A Measurement Based Spatial Correlation Analysis for MB-OFDM Ultra Wideband Transmissions

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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 an indoor light-of-sight(LoS) and non-light-of-sight(NLoS) UWB channel with one vertically polarized transmit antenna and two vertically polarized receive antennas. The analysis is supported by measurement results which confirms that the subcarriers in MB-OFDM system can be treated as narrow band signals, and an inter-sensor distance of 3cm is large enough to accomplish uncorrelated received signals for the given measurement environment.

I. 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 signaling scheme for UWB indoor transmission. MB-OFDM provides a variety of data rates from 53.3 Mbps to 480 Mbps [2]. 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 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. 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. Because of the reciprocal property of the channel, the result of the correlation analysis for the receive diversity presented in this paper also applies for the transmit diversity.

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 as a function of frequency and space is given in section IV. Conclusions are given in section V.

II. Introduction to 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 in each sub-band, which results in a sub-carrier frequency spacing of:

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

Frequency hopping is achieved in MB-OFDM system to improve the performance by using using time frequency code [2], where different sub-bands are used in different time slots. In the first generation of MB-OFDM system, time frequency code is restricted among the 3 sub-bands in group A.

A. 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 $1/\Delta_F$. Δ_F is made small enough comparing to the channel coherence bandwidth, which will be shown in section IV, so that the OFDM symbol length is much larger than the channel delay, thus ISI is negligible compared with the symbol length.

III. MEASUREMENT METHODOLOGY

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 Fig.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.

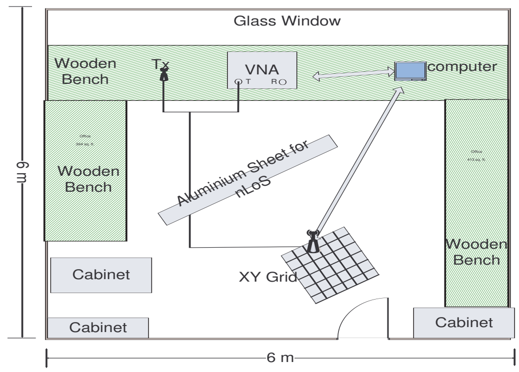

Fig. 1. Measurement Environment.

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, which is smaller than half of the wavelength corresponding to the central frequency of the UWB frequency range [1]. 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. It will be shown later that, as the frequency resolution is less than BW_c of the measured channels, the measurement data exhibits the properties of the channel experienced by the MB-OFDM system. 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 LoS data set, a clear line of sight was present, whilst for the nLoS case, a large grounded aluminium sheet was placed between the transmit and receive antennas in order to block the direct path.

IV. DATA ANALYSIS

In this section, the channel measurement data is analyzed to show the behavior of the coherence bandwidth and channel spatial correlation.

A. Coherence Bandwidth

The coherence bandwidth of the channels, BW_c, is compared with the sub-carrier spacing to see if the channel frequency response is flat across each sub-carrier. BW_c is closely related to the frequency auto-correlation function. Frequency auto-correlation function is also called the *spaced-frequency correlation function* in [4] and is defined as follows:

$$\rho(\Delta f) = E\{H(t_1, f) \cdot H^*(t_1, f - \Delta f)\} \tag{2}$$

where $H(t_1, f)$ is the channel transfer function at time t_1, * stands for complex conjugation, and Δf is the frequency difference to decorrelate $H(t_1, f)$ at different frequency f. The operation $E\{\cdot\}$ is carried out over the 100×100 possible receiver locations, which is shown in Fig.1.

For uncorrelated scatterers with the same delay, which is a very realistic assumption in practical case, $\rho(\Delta f)$ is only a function of Δf, not f itself [4]. The coherence bandwidth, BW_c, is defined to satisfy $\rho(BW_c) = C_{cor}$, where C_{cor} is a threshold. The signals with bandwidth larger than BW_c undergo frequency selective fading when passing through the channel. Since the assessment of coherence and distortion is subjective, there is no universal value for C_{cor}. The chosen value of correlation depends on the system designer and how sensitive the system is to frequency-selective fading. In this paper it is specified that $C_{cor} = 0.6$. However, values of 0.9 and 0.7 are also common.

The channel frequency auto-correlation function for both LoS and nLoS cases are given in Fig.2. The coherence bandwidths are found to be 31MHz and 29 MHz for nLoS case and LoS channels, respectively, in the given measurement environment. For both nLoS and Los channels, the coherence bandwidth is much larger than the sub-carrier spacing in MB-OFDM system, therefore confirms that each sub-carrier experiences flat channel fading in this environment and can be treated as a narrow band signal.

