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Characterization of Indoor Channels with Directional Antennas and Performance Evaluation

Xiaoya Zuo and Ding Wang

School of Electronics and Information, Northwestern Polytechnical University, Xi'an, 710072, China
zuoxy@nwpu.edu.cn

Abstract

Recently UWB beamforming attracts significant research attention to obtain spatial gain in the form of antenna array. It is commonly believed that directional antenna based communication could improve the system performance. In order to further make clear the relationship between system performance and the antenna radiation pattern, UWB indoor channels extracted from practical measurements are combined with circular horn antenna to characterize the channel properties and to evaluate the system performance. The direction related channel parameters like angle of departure (AOD) and angle of arrival (AOA) are obtained by SAGE algorithm from the measurement results. Using directional antenna with a certain half power beamwidth (HPBW), the channel delay will decrease because the multipath components the receiver could collect are reduced. In the line of sight (LOS) environments, the channel capacity increases with the beamwidth decreasing and is always larger than that of an omnidirectional antenna. Similarly, the bit-error-rate (BER) performance of RAKE receiver is improved with the beamwidth becoming smaller. However in the non-line of sight (NLOS) environments, the conclusions are not so simple. The capacity and BER performance are not always better with directional antennas. And the variation trend between the system performance and the antenna beamwidth disappears. This is mainly because that there exist no dominant strong path components like in the LOS environments. This reminds us that when antenna beamforming is used to obtain array gain, the beamwidth should be carefully designed to obtain optimal performance, especially in the NLOS environments.

Keywords: *UWB, channel, directional antenna, performance*

1. Introduction

UWB technology has become an ideal candidate for short-range broadband indoor wireless communication systems due to its good characteristics of high data rate, low cost and low power consumption. During the past years, the UWB performances have been well researched from single antenna system to multiple antenna system. Especially the multiple antenna systems are well developed to obtain array gain, diversity gain, and multiplexing gain. However nearly all of the researches are based on omnidirectional UWB channels, which do not consider the antenna radiation pattern. In practice, directional communications with aperture antennas or antenna array are commonly implemented, especially for the antenna array beamforming systems. Because the system performances are greatly affected by the channel properties, a detailed characterization of UWB channels with directional antenna is essential to accurately evaluate the system performance.

The single input single output (SISO) UWB channels are well researched and the IEEE 802.15.3a [1] and IEEE 802.15.4a [2] standard channel models are created. Recently the main focus about UWB channel modeling is not on the indoor environments. The main

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focuses are on more specific or unique environments, for example the underground mine [3], the vehicle inside [4] and the body area [5], *etc*. And some papers consider the channel modeling in the mobile environments [6].

There are not too many considerations about the antenna direction in the past channel modeling or system performance evaluation literatures. Paper [7] shows how antennas influence MIMO channels and presents a comparison of spiral and dipole antennas in MIMO systems. It shows that the pattern of the single antenna elements strongly influences the MIMO capacity. In [8], 3D nonisotropic MIMO multicarrier propagation channels employing directional antennas are considered. The numerical evaluations show the impact of different parameters of the propagation environment as well as the employed antennas on the resulting cross-correlation function between two subchannels. It doesn't give the analysis between the system capacity or BER performance and the antenna radiation pattern. Paper [9] gives the detailed description of outdoor-to-in-car channel with directional antennas. In [10-11], performances of relay systems with directional antennas are analyzed. Paper [12] gives the detailed performance analysis about system with directional antenna array elements in fading channels. It shows that the MIMO system with directional antenna elements can provide robust performance under the multipath fading channel with inter-symbol-interference (ISI), and outperform the conventional smart antenna systems due to the use of directional antennas and utilization of multipath diversity gain. As far as we know, this is one of the few literatures on the performance analysis for array systems with directional antenna elements.

The above directional antenna related analyses are not based on UWB channels. For UWB indoor channels, some early literatures present some intuitive conclusions about channel characteristics with directional antennas [13-14]. With directional antennas, the number of multipath components will be reduced, which also induces smaller channel delay. Another result is that the large scale fading factor will increase for directional antennas. With these simple conclusions, we can not obtain insight into the detailed relationship between the system performance and the antenna direction properties. However this is very important for recent beamforming systems. Recently UWB array systems gain much attention. One research aspect is the design of delay element [15-16]. Another research focus is on the beamforming algorithms, such as genetic algorithm, neural network based algorithm and particle swarm optimizer based algorithm [17–20]. There are also some work about experimental investigations [21-22]. For the beamforming systems, the performances are greatly affected by the array beamwidth and the beam direction. The directional channel properties are related with many problems such as beamforming algorithm design, antenna selection, and adaptive antenna array reception, *etc*. So it is very important to investigate the directional channels and its relationship with the system performances.

