CHAPTER 4

ANALYSIS OF INDOOR CHANNEL AND SPATIAL MULTIPLEXING IN LOS FOR MILLIMETER WAVE BAND USING TRIPLE SALEH VALENZUELA MODEL
ANALYSIS OF INDOOR CHANNEL AND SPATIAL MULTIPLEXING IN LOS FOR MILLIMETER WAVE BAND USING TRIPLE SALEH VALENZUELA MODEL

The channel model depicts the nature of environment. Analysis of the model is important to understand the time dispersive and time varying characteristics of the channel. The main objective of this chapter is, the channel model for 60 GHz proposed by National Institute of Information and Communication Technology (NICT), Japan is studied and analyzed. The model is recommended by IEEE as the empirical model conforming to 802.15.3c WPAN standard. It has been modeled for residential, office and desktop environments. With channel parameters analyzed, gigabit communication system using spatial in line of sight (LOS) is considered. The chapter is organized with section 4.1 discussing the survey of the reported results on physical layer modeling, section 4.2 detailing the TSV model, section 4.3 discussing the spatial multiplexing for MMW for two path channel with LOS dominating the first order reflected path and the different equalization techniques, section 4.4 deals with the power delay and power angle profile analysis of TSV channel, performance evaluation of the 2x2 4x4 and 8x8 spatial multiplexed BPSK systems with Zero Forcing (ZF), Minimum Mean Square Error (MMSE), Maximum Likelihood (ML) equalization techniques and section 4.5 presents the observations and comments.

4.1 Introduction

This section presents the ray tracing and empirical channel model available in the literature. Multipath dominated small scale fading effects proposed by SV is further extended as TSV to suit the propagation characteristics of the indoor environment. The multi-antenna configuration using the channel model is discussed.

4.1.1 Review of research work on indoor channel environments

Modeling indoor propagation environment is complicated by large variability in building layout and construction materials. Environment can change radically by movement of people, blockage by walls and furniture. Another important element of indoor wireless
operation that should be taken into account is interference. Indoor path loss can change dramatically with either time or position, because of multipath present (Seybold, J.S. 2005). The indoor channel models for MMW personal communication has to address propagation issues such as oxygen absorption, huge transmission loss and free space path loss (Xiao, S-Q. et al., 2008; Seybold, J.S. 2005). The existing models for Ultra Wideband (UWB) and WLAN cater to low frequency range and are also antenna specific. Several experiments with the option of antenna selection have been conducted for MMW. Site- specific and Site-general modeling are the two general types of propagation modeling present. Site-specific modeling requires information on building layout, furniture, walls, floors etc. This modeling is generally performed using ray- tracing methods. Site-general models give statistical predictions of the path loss for a link design. This model tends to be the more widely used model. Millimeter Waves are mostly affected by small-scale fading that encompasses the fading that occurs with very small changes in the relative position of the transmitter and receiver and reflectors in the environment (Torkildson, E. et al., 2009). This is attributed to the summation of multiple reflected signals arising with different phases and amplitudes. Due to the presence of single- dominant component such as line-of-sight path, this channel model has taken Rician probability density function in consideration (Poon, A.S.Y et al., 2005; Bohagen, F. et al., 2007). As the path loss combines with other channel parameters like delay spread, there arises a need to use directional antennas for reliable communications. To obtain better Signal to Noise Ratio (SNR) in MMW band and in order to effectively use frequency with space division method, the effect of antenna directivity has to be considered (Ranvier, S. et al., 2009). Ray tracing using directional antenna exhibits very low delay spread (Yong, S.K. and Chong, C-C. 2007). Low delay spread increases the data rate and removes the requirement of a channel equalizer in the receiver (Xu, H. et al., 2002).

Channel models were developed based on extensive channel measurements campaigns in angiography room and ultrasonic imaging room in hospital. Power Delay Profile (PDP) in angiography room consists of several narrow peaks and an exponentially decaying power distribution as discussed in chapter 2. PDP in the ultrasonic imaging room consist of one or several clusters which start from a distinguishable peak followed by a sharp decaying tail having power law slope (Kyro, M. et al., 2012). Received power, PDP in narrow straight
corridor and wide straight corridor were analyzed using ray tracing technique. It was analyzed that the antenna radiation pattern has a significant effect on the received power and the use of directive horn antennas greatly improved power performance in comparison to its omnidirectional counterpart (Rao, T. et al., 2011).

