UWB Spatial-Frequency Channel Characterization

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Abstract—**This paper investigates the spatial-frequency channel characterization of Ultra-wideband (UWB) wireless communication systems. Firstly, a novel frequency dependent UWB channel model is constructed based on the theory of electromagnetic diffraction mechanism, which causes the field strength to vary with the frequency in each multipath. Secondly, we build a space-frequency model, which includes spatial characteristics such as angular power spectrum, and physical sampling points in space. The space-frequency model has two special cases (i) discrete multipath model, and (ii) cluster model, which can be readily used to generate channel data for any arbitrary set of sensor locations. The reconstruction results from channel measurements show the accurateness of the novel frequency dependent model, with reconstruction error decreasing by 40%, compared to the traditional Turin model.**

Index Terms—**Ultra-Wideband, Spatial-Frequency Channel Modelling, Frequency Dependency, Geometrical Theory of Diffraction (GTD)**

I. Introduction

Ultra-Wideband (UWB) technology has recently emerged as a potential significant candidate for indoor short distance wireless communications [1], [2], [3]. FCC [4] report in 2002 further excited the development of UWB technology. The analysis and design of UWB systems requires an accurate channel model to determine the maximum achievable data rate, to develop efficient modulation schemes and associate algorithms. Because of the ultra-wideband nature of UWB signals, the UWB channel is regarded as frequency selective. And traditional Turin model, or stationary linear filter, is widely adopted for UWB channel modelling. However, based on the measurements from various working environments [5], the UWB channel has a distinct characteristic: the physical environment has a much more significant impact on the time dispersive nature of the channel than distance. And one of outstanding drawbacks of traditional Turin statistical simulation model[6] is that it can not be easily changed for different environments and often requires further measurements, as no site-specific information is incorporated in the model. Originating from UWB radar scattering analysis, we believe frequency dependence, resulting from the electromagnetic diffraction mechanism and causing the field strength to vary with the frequency in each ray, can be incorporated as a environment-specific input in order to obtain a more accurate model.

In addition, the study of spatial aspects of multipath has become increasingly important in wireless communications, as spatial diversity promises to provide enhanced system performance, including communication range expansion, capacity enlargement, high data rates and low bit error rate [7], [8]. However, little work has been done on UWB spatial channel characterization until now. The traditional way to resolve the angle of arrival is by steering an antenna array to a certain direction and measure the signal strength at that direction [9]. Obviously, it is difficult to determine much about the angle-of-arrival of the multipath components by inspecting the trace using traditional methods. In this work, we develop a new theoretical single input multiple output (SIMO) UWB channel model to examine UWB signal spatial propagation. Using this model, the angle of arrival of each path, angular power distribution and even spatial correlation can be obtained, which could be further applied to the UWB receiver diversity design, such as an antenna array receiver.

The following part of this paper is organized as follows. In Section II, a novel exponential UWB channel model, including frequency dependence of each ray, is developed from the electromagnetic diffraction mechanism. In Section III, we introduce a new theoretical framework to build UWB spacial model. Finally, in the channel reconstruction stage, we employed efficient modified Prony's algorithm [10] to reconstruct the channel from the novel model and practical measurements. Compared with the traditional model, the proposed new model gives much better fit to data, with reconstruction error decreasing by 40%. In addition, the angle of arrival information and azimuth power distribution from our SIMO model are obtained to characterize UWB signal spatial propagation.

II. UWB Channel Model incorporating Frequency Dependency

From radar scattering analysis [11], [12], among three typical propagation mechanisms (multiple reflections, transmission, and diffractions), only diffraction causes the strength to be frequency dependent. Moreover, the Geometrical Theory of Diffraction (GTD) [13] predicts that the scattering follows

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$(jk)^{\alpha}$ frequency dependency, where, $k = 2\pi/\lambda$, or $k = w/c$, is the wavenumber, $j = \sqrt{-1}$, c is the speed of wave propagation and α is an integer multiple of $1/2$. And the frequency dependence factor α is determined by the ray path propagation mechanism and geometric configurations of the objects as listed in Table 1.