In this paper, we will investigate the double directional channels and provide insight about the relationship between the system performance and the antenna radiation pattern. Firstly practical experiment measurements with omnidirectional antennas are performed based on the double directional channel models. Then direction-related parameters such as AOD, AOA, angle spread (AS) are extracted from the measurement results by the SAGE algorithm. It should be heightened that these parameters are associated with the omnidirectional antennas. With circular horn antenna radiation patterns, the maximum antenna gain is assumed to aim at the strongest multipath component direction. Channel parameters are extracted and compared with these circular horn antennas. At last system capacity and BER performance with directional antennas are analyzed and simulated. Also the results are compared with those of omnidirectional antennas. The analysis and simulation results provide detailed information about the directional channel characteristics and the system performance with directional antennas. The rest of this paper is organized as follows. Section II gives simple description of double directional channel models. Section III describes the measurement setup and scenarios. In Section IV, measurement results coupled with discussions are presented. Section V gives the capacity analysis and Section VI gives the BER performance analysis. Finally, Section VII provides some concluding remarks.

2. Double Directional UWB Channel Model with Directional Antenna

According to literatures, for the indoor environments, when the elevation angle is among ±40°, its impact can be discarded. So when the distance between the transmitter and receiver is two times larger than the room height, which promises that the elevation angle is small, the impact of elevation angle could be abandoned. Here we only consider the 2D channel model. Combining the directional spatial channel model (SCM) [23], the IEEE 802.15.3a standard channel model [24] and the directional antenna properties [8], the 2D UWB channel model with directional antenna can be described as

$$h(t) = \sum_{l}\sum_{k} G_T\left(\psi_{k,l,AOD}\right) a_{k,l} G_R\left(\psi_{k,l,AOA}\right) \delta\left(t - T_l - \tau_{k,l}\right), \quad (1)$$

where $a_{k,l}$ are the multipath gain coefficients, $G_T\left(\psi_{k,l,AOD}\right)$ and $G_R\left(\psi_{k,l,AOA}\right)$ are gains of antenna patterns for both the transmitter and the receiver, $\psi_{k,l,AOD} = \left(\theta_{l,AOD} + \phi_{k,l,AOD}\right)$ and $\psi_{k,l,AOA} = \left(\theta_{l,AOA} + \phi_{k,l,AOA}\right)$ are the AOD and AOA for the corresponding path component, $\theta_{l,AOD}$ and $\theta_{l,AOA}$ are the AOD and AOA for the lth cluster, $\phi_{k,l,AOD}$ and $\phi_{k,l,AOA}$ are the offset angles for the kth component of the lth cluster, T_l is the delay of the lth cluster, $\tau_{k,l}$ is the delay of the kth multipath component relative to the lth cluster arrival time T_l. According to the standard channel model and some empirical measurements, characteristics of indoor channels are commonly regarded as following:

- Cluster and component delays are distributed according to a Possion law.
- Component amplitudes are governed by log-normal distribution.
- $\theta_{l,AOD}$ and $\theta_{l,AOA}$ are uniformly distributed over [0, 2π], $\phi_{k,l,AOD}$ and $\phi_{k,l,AOA}$ are Laplacian distributed with a certain variance. The variance is determined by the measurement environment.

3. Measurement Setup and Campaigns

In order to investigate the channel characteristics, the channel measurements should be made to extract the channel impulse responses (CIR). An intuitive and efficient way of recording the CIR is to emit a very narrow pulse, and record the received signal by a digital sampling oscilloscope (DSO).The Hyberlabs HL9200 pulse generator is used for channel extraction, and the pulse character is shown in Figure.1. The pulse duration is about 2 ns and its spectrum is from 0.5 GHz to 2.5GHz with central frequency about 1.5 GHz. The diagram of measurement setup is shown as Figure 2. The TX an RX antennas are Electrometric EM-6865 biconical, omnidirectional antennas with vertical polarization. At the transmitter end, the pulse is generated and radiated by the antenna. At the receiver end, the received signal is first amplified by a low noise amplifier before sampling by the Agilent 81004A DSO. Then the data are processed by a personal computer. The synchronization is promised by the arbitrary waveform generator and the DSO.