The statistical characteristics (spatial and temporal) of 60 GHz indoor channel catering to large scale and small scale fading effects were studied. Small scale effects include study of instantaneous doppler spread, delay spread and angular spread. Doppler spread reveals indoor channel as slow fading, delay spread reveal that RMS delay spread can be made very small, i.e., in the order of 1 ns, by using narrow beam antennas. Angular spread gives the directional distribution of multipath power. The average of the measurements yielded large scale fading effects (Smulders, P.F.M. 2009). The propagation model for indoor radio channel characteristics at MMW frequencies can also be modeled using “Geometric Optics”. Objects inside the room superstructure affect the indoor radio channels (Hansen, J. 2002). Tools like Ray-Tracing are used for simulation to measure all kinds of scenarios with all kinds of antennas. At this frequency band, power contribution from diffracted rays is not significant when compared to reflected rays. Hence Geometric Optics is used. Ray-like behavior is more pronounced for shorter wavelengths. The channel was represented by multiple paths or rays having real positive gains $\beta_n$, propagation excess delays $\tau_n$, and associated phase shifts $\theta_n$, where n is the path index between 0 and N, N being the number of significant rays (Hansen, J. 2002).

Accurate grasp of the propagation characteristics of targeting frequency band is important for creating appropriate channel models. Regarding the channel model used in Task Group (TG3a), the channel model called Saleh and Valenzula (S-V) was developed. Even though the assumed bandwidth of TG3a and TG3c are same, the TG3c tried to adopt S-V as channel model but some contributions to TG3c from NICT showed that two paths model is more suited than S-V model owing to use of directional antennas on desktop and LOS environment. Blockage of LOS component results in signal loss. Hence for information retrieval, receiver depends on reflected components. The reflected path with certain statistical distribution had to be accounted, this resulted in the merger of the two-path model with S-V to obtain Triple Saleh Valenzuela model (TSV). TSV was proposed by NICT as one of the statistical channel model suitable for frequency band 57-66 GHz (Sawada, H. et al., 2006).
4.1.2 Review of Spatial Multiplexing

The data rate of the system can be increased using multiple antenna at the transmitter and receiver. The Personal Area Network (PAN) MIMO channels were modeled using LOS MIMO model by considering channel as a sum of dominant and fading part (Karedal, J. 2010). The use of multiple channels for transmission and reception leads to Spatial Multiplexing (SM). SM is a widely considered concept for MIMO that offers large capacity gains if the spatial correlation is low. The increase in capacity achieved with no additional power or bandwidth (Wolniansky, P. et al., 1998). SM gain achieved by transmitting independent data signals from individual antennas (Foschini, G.J. and Gans, M. 1998). Under rich scattering environment, the receiver can separate the different streams resulting in a linear increase in capacity.

SM in conjunction with polarization diversity is a viable option for 60 GHz LOS (Pollok, A. et al., 2008). The channel properties influence the available array, spatial diversity and multiplexing gains. Analysis addressing multipath effects using array of subarrays target improving directivity and spatial multiplexing gains whose performance compared with the dominant eigenmode transmission (DET) benchmarked reference (Torkildson, E. et al., 2009).

The LOS channel is modeled here using the TSV model. This model is found to be much suitable for the indoor environment because of its capability to describe both the LOS and NLOS components. Using this channel model, SM system for LOS analyzed and the Bit Error Rate (BER) performance compared for different receivers. Assuming perfect channel estimation, the BER of the system is investigated for Zero Forcing, Minimum Mean Square and Maximum Likelihood receivers for 2x2, 4x4 and 8x8 MIMO systems using constant envelope modulation scheme i.e BPSK scheme.

4.2 TSV model for indoor environment

Based on the literature survey of channel models for 60 GHz, the TSV channel model singled out due to its prediction and performance. It is a merger of a statistic two path model which expresses the device-position dependent fading and the statistic Saleh-Valenzuela model that is commonly used in the 802.15 standardization groups. The indoor channel is modeled in the form of ray and cluster. The clusters are formed by the building superstructure, while the
Individual rays are formed by objects in the vicinities of the transmitter and the receiver (Saleh, A.A.M. and Valenzuela, R.A. 1987).