[1]The central frequency of the UWB frequency range is $f_C = \frac{f_H - f_L}{2} = 6.85GHz$. The wavelength corresponding to f_C is $\lambda_C = 0.044m$

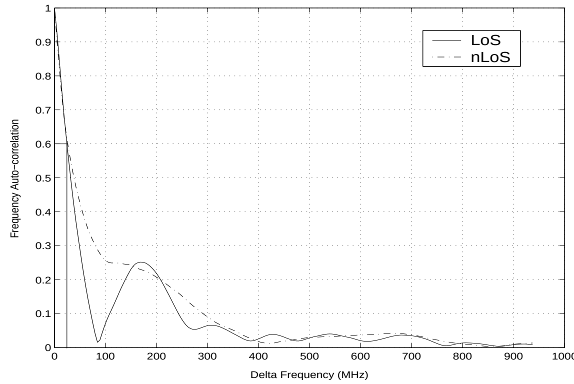

Fig. 2. Frequency Auto-Correlation Function for LoS and nLoS

B. Spatial Correlation

The complex spatial correlation coefficient for the received signals carried by the n^{th} sub-carrier is given in Eq.3 as follows,

$$\rho_s(n,d) = \frac{E\{\left(H_i(n) - \overline{H_i(n)}\right)\left(H_j(n) - \overline{H_j(n)}\right)^*\}}{\sqrt{E\{\mid H_i(n) - \overline{H_i(n)} \mid^2\}}\sqrt{E\{\mid H_j(n) - \overline{H_j(n)} \mid^2\}}} \tag{3}$$

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.

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 (3) 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 [6]. 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

$$\rho_s|_{d=d_c} = 0.6 \tag{4}$$

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] [4]. 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 [4]. To the author's best knowledge, there is not yet a proper diversity model for indoor wireless communications and for UWB systems in particular.

During data processing, the expectation operation in the numerator of (3) 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 (3) is replaced by averaging over all of the 100×100 receiver locations. The data processing procedure is shown in Eq.5 as follows,

$$\rho_s(n,d) = \frac{\frac{1}{N_d}\sum_{D_{ij}=d}\left(H_i(n) - \overline{H_i(n)}\right)\left(H_j(n) - \overline{H_j(n)}\right)^*}{\sqrt{\frac{1}{100\times 100}\sum_{Rx_{loc}}\{\mid H_i(n) - \overline{H_i(n)} \mid^2\}}\sqrt{\frac{1}{100\times 100}\sum_{Rx_{loc}}\{\mid H_j(n) - \overline{H_j(n)} \mid^2\}}} \tag{5}$$

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.

C. Data Processing Results

The results of the data processing on the spatial correlation, and the analysis for both correlation coefficient at fixed inter sensor distance and the spatial correlation distance based on the processing results are given as follows.

Correlation coefficient with an inter-sensor distance of 2cm is shown in fig 3. Although 2cm is usually not a practical spatial diversity distance considering the size of the antenna, fig 3 clearly shows the trend of decaying correlation coefficient as frequency increases. It can be seen that for a fixed inter-sensor distance, systems operating at low frequency have a higher

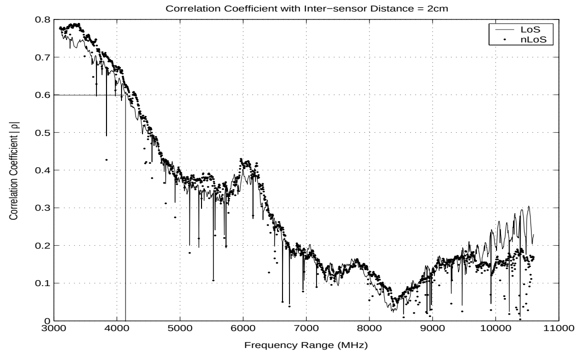

Fig. 3. Correlation Coefficient for an inter-sensor distance of 2cm, LoS and nLoS

correlation and thus benefit less from the spatial diversity. It is also shown that at an inter-sensor distance of 2cm, subcarriers with frequency lower than 4GHz suffer high spatial correlation ranging from 0.6 to 0.8.

Fig 4 shows how the spatial correlation distance, which is defined in Eq.4, 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 distance experiences similar

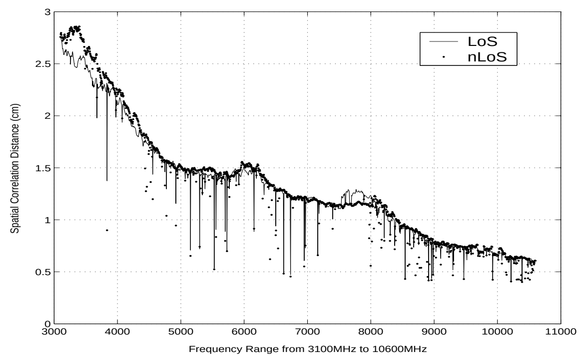

Fig. 4. Spatial Correlation Distance vs frequency

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 $\rho_s \leq 0.6$.

V. 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 in the given measurement environment since the sub-carriers spacing is less than the coherence bandwidth. 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 for a fixed inter-sensor distance, systems working in the low frequency bands assigned for the MB-OFDM benefit less from the diversity combining because of higher correlation coefficient. It is also shown that 3cm is a theoretical correlation distance for all the MB-OFDM sub-carriers.

The measurements were carried out in typical LoS and nLoS indoor environments. The results are applicable to transmit/receive diversity and multi-input-multi-output(MIMO) analysis for MB-OFDM UWB system.

VI. Acknowledgement

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