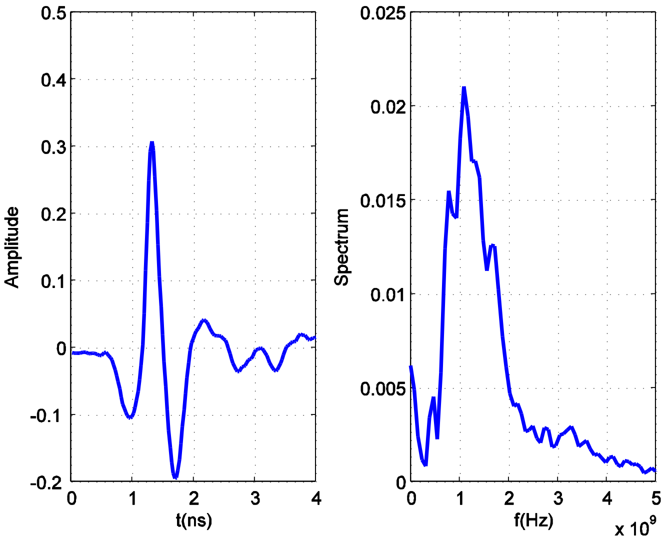

Figure 1. HL9200 Pulse Shape and Spectrum

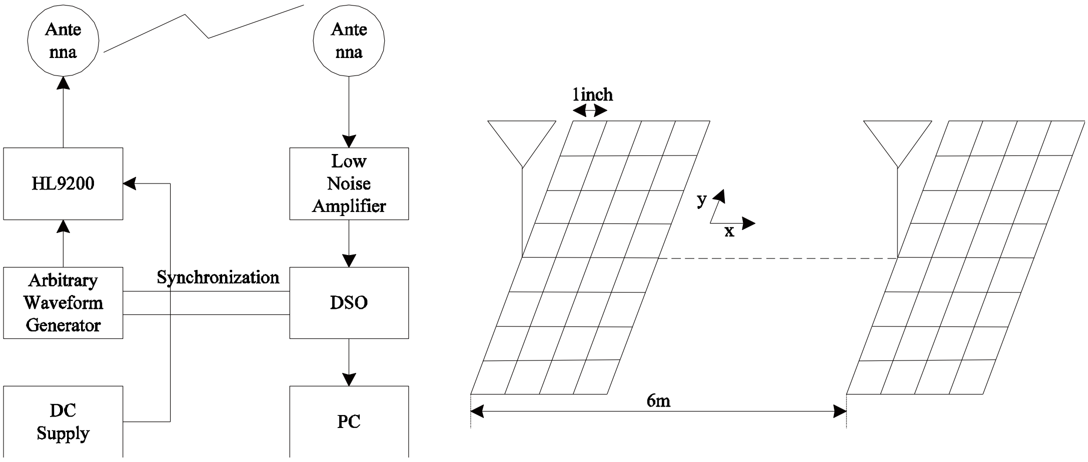

Figure 2. Diagram of System Setup and Grid for Measurement

To capture the dynamic change of the indoor UWB channel, it is necessary to record a long time period with a relatively high repetition rate, and at the same, hold the high sampling rate as well to meet the Nyquist sampling necessity. Thanks to a technique called segmented memory provided by Agilent, the DSO can store information only during the active bursts or pulses; they store no information during the inactive periods. Because the valuable memory is not used during the inactive periods, we can capture more of the critical signal activity. Using segmented memory, we could capture the CIR with a repetition time of 1 ms for 4.096 s, which consists of 4096 sets of CIR. In each set, 100 ns long signal sampled at 40 G samples/s is stored, which captures the majority of the multipath in a typical indoor environment.

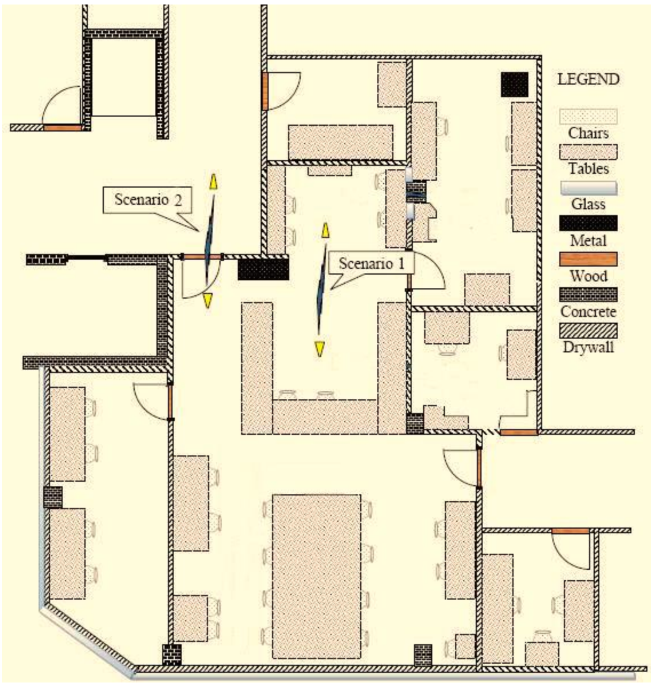

Figure 3. Lab Layout for Channel Measurement

All the measurements were conducted in the Wireless and Networking Research Laboratory at the University of Victoria. The layout of the measurement environment is shown in Figure 3. The lab is made out of general construction materials such as glass, metal, wood and concrete. As shown in Figure 3, we perform the measurements in two typical scenarios which are LOS and NLOS propagation environments. At each scenario, over 64 measurements are averaged by DSO before storage and processing. To perform double directional measurements, virtual arrays are used on a X-Y positioning 9×9 grid at both transmit and receive end, as shown in the right part of Figure 2. With virtual antenna array, the channels are required to be static during the measurement period. So the measurement is carried out in the midnight and nobody is moving in the lab. No mutual coupling is considered in the virtual array. The distance between transmit array and receive array is 6 meters, while the spacing among the array element is 1 inch.

For the AOA and AOD derivation, we should use the data collected from all the grids. While for performance analysis, we only utilize the data collected along the Y direction.