Physical Mechanism	Frequency Dependence Factor α
Line of Sight	0
Reflection	0
Diffraction from smooth or flat surface	0
Diffraction by edge	-0.5
Diffraction by Corner or tip	-1
Diffraction by Axial Cylinder Face	+0.5
Diffraction by Broadside of a Cylinder	+1

TABLE I

PHYSICAL MECHANISM VERSUS FREQUENCY DEPENDENCE w^{α} [13]

To better characterize the UWB ray path, we firstly build a GTD based modified model to incorporate frequency dependency described above. As wavenumber $k = w/c$, the modified model has a frequency dependent factor $(w/w_0)^{\alpha}$ to account for the impact of frequency dependency on channel impulse response. Therefore, we write the impulse response of the modified multipath fading channel in the frequency domain as:

$$H(w) = \sum_{\ell=1}^{L} a_{\ell} \big(\frac{w}{w_0}\big)^{\alpha_{\ell}} e^{-jw\tau_{\ell}} \qquad (1)$$

where L is the number of multpath signals, $\{a_{\ell}, \tau_{\ell}\}$ are random complex amplitude and time delay of each ray and frequency dependent factor α_{ℓ} are shown in Table 1. From this formula, it is obvious that for narrowband systems, frequency dependency can be neglected, as w is close to w_0 and the frequency dependent factor is always 1.

At the reconstruction stage (see Section IV), an efficient subspace-based method is employed to resolve parameters $\{a_{\ell}, \alpha_{\ell}, \tau_{\ell}\}$ from Communication Technology Laboratory, Swiss Federal Institute of Technology (SFIT) measurements [14]. The reconstruction results show that above GTD based modified model can be easily used to estimate the path arrivals. However, it is very difficult to estimate the frequency dependence factor.

Thus, we derive a novel UWB channel model to find frequency dependence coefficients easily. In (1), we have $(w/w_0)^{\alpha}$ frequency dependence factor; now, we sample the signals using $w = w_0 + qw_s$, $q = 1, 2, ...Q$, where w_0 is the lowest angular frequency, w_s is the sampling interval in frequency domain, q is the sample index, and Q is the total number of samples in the frequency domain. Using a Taylor Series, we have

$$\begin{aligned}\big(\frac{w}{w_0}\big)^{\alpha_{\ell}} &= \big(1 + q\frac{w_s}{w_0}\big)^{\alpha_{\ell}} \\ &= \exp\big[q\alpha_{\ell}\frac{w_s}{w_0} - \frac{1}{2}\alpha_{\ell}(q\frac{w_s}{w_0})^2 + \frac{1}{3}\alpha_{\ell}(q\frac{w_s}{w_0})^3 + \cdots\big].\end{aligned} \qquad (2)$$

When the sampling interval, w_s, is much smaller than the lowest angular frequency w_0, the condition $Qw_s \ll w_0$ can be satisfied. Thus, Eq. (2) can be approximated by its first order, and we get:

$$H(q) = \sum_{\ell} a_{\ell} \exp[(\frac{\alpha_{\ell}}{w_0} - j\tau_{\ell}) * qw_s]. \qquad (3)$$

Equation (3) can be viewed as a damped exponential model and is consistent with Prony model [15], another widely used model to analyze radar scattering especially for the high frequency scattering. Thus, in this section we build a new model, using (3), to obtain the frequency dependence coefficients and ray arrival times simultaneously

$$H(w) = \sum_{\ell=1}^{L} a_{\ell} e^{\beta_{\ell} w} e^{-jw\tau_{\ell}} \qquad (4)$$

where β_{ℓ} is the frequency dependence coefficient. Compared with (3), it can be seen that $\beta_{\ell} = \alpha_{\ell}/w_0$. Now, the impulse response of the channel is expressed as a set of complex exponentials that can be estimated by a number of algorithms in the Spectral Estimation theory. In practice, this novel exponential model is faster and more convenient to measure or simulate the channel impulse response in the frequency domain compared with (1). Especially, compared with traditional models, accurately estimated received pulses from the novel model could be used to generate a correlator receiver.

