemes for narrow band wireless communications with uncorrelated branches. In [5], Stein gives general equations for both dual-diversity selection combining and maximum ratio combining (MRC) schemes describing the effect of correlated fading across diversity branches. The two key parameters determining the diversity gain are: the level of the mean power difference between branches; and the correlation between them. Similar mean powers and low correlation leads to a good diversity performance [3]. In wireless communications, diversity techniques have become an essential means of enhancing the capacity, one of which is spatial diversity. In the case of spatial diversity, the closer the receivers are located together, higher signal correlation and lower level of mean power difference are experienced by the receivers due to similar scattering environments. In this paper, a simple tranceiver system consisting of one transmitter and two receivers is considered in order to access the spatial diversity performance of a MB-OFDM system. Since similar received mean power levels are often achieved in practical spatial diversity application, only the correlation of the received signals is analysed here.

The transeiver system considered here can be considered as a 1×2 Multi-Input-Multi-Output (MIMO) system. The correlation among the channels is the key to analysing capacity of the MIMO system. Higher order MIMO configuration can be applied to the UWB system to achieve in the future research, and the correlation analysis method can be based on the frame work presented in this paper.

The remainder of this paper is organized as follows. A brief introduction to MB-OFDM is given in section II. Details of the measurement environment are shown in section III, and the data analysis of the correlation coefficient among branches are given in section IV. Conclusions are given in section V.

2 Introduction to MB-OFDM

A brief introduction to MB-OFDM is given in this section. The focus is on the frequency allocation and signal structure of MB-OFDM.

2.1 Frequency allocation of MB-OFDM

In MB-OFDM systems, the bandwidth, ranging from 3.1GHz to 10.6GHz, is divided into 13 sub-bands, with a bandwidth of 528MHz for each [2]. The 13 sub-bands are numbered from 1 to 13, with number 1 having the lowest center frequency and number 13 the highest center frequency. All the bands are organized into four groups. Sub-bands 1 to 3 belong to group A, 4 to 5 group B, 6 to 9 group C and 10 to 13 group C. Group A is intended for first-generation devices, whilst the other three groups are reserved for future use.

For the proposed standard, an IFFT/FFT of size 128 points is used for OFDM signaling, which results in a sub-carrier frequency spacing of:

$$\Delta_F = 528MHz/128 = 4.125MHz \tag{1}$$

6 of the sub-carriers, including the DC component, are set to NULL. 10 of the remainer are used as guard carriers, 12 are used as pilot carriers, and the other 100 are used to bear data. A zero padding sequence with a length of 70.08ns (which is equivalent of 37 samples with sampling frequency 528MHz) is added to the output of the IFFT block. Hence an OFDM symbol at the output of the IFFT can be written as [2]:

$$s(t) = \begin{cases} \sum_{n=-N_{FFT}/2}^{N_{FFT}/2} C_n exp(j2\pi n\Delta_F(t) & t \in [0, T_{FFT}] \\ 0 & t \in [T_{FFT}, T_{FFT} + T_{ZP}] \end{cases} \tag{2}$$

where N_{FFT} is the size of the FFT, and C_n corresponds to the null inputs to the FFT block are set to zero. T_{FFT} is the IFFT/FFT period, which is equal to $1/\Delta_F = 242.42ns$. T_{ZP} is the zero padding duration, which is equal to $32/528MHz = 70.08ns$. Thus The length of an MB-OFMD symbol is $T_{FFT} + T_{ZP} = 312.5ns$.

2.2 MB-OFDM and frequency selective fading

In the time domain, one of the main advantages of an OFDM system is the ability to avoid Inter-Symbol-Interference (ISI) without using an equalizer. The length of one OFDM symbol (not including the zero padding sequence) is equal to $1/\Delta_F$, where Δ_F is the sub-carrier spacing. Δ_F is made small enough comparing to the channel coherence bandwidth, so that the OFDM symbol length is much larger than the channel delay, thus ISI is negligible compared with the symbol length.