4. Measurement Results and Discussions

In this section, the collected data will be handled to extract the CIR and the direction related parameters. And some results will be discussed and compared.

4.1. AOD and AOA Derivation

In the directional channel models, the AOD and AOA are important parameters. In the literatures about double directional indoor channels, the AOD and AOA are mostly considered to be Laplacian distribution with zero mean and different variances. The variance is considered to be determined by the building architecture [25]. There are many methods to derive the angles of multipath components, like Sensor-CLEAN algorithm [25], ESPRIT algorithm [26] and SAGE algorithm [27]. ESPRIT is used for uncorrelated signals on good signal-to-noise ratio (SNR) conditions. Compared with Sensor-CLEAN, the convergence of SAGE algorithm is faster and easily guaranteed. So here SAGE algorithm is applied to derive the CIR and the angles of multipath components.

According to the theory, the estimation error of angle is related to the spacing between array elements, array size and the distance between transmit and receive arrays. When the distance between transmit and receive arrays are larger, the parallel ray approximation seems more reasonable. The AOD and AOA here are the azimuth angles.

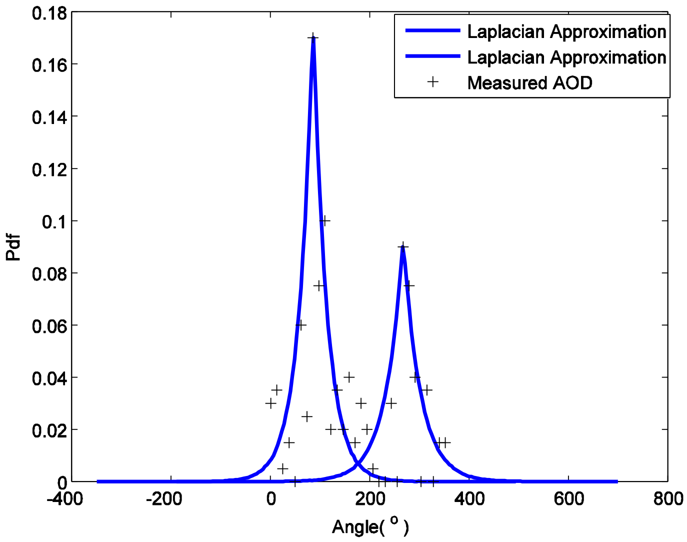

Figure 4. Probability Density Function of AOD and Laplacian Approximation

With SAGE algorithm, the AOD and AOA are derived from the collected data. Firstly the LOS environment in scenario 1 is considered. The maximum number of investigated multipath components is set to be 200. The probability density function (pdf) of AOD is shown in Figure.4. From Figure.4, we can see that there exist two angle clusters in the measurement. The mean of each cluster is 98° and 255° separately. It indicates that the main components come from LOS direction and the reflection direction of LOS. By Laplacian distribution approximation, the angel spread variance of AOD is about 40° .

In the same way, the AOA can be derived from the measured data. The pdf of AOA can also be approximated by Laplacian distribution. The only difference is the variance of AOA is about 30◦, smaller than that of AOD. So in this measured environment, the AOD and AOA could be regarded as zero mean Laplacian distribution with variance of 40° and 30° for components during each cluster. The mean angle of each cluster could be regarded as uniformly distributed in the channel modeling.

Figure.5 gives the scatter plot of AOD versus AOA in the scenario 1. From separate AOD or AOA perspective, there exit two clear angle cluster distributions. So from the figure of AOD versus AOA, there exist four obvious angle clusters. The angle spread of AOA is smaller than that of AOD.