III. UWB CHANNEL MODEL IN SPACE DOMAIN

In this section, we develop a SIMO (Single Input Multiple Output) channel model which can be applied to UWB receiver diversity systems. We have made two assumptions: (i) we only consider two dimensional (2D) propagation environment. This is because according to [16], given an azimuth distribution, the elevation distribution has relatively small effects on spatial correlation of each receiver in horizontal domain; (ii) the multipath signals come from farfield sources, which is a reasonable assumption considering the order of wavelength of UWB signals.

A. General Model

Let $A(\phi, w)$ be the gain of the signal arriving from an angle ϕ measured at the origin. Then the channel frequency response at a point $\boldsymbol{x}$, where $\boldsymbol{x} = (|\boldsymbol{x}|, \phi_{\boldsymbol{x}})$ from the receiver origin is given:

$$H(w, \boldsymbol{x}) = \int_{-\pi}^{\pi} A(\phi, w) e^{jk\boldsymbol{x}\cdot\hat{\boldsymbol{\phi}}} d\phi \qquad (5)$$

where $\hat{\boldsymbol{\phi}}$ is a unit vector along the direction ϕ.

Note that, generally we could write $A(\phi, w)$ using Fourier Series expansion:

$$A(\phi, w) = \sum_{m=-\infty}^{\infty} \gamma_m(w) e^{jm\phi} \tag{6}$$

and

$$\gamma_m(w) = \frac{1}{2\pi} \int_{-\pi}^{\pi} A(\phi, w) e^{-jm\phi} d\phi. \tag{7}$$

Here, $A(\phi, w)$ could be viewed as the angular frequency dependent fading gain or angular frequency response.

Furthermore, using the mathematical identity [17],

$$e^{jk\mathbf{x}\cdot\hat{\boldsymbol{\phi}}_\ell} = \sum_{m=-\infty}^{+\infty} J_m(k|\boldsymbol{x}|) e^{jm(\phi_{\boldsymbol{x}}+\frac{\pi}{2})} e^{-jm\phi_\ell} \tag{8}$$

where $J_m(\cdot)$ is the order mth first kind of Bessel function [18]. Note that according to [19]: only a few terms ($M \approx 8.54R/\lambda$, where R is the maximum $|\boldsymbol{x}|$ of interest and λ is the wavelength) of $J_m(\cdot)$ need to be calculated for obtaining a good approximation as the higher order Bessel functions have small values when arguments are near zero. In our channel simulator stage, we have $M = 20$.

By substituting (8) into (5), a novel spatial-frequency UWB channel model is written as:

$$H(w, \boldsymbol{x}) = \sum_{m=-M}^{+M} \gamma_m(w) J_m(k|\boldsymbol{x}|) e^{jm(\phi_{\boldsymbol{x}}+\frac{\pi}{2})}. \tag{9}$$

1) Angular Power Spectrum: We define the *angular power spectrum* as the average power received at the receiver origin as a function of frequency and arrival angle:

$$P(\phi, w) = \frac{E\big[|A(\phi, w)|^2\big]}{\int_{-\infty}^{+\infty}\int_{-\pi}^{+\pi} E\big[|A(\phi, w)|^2\big] d\phi dw}. \tag{10}$$

Since $P(\phi, w)$ is a periodic function of angles, we use Fourier Series expansion to write:

$$P(\phi, w) = \sum_{m=-\infty}^{+\infty} \zeta_m(w) e^{jm\phi} \tag{11}$$

where $\zeta_m(w)$ are the frequency dependent Fourier Series coefficients. Since $0 \leq P(\phi, w) \leq 1$, we have the following constraint on $\zeta_m(w)$:

$$2\sum_{m=1}^{\infty} |\zeta_m(w)| \leq \zeta_0(w) \leq 1 - 2\sum_{m=1}^{\infty} |\zeta_m(w)| \tag{12}$$