3 Measurement Methodology

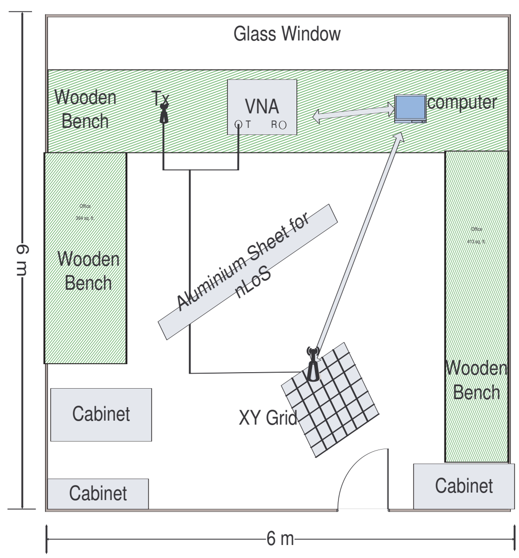

Figure 1: Measurement Environment.

In order to investigate the spatial correlation behavior of an MB-OFDM system, channel measurements have been carried out. The measurement plan is specified in this section, and in the following section the data is analysed based on the frequency allocation for the MB-OFDM system.

The measurement environment is shown in figure 1. The measurements were taken in an indoor environment typical of an office. The room is of a size of 6m by 6m, with concrete walls, floor and ceiling. It is a workshop and contains metallic and wooden objects, equipment and furniture. In order to maintain spatial and temporal stationarity no body enters the room and no object in the room moves when the measurement is in progress. The measurement process was completely automated, and calibration was completed before the measurement started.

Two identical, vertically polarised discone antennas were used for the measurement. The receive antenna was mounted on top of an xy-positioner while the transmit antenna was fixed. The positioner moved the receive antenna in a 1 m x 1 m square grid with a 0.01m spacing. At each point in this grid, the complex frequency transfer function was measured using a vector network analyser (VNA). The frequency span, f_{sweep}, covered the FCC UWB band, i.e., 3.1 GHz to 10.6 GHz. In this band, channel sounding was performed at $n_f = 1601$ individual frequencies, yielding a frequency resolution of $f_{res} = f_{sweep}/n_f = 4.6875$ MHz, which is close to the frequency spacing of MB-OFDM sub-carriers. The distance between the transmit antenna and the center of the measurement grid is 4.5m. Both the transmitter and the receiver were 1.5 m above the floor.

For the Light-of-Sight (LoS) data set, a clear line of sight was present, whilst for the non-Light-of-sight (nLoS) case, a large grounded aluminium sheet was placed between the transmit and receive antennas in order to block the direct path.

4 Data Analysis

In this section, an MB-OFDM channel model is constructed first before further analysis on the channel spatial correlation behavior.

4.1 MB-OFDM Channel Model

For each of the sub-carriers in the MB-OFDM system, the channel frequency function is flat enough to be considered as constant in $[f_n - \Delta_F/2,\ f_n + \Delta_F/2]$, where$f_n$ is the the n_{th} sub-carrier, and Δ_F is the frequency spacing between the adjacent sub-carriers. The channel transfer for a certain band can be modeled as followed:

$$H(f) = \sum_{n=-N_{FFT}/2}^{N_{FFT}/2} H_n \delta(f - n\Delta_F) \tag{3}$$

where H_n is the complex gain for the nth sub-carrier. The center frequency of the band is not considered in equation (3).

In an MB-OFMD system, only one band is used at anytime. Not considering the noise, the received MB-OFDM symbol in the frequency domain is given as follows:

$$R(f) = \int_{-\infty}^{\infty} s(t) e^{-j2\pi f t} dt \cdot H(f) \tag{4}$$

substituting (2) and (3) into (4) leads to

$$\begin{aligned} R(f) = & \sum_{n=-N_{FFT}/2}^{N_{FFT}/2} 2\pi C_n \delta(f - n\Delta_F) \cdot \\ & \sum_{n=-N_{FFT}/2}^{N_{FFT}/2} H_n \delta(f - n\Delta_F) \\ = & \, 2\pi \sum_{n=-N_{FFT}/2}^{N_{FFT}/2} C_n H_n \delta(f - n\Delta_F) \end{aligned} \tag{5}$$

In (5), $C_n H_n$ are the outputs of the FFT block on the receiver side. It can be seen that the magnitude of each received sub-carrier is the multiplication of the transmitted sub-carrier magnitude with the corresponding discrete channel magnitude gain. In the following discussion, the factor of 2π in equation (5) will not be considered since it plays the same role to all the frequency elements.