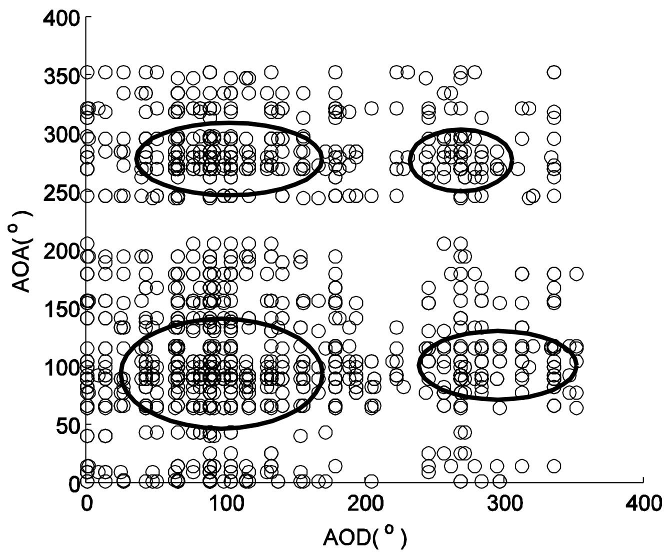

Figure 5. Scatter Plot of AOD Versus AOA in Scenario 1

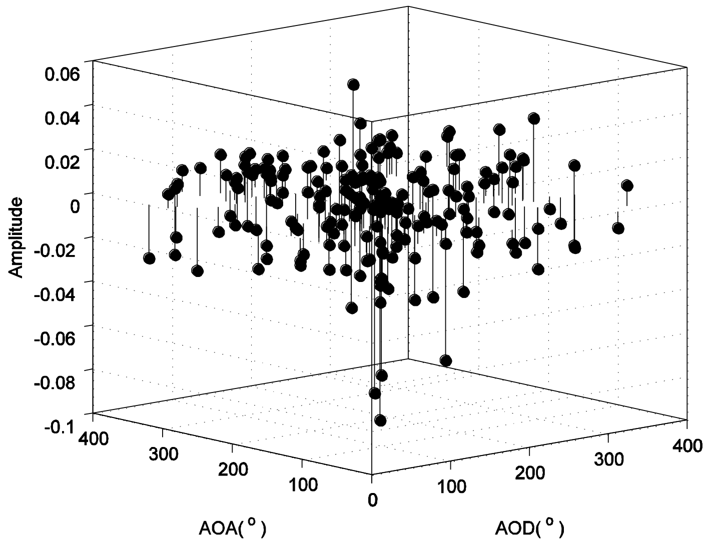

Figure 6. Multipath Amplitudes Versus AOD and AOA in Scenario 1

Associating the AOD and AOA with the multipath amplitudes, we can get the 3D figure of multipath components with the directions in Figure.6. This property is helpful to evaluate system performance when we use directional antennas.

The scatter plot of AOD versus AOA in scenario 2 is given in Figure.7. From the figure, the AODs and AOAs of multipath components are more disperse, which means that the angle spread in NLOS scenario is larger. We can also see that the multipath components are mostly come from the line direction between the transmitter and the receiver.

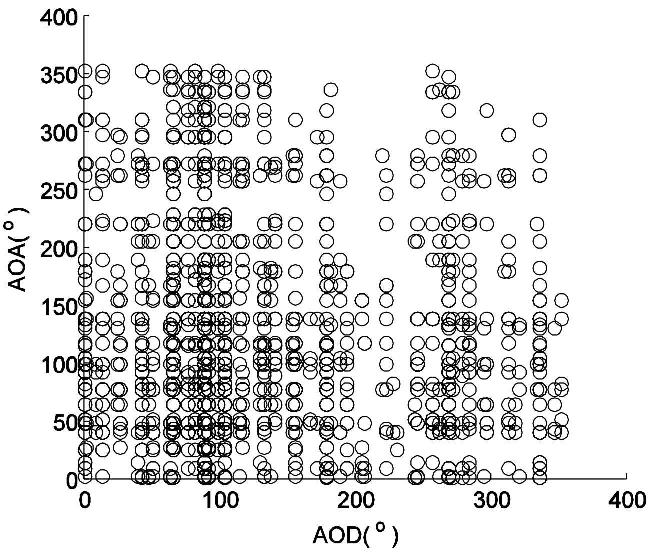

Figure 7. Scatter Plot of AOD Versus AOA in Scenario 2

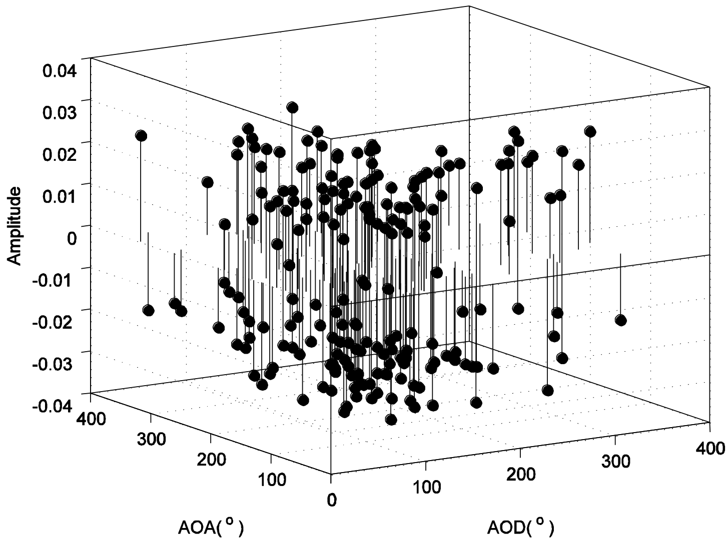

Figure 8. Multipath Amplitudes versus AOD and AOA in Scenario 2

Figure.8 gives the multipath amplitudes versus AOD and AOA in scenario 2. Compared with Figure.6, the amplitudes are less fluctuational but relatively smaller because there exist no LOS components.

4.2. Evaluation of CIR Parameters with Directional Antennas

From the measurements, we can extract the channel parameters with SAGE algorithm, like multipath amplitudes, delays, associated AODs and AOAs. In the measurements, the omnidirectional antennas are used. In order to evaluate the system performance with directional antennas, the channel CIRs extracted from the measured data will be combined with directional antenna radiation pattern for analysis and simulation.