2) Statistical Properties of $\gamma_m(w)$: As all surrounding scatters can be treated as widesense stationary uniformly distributed, we assume that $A(\boldsymbol{\phi}, w)$ are independently distributed (i.i.d) for different angles, $E\big[A(\phi, w)A^*(\phi', w)\big] = 0$, if $\phi \neq \phi'$. Therefore, $E[\gamma_m(w)] = 0$, and:

$$E[\gamma_m(w)\gamma_m'^*(w)] = \int P(\phi, w) e^{-j(m-m')\phi} d\phi = \zeta_{m-m'}(w) \tag{13}$$

where $(\cdot)^*$ denotes the complex conjugate operation. By viewing (7) as an infinite summation of independent random processes, we conclude that $\gamma_m(w)$ is a complex Gaussian distribution with mean of zero and variance of ζ_0; moreover, the covariance of different $\gamma_m(w)$ is given in (13). Thus, if we could resolve $\gamma_m(w)$ and $\zeta_m(w)$ from measurement data, the azimuth power spectrum and the statistical surrounding scatter distribution can be identified. Further, the analysis above shows that we could use $P(\phi, w)$ to generate $\gamma_m(w)$ and even the channel frequency impulse response.

B. Discrete Multipath Model

$A(\boldsymbol{\phi}, w)$ is generally a continuous function of the arrival angle $\boldsymbol{\phi}$. However, if we approximate it by a discrete arrival angles, we could use the SISO model developed in Section II to write:

$$A(\boldsymbol{\phi}, w) = \sum_{\ell=1}^{L} a_\ell e^{\beta_\ell w} e^{-jw\tau_\ell} \delta(\boldsymbol{\phi} - \boldsymbol{\phi}_\ell). \tag{14}$$

Here, L is the number of multipath; $\{a_\ell, \beta_\ell, \tau_\ell\}$ are the random complex amplitude, the frequency dependence coefficient and the time delay of each path; and ϕ_ℓ is the angle of each path.

By substituting (14) in (5), we have:

$$H(w, \boldsymbol{x}) = \sum_{\ell=1}^{L} a_\ell e^{\beta_\ell w} e^{-jw\tau_\ell} e^{jk\boldsymbol{x}\cdot\hat{\boldsymbol{\phi}}_\ell}, \tag{15}$$

which is a generalization of the SISO UWB model (4) developed in Section II. Using (7), we could write (15) in the form of (9) where

$$\gamma_m(w) = \sum_{\ell=1}^{L} a_\ell e^{\beta_\ell w} e^{-jw\tau_\ell} e^{-jm\phi_\ell}. \tag{16}$$

This novel spatial-frequency channel model provides a theoretical way to solve the angle of arrival of each path ϕ_ℓ from measured channel frequency impulse responses. It can also be used to generate the channel frequency response at any point $\boldsymbol{x}$ after estimating $\{a_\ell, \beta_\ell, \tau_\ell, \phi_\ell\}$ from channel measurements.

C. Cluster Model

We further spread each cluster (path) over a small angle spread and assume all rays in the cluster have same frequency dependence coefficients and time delays. Let $A_\ell(\phi)$ denote the spread gain of each cluster, the cluster model can be expressed as:

$$H(w, \boldsymbol{x}) = \sum_{\ell=1}^{L} \int_{-\pi}^{\pi} A_\ell(\phi) e^{jk\boldsymbol{x}\cdot\hat{\boldsymbol{\phi}}} e^{\beta_\ell w} e^{-jw\tau_\ell} d\phi \tag{17}$$

where L main paths are regarded as L clusters.