4.2 Spatial Correlation

The complex spatial correlation coefficient for the received signals carried by the n^{th} sub-carrier is given in equation (6):

$$\rho_s(n,d) = \frac{E\{\left(C_nH_i(n) - \overline{C_nH_i(n)}\right)\left(C_nH_j(n) - \overline{C_nH_j(n)}\right)^*\}}{\sqrt{E\{\mid C_nH_i(n) - \overline{C_nH_i(n)}\mid^2\}}\sqrt{E\{\mid C_nH_j(n) - \overline{C_nH_j(n)}\mid^2\}}} \tag{6}$$

where $H_i(n)$ and $H_j(n)$ are the discrete channel transfer functions for the two receivers with an inter-sensor distance of d.

No channel information is used at the transmitter side in MB-OFMD system, so that C_n and H_n are independent. Thus equation(6) can be simplified to equation (7):

$$\rho_s(n,d) = \frac{E\{\left(H_i(n) - \overline{H_i(n)}\right)\left(H_j(n) - \overline{H_j(n)}\right)^*\}}{\sqrt{E\{\mid H_i(n) - \overline{H_i(n)}\mid^2\}}\sqrt{E\{\mid H_j(n) - \overline{H_j(n)}\mid^2\}}} \tag{7}$$

The magnitude of the complex correlation coefficient, varying from 0 to 1, indicates how much the received signals from different branches are correlated with one another. In the rest of this paper, the correlation coefficient is referred to the magnitude as the complex correlation coefficient, i.e., $|\rho_s|$.

It can be seen from (7) that the correlation coefficient can be fully determined by the channel experienced by different sensors. The larger distance between the sensors results in less correlation between $H_i(n)$ and $H_j(n)$ and thus leads to a lower correlation coefficient. The effective dual-diversity action at low outage rates seems to hold for correlation coefficients as high as 0.8 [5], and systems with correlation coefficients of 0.5 can already bring remarkable diversity gain [7]. In [3] the correlation distance refers to where the spatial correlation coefficient drops to 0.7. In this paper, a correlation distance, d_c, is defined to satisfy $|\rho_s| = 0.6$. Sensors with distances larger than d_c are therefore considered uncorrelated.

For the narrow-band system, many works have been reported on theoretical spatial correlation dependent on inter-sensor distance and carrier frequency [3] [6]. Most of the work refers to base-station diversity in macro or micro cellular systems. Different scatter models lead to a different expression for the spatial correlation [6]. To the author's best knowledge, there is not yet a proper diversity model for indoor wireless communications and for UWB systems in particular.

The measurement data is processed using Matlab. In the data processing program, the expectation operation in the numerator of (7) is replaced by normalizing the sum of the conjugate multiplications of channel responses with a fixed inter-sensor distance d. The expectation operation in the denominator of (7) is replaced by averaging over all of the 100×100 receiver locations. The data processing procedure is shown in equation (8):

$$\rho_s(n,d) = \frac{\frac{1}{N_d}\sum\limits_{D_{ij}=d}\left(H_i(n) - \overline{H_i(n)}\right)\left(H_j(n) - \overline{H_j(n)}\right)^*}{\sqrt{\frac{1}{100\times 100}\sum\limits_{Rx_{loc}}\{\mid H_i(n) - \overline{H_i(n)}\mid^2\}}\sqrt{\frac{1}{100\times 100}\sum\limits_{Rx_{loc}}\{\mid H_j(n) - \overline{H_j(n)}\mid^2\}}} \tag{8}$$

where N_d is the number of pairs of receiver locations with a distance of d, D_{ij} is the inter-sensor distance between any two of the receiver locations, and Rx_{loc} is the aggregate of all the possible receiver locations. The processing result, $\rho_s[n,d]$, is a matrix containing all the correlation coefficients with different inter-sensor distances and frequency. Note that n is the index of the frequency and $(d-1)$cm is the inter-sensor distance. The actual frequency component is $3.1GHz + (n-1) \times 4.6875MHz$. The actual inter-sensor distance is $(n-1)cm$. The n^{th} row of matrix $\rho_s[n,d]$ is divided by $\rho_s[n,1]$, so that the spatial auto-correlation value, which is the correlation coefficient with an inter-sensor distance of 0, for each frequency component is normalized to 1.