Ideal circular horn antenna will be used in the simulations. Uniform circular horn is the simplest directional antenna form with its radiation pattern function as follow.

$$f(\theta) = 2J_1(u)/u \,, \tag{2}$$

Where $u = 2r\pi\sin(\theta)/\lambda$, r is circular horn radius and λ is the wavelength. The HPBW is $29.22\lambda/r$ in degree. And the maximum horn gain is

$$G = (2r\pi/\lambda)^2. \tag{3}$$

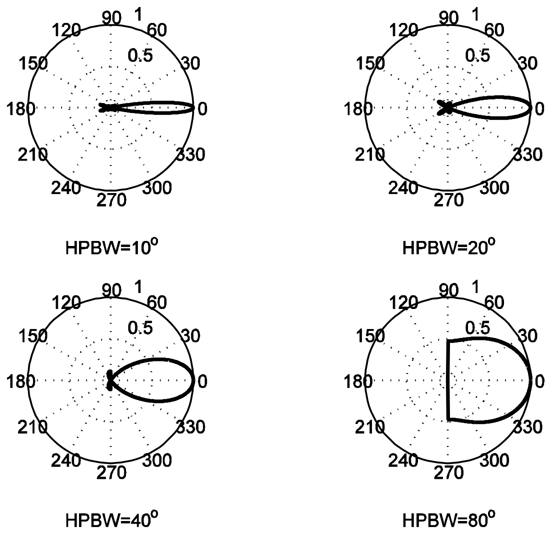

Figure 9. Circular Horn Antenna Radiation Pattern Diagram with Different HPBWs

Four different horn patterns will be adopted in our simulations. The antenna radiation patterns are illustrated in Figure.9. The HPBWs are separately 10, 20, 40 and 80 degrees. The transmitter and receiver are assumed to use the same pattern antennas. The maximum antenna gain aims at the strongest multipath component direction. With smaller beam width, fewer multipath components which fall into the beam are effective but the horn gain is larger.

Table 1. Channel Parameter Change with Antenna Radiation Pattern

Scenario	Antenna Pattern	MRMS(ns)	NP
1	Omnidirectional	14.32	200
1	HPBW=10°	10.42	38
1	HPBW=20°	11.33	49
1	HPBW=40°	11.66	68
1	HPBW=80°	12.64	90
2	Omnidirectional	15.39	200
2	HPBW=10°	9.83	21
2	HPBW=20°	11.10	27
2	HPBW=40°	12.40	50
2	HPBW=80°	14.54	84

Here we will give simple indications about the relationship between CIR parameters and antenna radiation patterns. For the omnidirectional antenna, the CIR parameters are the same with the measurement results. For the different HPBWs, the multipath components falling into the beam are considered to be effective. So the number of multipath components will be reduced. The corresponding RMS delay spread is also averaged to evaluate the channel delay. TABLE I shows that how parameters like mean RMS (MRMS) and number of multipath components (NP) change with radiation patterns.

As it is shown in early literatures, with directional antennas the number of multipaths and channel delay will decrease. With the decrease of antenna beamwidth, the channel delay and number of multipaths become smaller. These conclusions are straightforward because the consequence of directionality is that the channel between the transmitter and receiver is dominated by a few paths which fall within the transmitting and receive antenna beamwidth. However does the performance change so easily with antenna beamwidth? The question will be investigated as follows.

5. Evaluation of Channel Capacity

For UWB indoor slow fading channels, conditional on a realization of channel h, the channel could be regarded as an AWGN channel with received SNR of $|h|^2 \, SNR$. Then the capacity of this channel is

$$C = \log_2\left(1 + |h|^2 \, SNR\right) bits/s/Hz . \quad (4)$$

The quantity does not consider the gain of antenna radiation pattern. It is used to calculate the capacity of channel with omnidirectional antenna. However the antenna gain strongly influences the capacity. Considering the circular horn gain G, then the capacity is given as

$$C = \log_2\left(1 + G|h|^2 \, SNR\right) bits/s/Hz . \quad (5)$$

From the above quantities, the capacity is a function of the random channel gain h and is therefore random. Here we consider the average capacity of the practical measurement channels.