We express angular spread of each cluster as:

$$A_\ell(\phi) = \sum_{m=-\infty}^{\infty} \gamma_m^\ell e^{jm\phi}. \tag{18}$$

Equation (17) could be written in the form of (9), where:

$$\gamma_m(w) = \sum_{\ell=1}^{L} \gamma_m^{\ell} e^{\beta_\ell w} e^{-jw\tau_\ell}. \tag{19}$$

Let $P_\ell(\phi) = E\big[|A_\ell(\phi)|^2\big]$ be the angular power distribution of each cluster. Then we can write $P_\ell(\phi) = \sum_{m=-\infty}^{+\infty} \zeta_m^{\ell} e^{jm\phi}$. Similarly to (13), we also have $E\big[\gamma_m^{\ell}\gamma_{m'}^{\ell}\big] = \zeta_{m-m'}^{\ell}$. For simulation purposes, we could assume that each cluster has a Laplacian angular distribution (or other suitable distribution). Fourier coefficients ζ_m^{ℓ} were given in [16] for all common angular power distributions such as Laplacian, von-Mises etc.

D. UWB Channel Simulation

We use the clustering model developed in Section III-C to build a simple space-frequency channel simulator. A desired scattering environment can be specified by choosing the number of clusters L, parameters $\{\beta_\ell, \tau_\ell\}$ for each cluster and angular spread σ_ℓ for each cluster, assuming all of $A_\ell(\phi)$ are Laplacian distributed. Now, we can use (17) and (9) to generate any number of channel data at arbitrary points in space and frequency. Then different receiver designs performance could be evaluated based on the channel simulation results.

IV. Example: Channel Reconstruction and Simulation

In this section, we use well studied high-resolution harmonic retrieval methods to obtain estimation for the unknown parameters of the spatial-frequency UWB channel model. We firstly investigate the accurateness and characteristics of the novel exponential channel model. The subspace-based approach [20] is adopted to estimate the traditional Turin [9,10] and GTD based modified UWB channel model. Then for the novel exponential UWB channel model, modified Prony's method is employed to estimate frequency dependence [10]. The SFIT measurements from 2-8 GHz with 3202 samples [14] are used as channel impulse responses in frequency domain.

Even though the measurement is taken from 2 to 8 GHz, our channel reconstruction is performed on 3-5 GHz bandwidth. The reasons are two folds: i) these frequencies are commonly used for UWB systems; ii) the condition for channel impulse response $Qw_s \ll w_0$ are met, thus the novel exponential model can be effectively employed. In order to make the comparison more clear, the Root-Mean-Square-Error (RMSE) between original and reconstructed channel impulse responses from these three models: i) Turin model; ii) GTD based modified and iii) novel exponential models is shown in Figure 1. It is clear that the traditional Turin model produces larger deviation between reconstructed and original impulse response (24.79%) as signal bandwidth increases to 2GHz; while the exponential UWB channel model with frequency dependence provides much more accurate fit (with error less than 14% for 2GHz bandwidth). This results prove that frequency dependence needs to be considered for large bandwidth. Furthermore, the novel exponential channel model is more stable and can also be used to efficiently estimate frequency dependence of each path, which has greater physical meanings. For example, from the reconstruction results, we observed that most paths undertake line-of-sight or reflection, which is frequency independent ($\alpha = 0$), or one time diffraction ($\alpha = -1/2$). This result is very reasonable in indoor environment.