4.3 Data Processing Results

The results of the data processing on the spatial correlation and the analysis based on the processing results are given as follows.

The matrixes of $\rho_s[n,d]$ for both cases of LoS and nLoS are plotted in Figs 2 and 3, respectively.

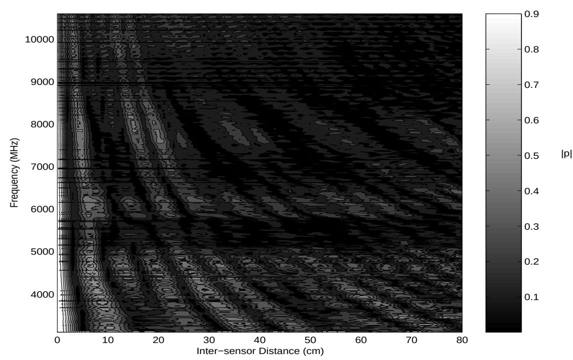

Figure 2: Correlation coefficient as a function of inter-sensor distance and frequency component, LoS, vertical polarized transmit antenna and vertical polarized receive antenna

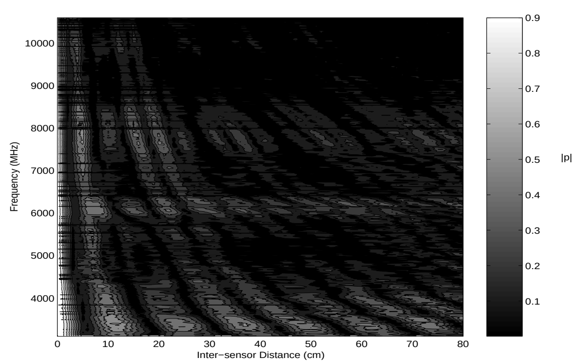

Figure 3: Correlation coefficient as a function of inter-sensor distance and frequency component, nLoS, vertical polarized transmit antenna and vertical polarized receive antenna

The frequency spans from 3.1GHz to 10.6GHz, covering the assigned UWB frequency range. The frequency resolution is 4.6875MHz, which is slightly smaller than the sub-carrier spacing specified in MB-OFDM. It can be seen that for all the frequency components the correlation coefficient decreases as d, the inter-sensor distance, increases. Although peaks can be observed as d increase, the correlation coefficient never exceeds 0.6 again after the first peak appears. It can also be seen that the correlation distance, d_c, where the correlation coefficient is 0.6, decreases slightly as frequency increases. Also, the peaks vanish to 0 much faster for high frequencies than for low frequencies. For the same range of inter-sensor distances, the peaks are less dense for the case of nLoS. Thus it can be predicted that the diversity performance for the case of nLoS is better than for LoS conditions.

Correlation coefficient with an Inter-sensor distance of 2cm is shown in fig 4. Although 2cm is usually not a practical spatial diversity distance considering the size of the antenna, fig 4 clearly shows the trend of decaying correlation coefficient as frequency increases. It can be seen that for a

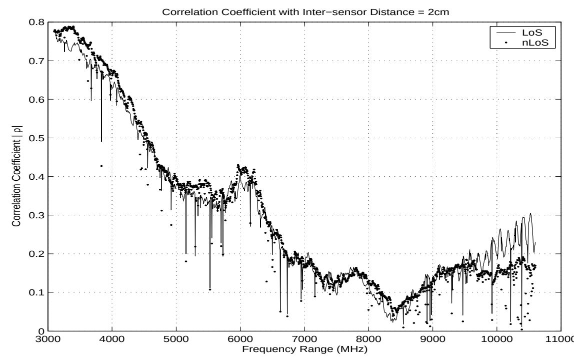

Figure 4: Correlation Coefficient for an Inter-sensor Distance of 2cm, LoS and nLoS

fixed inter-sensor distance, systems operating at low frequency have a higher correlation and thus benefit less from the spatial diversity.