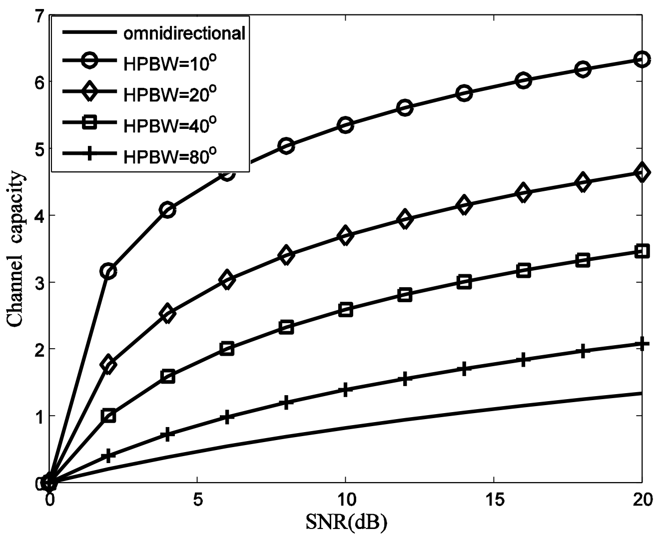

Figure 10. Channel Capacity with Different HPBW in Scenario 1

Figure.10 gives the capacity variety with the antenna radiation beamwidth in scenario 1. As we all know, channel capacity increases with the multipath richness. If antenna gain is ignored, the channel capacity should decrease with the beamwidth becoming smaller. As for the smaller beamwidth, the receiver gets less effective multipath components. However in the scenario 1, that is LOS environment, from the figure we can see the capacity increases with the beamwidth decreasing. This is mainly due to the antenna gain. The smaller beamwidth has larger antenna gain. Besides, the beam direction always aims at the strongest LOS multipath components. In the LOS environments, the capacity of channels with directional antenna is larger compared with capacity of channels with omnidirectional antenna.

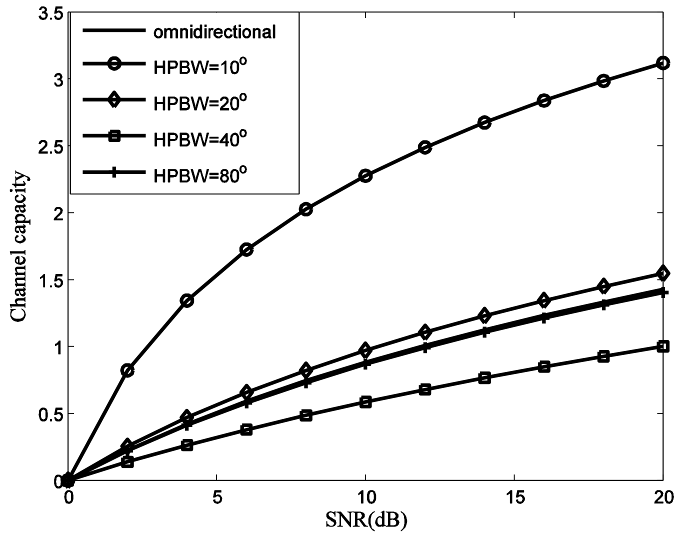

Figure 11. Channel Capacity with Different HPBW in Scenario 2

The capacity with different HPBWs in scenario 2 is given in Figure.11. From the figure we can see that the capacity no longer increases accordingly with the HPBW decreasing. Obviously the capacity with 40 degree HPBW is smaller than the capacity with 80 degree HPBW. Above all, the capacity with directional antenna is not always larger than that with omnidirectional antenna. The capacity with 20 degree HPBW is only a litter larger than capacity of omnidirectional antenna. The capacity with 80 degree HPBW is almost the same. And the capacity with 40 degree HPBW is even smaller. In the scenario 2, that is NLOS environment, from above analysis we know that there exist no dominant strong path components like in the LOS environment. So the capacity is more influenced by the antenna gain. In some conditions, the capacity with directional antenna becomes smaller than that with omnidirectional antenna. This reminds us that when antenna beamforming is used to obtain array gain, the beamwidth should be carefully designed to obtain optimal gain, especially in the NLOS environments.

6. Evaluation of BER Performance of UWB RAKE Receiver

Performances of UWB RAKE receiver are widely researched in many past literatures [28, 29]. Here our emphasis is on the impact of antenna beamwidth. With L resolved multipath components, the received baseband signal $r(t)$ can be written as

$$r(t) = \sum_{l=1}^{L} \alpha_l G(\psi_l) s(t-\tau_l) + n(t), \tag{6}$$

Where $s(t)$ is the transmitted symbol, α_l and τ_l indicate the amplitude and delay of lth path, $n(t)$ is AWGN and $G(\psi_l)$ is the antenna gain associated with lth path. The antenna gain could be given as $G = G_0 B(\theta)$, where G_0 is the maximum gain of the antenna and θ denotes the angle offset of the desired direction with reference to its maximum gain direction, *i.e.*, $G_0 B(0) = G_0$ and $B(\theta) \le 1$. In our simulation, circular horn antenna as above is used. For simplicity, all the paths in the antenna beamwidth are assumed to possess the same antenna gain $G_0 = 2r\pi/\lambda$.