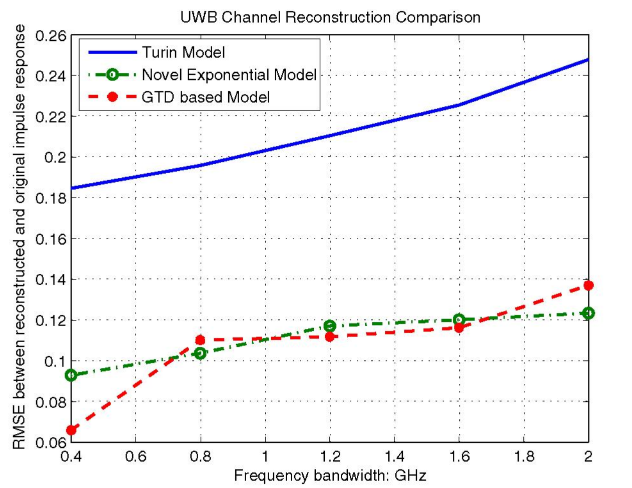

Fig. 1. UWB channel reconstruction error comparison via increasing bandwidth

We then use methodology introduced in Section III-D to generate a spatial-frequency UWB channel. The signals are received at an uniform circular array with 21 antenna elements located at 0.07m to the receiver origin. The parameters used for the channel model are: $L = 5$, $\sigma_\ell \in [1.1, 2, 1]$, $\phi_\ell \in [0, 2\pi)$; β_ℓ are randomly selected from $[0, -0.5, -1, -1.5, -2, -2.5, -3]$. Then, simulated channel spatial-frequency impulse response and azimuth power spectrum are shown in Fig. 2-3. Currently we do not have a suitable set of space domain UWB channel measurement to validate the applicable of our space-frequency model developed in Section II. We are actively seeking a measurement data set or collaboration who may have measurement capability. Further, the figures show that UWB transmission channels in indoor environments are always impacted by deep multipath fading. In such fading scenarios, an antenna array receiver may be used to exploit spatial diversity in order to reduce the probability of deep fades.

V. Conclusion

Because of similarities between wireless channel modelling and radar scattering analysis, a novel exponential UWB channel model incorporating frequency dependence is firstly proposed in this paper. The new model originates from electromagnetic diffraction mechanism and geometric diffraction mechanism. SFIT measurements reconstruction demonstrates the accurateness of our novel exponential model. Then by adding a new factor, receiver antenna position with respect to the receiver origin, we build a general space-frequency channel model. The generic model is further developed into two special cases for UWB systems: discrete multipath and

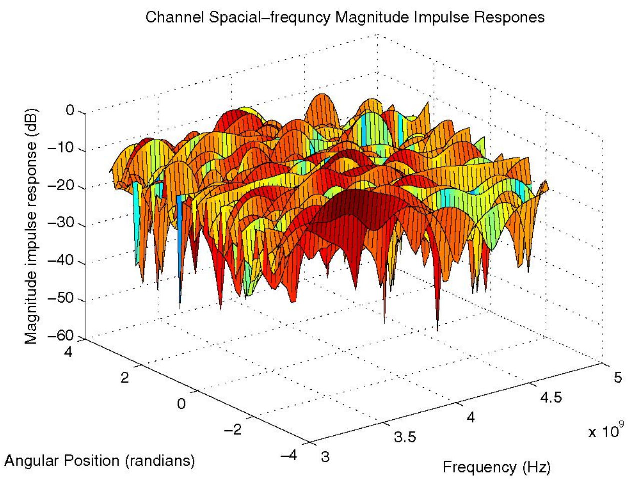

Fig. 2. Generated channel spatial-frequency impulse response from 21 circular array with 0.07m radius

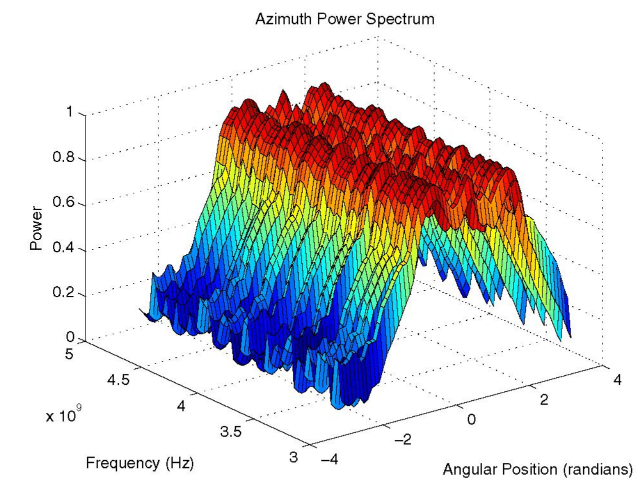

Fig. 3. Generated angular power spectrum from 21 circular array with 0.07m radius

cluster models. The novel spatial-frequency models provide two major contributions: i) an efficient way to generate a channel simulator; ii)the insight into the correlator and antenna array receiver designs.

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