Fig 5 shows how the spatial correlation distance behaves as a function of frequency of the MB-OFDM sub-carriers. It can be seen that for both nLoS and LoS cases, the spatial correlation

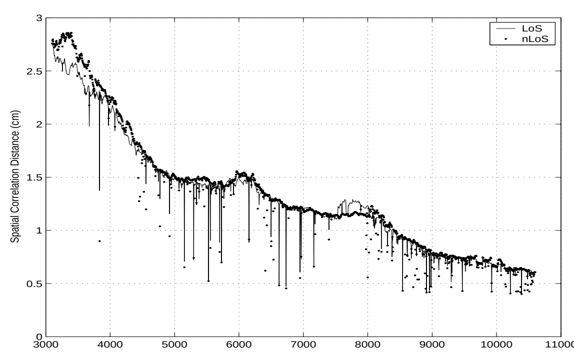

Figure 5: Spatial Correlation Distance vs the frequency

distance experiences similar behavior, decaying from around 2.8cm to 0.6cm as the frequency increases from 3.1GHz to 10.6GHz. According to the experimental results, an inter-sensor distance of at least 3cm on the receiver side satisfies the correlation requirement for all the frequency bands of the MB-OFDM system, assuming that $\rho_s \leq 0.6$. However, as shown in fig 2 and fig 3, for both cases of nLoS and LoS, the first peak of the correlation coefficient is very close to 0.6 at low frequencies, where the 3 bands of group A of the MB-OFDM system are located. Therefore a distance for the spatial diversity for MB-OFDM group A should be beyond the first peak. As shown in fig 2 and fig 3, 15cm is a practical choice and it is not difficult to accomplish for some indoor wireless applications, such as laptop and wireless speakers.

5 Conclusion

UWB channel measurements have been carried out and the data used to analyze the channel characteristics for a one-transmitter two-receiver spatial diversity system for MB-OFDM. As the data shows, each sub-carrier of the MB-OFDM can be treated as narrow band. Thus the received signal carried by each sub-carrier is the multiplication of the transmitted signal with the corresponding channel coefficient for the sub-carrier frequency. Based on this, the spatial correlation behavior over the whole UWB frequency range is analyzed. It is shown that 3cm is a theoretical correlation distance for all the MB-OFDM sub-carriers, while 15cm is a practical correlation distance for the MB-OFMD group A applications with correlation coefficient being less than 0.5 for both LoS and 0.45 for nLoS situation.

The measurements where is carried out in typical LoS and nLoS indoor environment.

6 Acknowledgement

Ben Allen gratefully acknowledges financial support provided by The Nuffield Foundation (NUF-NAL04) that has assisted in the preparation of this paper.

References

[1] Ian Oppermann, Matti Hamalainen and Jari Iinatti, "UWB Theory and Applications", Pub Wiley 2004, pp2

[2] MultiBand OFDM Physical Layer Proposal for IEEE 802.15 Task Group 3a, Sep 2004.

[3] Rodney Vaughan and Jorgen Bach Andersen, "Channels, Propagation and Antennas for Mobile Communications", Pub IEE 2003, section 8.4.2, pp 272

[4] D.G.Brennan, "Linear Diversity Combining Techniques", Proceedings of the IEEE, vol. 91, pp. 331–355, Feb. 2003.

[5] Mischa Schwartz and William R. Bennett and Seymour Stein, "Communication Systems and Techniques", Pub McGRAW-HILL BOOK Company 1966, pp 471

[6] James K. Cavers, "Mobile Channel Characteristics", Pub Kluwer Academic Publishers Inc. 2000, section 5.2, section 8.3

[7] Marvin K. Simon and Mohamed-Slim Alouini, "A Unified Permormance Analysis of Digital Communications with Dual Selective Combining Diversity over Correlated Rayleigh and Nakagami-m Fading Channels", IEEE Transaction on Communications, Vol. 47, No. 1, Jan. 1999