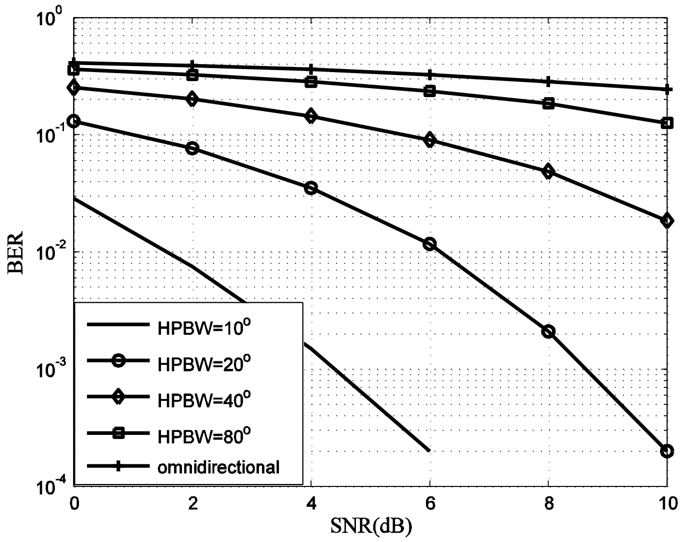

Figure 12. BER Performance of RAKE Receiver with Different HPBW in Scenario 1

Figure.12 and Figure.13 separately give the BER performances of RAKE receiver with different antenna beamwidths in scenario 1 and scenario 2. The figures indicate that the conclusions are similar with the channel capacity. In the LOS environment, the system has better BER performance with directional antenna than that of with omnidirectional antenna. With the antenna beamwidth decreasing, the BER performance is improved significantly. However in the NLOS environment, the situation is not so simple. The performance is not always better with directional antenna. And the performance is not mainly depended on the antenna beamwidth. In our simulation figure, the BER performance with 40 degree HPBW is worst. This is mainly because that there exist no dominant strong multipath components in the NLOS environment. So only the best compromise between the amplitude energy and the antenna gain could result in the best performance.

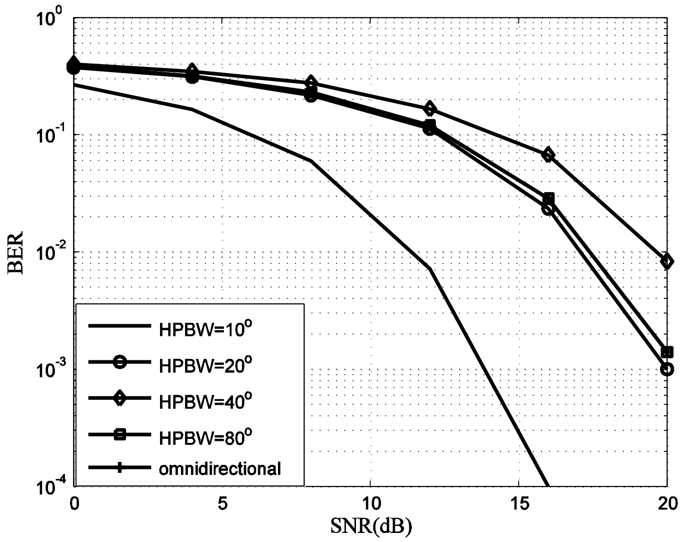

Figure 13. BER Performance of RAKE Receiver with Different HPBW in Scenario 2

7. Conclusions

UWB indoor channels with directional antennas are characterized and system performances under such channels are evaluated. Under double directional channel models, practical measurements under LOS and NLOS environments are separately carried out in the lab. By the SAGE algorithm, the parameters of channel impulse responses are extracted from the measurement data, especially the direction-related AOD, AOA, and corresponding amplitudes. The measurements are based on omnidirectional antennas. Combined with the radiation pattern of circular horn antenna, the relationships between antenna pattern and system performance are investigated. Using directional antenna with a certain HPBW, the channel delay will decrease because the multipath components which the receiver collects are reduced. In the LOS environments, the channel capacity increases with the beamwidth decreasing and is always larger than that of omnidirectional antenna. Similarly, the BER performance of RAKE receiver is improved with the beamwidth decreasing. In the NLOS environments, the conclusions are not so simple. The capacity and BER performance are not always better with directional antenna. The capacity and BER performance with 40 degree HPBW is even worse than those of omnidirectional antenna. And the variation trend between performance and antenna beamwidth disappears. The performance with 80 degree HPBW is better than that with 40 degree HPBW. This is mainly because that there exist no dominant strong path components in the NLOS environments. Only the best compromise between the amplitude energy and the antenna gain could result in the best performance. This reminds us that when antenna beamforming is used to obtain array gain, the beamwidth should be carefully designed to obtain optimal performance, especially in the NLOS environments.

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Authors

Xiaoya Zuo, he received the B.S, M.S. and PhD degrees in communication engineering from Northwestern Polytechnical University, Xi'an, China, in 2005, 2008 and 2011 respectively. He is currently a lecturer in the School of Electronics and Information, Northwestern Poly-technical University. From September 2008 to September 2009, he was a visiting scholar in the Department of Electrical and Computer Engineering, University of Victoria, Victoria, British Columbia. His research interests include broadband wireless communications, ultra-wideband communications, single carrier communication systems with frequency domain equalization and multiple-input multiple-output ultrawideband communication systems.

Ding Wang, he received the PhD degree in communication engineering from Northwestern Polytechnical University, Xi'an, China, in 2006. He is currently an associate professor in the School of Electronics and Information, Northwestern Polytechnical University. From September 2009 to September 2010, he was a visiting scholar in the Department of Electrical and Computer Engineering, University of Victoria, Victoria, British Columbia. His research interests are mainly about anti-interference in wireless communication systems