The impulse response \( h(t) \) of the S-V model in equation (4.1) takes into account only the complex amplitude of each ray and the time-of-arrival (ToA) information of each ray in a cluster.

\[
h(t) = \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \alpha_{lm} \delta(t - T_l - \tau_{l,m}) \tag{4.1}
\]

where \( \alpha_{lm} \) is the complex amplitude of \( ml^th \) ray in \( l^th \) cluster, \( t \) is time, \( T_l \) is the delay time of \( l^th \) cluster, and \( \tau_{l,m} \) is the delay time of the \( ml^th \) ray related in the \( l^th \) cluster (Saleh, A.A.M. and Valenzuela, R.A., 1987). The statistical distributions of generation of cluster and ray follow Poisson process described in equation (4.2) and equation (4.3).

\[
p(T_l | T_{l-1}) = \Lambda \exp[-\Lambda(T_l - T_{l-1})] \tag{4.2}
\]
\[
p(\tau_l | \tau_{l-1}) = \lambda \exp[-\lambda(\tau_l - \tau_{l-1})] \tag{4.3}
\]

\( \Lambda \) and \( \lambda \) are the parameters that show the ratio of arrival of each cluster and ray respectively.

To analyze the directional distribution of multipath power, the model in equation (4.1) was modified to include the angle-of-arrival (AoA) characteristics as shown in equation (4.4)

\[
h(t) = \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \alpha_{lm} \delta(t - T_l - \tau_{l,m}) \delta(\phi - \psi_l - \psi_{l,m}) \tag{4.4}
\]

where \( \psi_l \) is the angle of arrival of the \( l^th \) cluster, \( \psi_{l,m} \) is the angle of arrival of the \( ml^th \) ray related in the \( l^th \) cluster. Angular distribution is assumed as Laplacian distribution shown in equation (4.5).

\[
p(\psi_{l,m}) = \frac{1}{\sqrt{2\sigma_{\phi}}} \exp[-\sqrt{2} \psi_{l,m} / \sigma_{\phi}] \tag{4.5}
\]

where \( \sigma_{\phi} \) is the angle spread of rays in the cluster.
Thus the channel dispersion parameters ToA and AoA of cluster and ray combined with two-path model that included a LOS and first order reflected path formed the TSV model as shown in Figure 4.1.

Figure 4.1: Two path model showing specular (LOS) and first order reflected path

In Figure 4.1, $h_1, h_2$ are the heights of the transmit and receive antenna, $d_1$ and $d_2$ are the distance travelled by the LOS and reflected signals, $D$ is the transmit and receive antenna separation distance.

The Channel Impulse Response (CIR) of the TSV model (Sawada, H. et al., 2006; Sato, K. et al., 2007) is given by

$$h(t) = \beta \delta(t) + \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \alpha_{l,m} \delta(t-T_l-\tau_{l,m}) \delta(\phi-\psi_l-\psi_{l,m})$$  \hspace{1cm} (4.6)

where $\beta$ is the direct wave component that holds the information about the heights of the transmitter and receiver antenna, distance between the antenna, $\Gamma_0$ reflection co-efficient and the $\lambda_f$ wavelength of the center frequency is given by

$$\beta = \frac{\mu_D}{D} \left| G_{t1}G_{r1} + G_{t2}G_{r2}\Gamma_0 \exp[-j \frac{2\pi 2h_1h_2}{\lambda_f D}] \right|$$  \hspace{1cm} (4.7)
The directivity functions of the transmitting and receiving antennas are assumed to be $G_t$ and $G_r$. $G_{t1}$, $G_{r1}$, $G_{t2}$ and $G_{r2}$ are the amplitudes of the direction of the direct pass and the amplitude of the direction of the reflection pass respectively is depicted in Figure 4.2.

In equation (4.6), $\alpha_{l,m}$ is the complex amplitude of each ray, $t$ is the time, $T_l$ is the delay time of the $l^{th}$ cluster, $\tau_{l,m}$ is the delay time of the $m$-th ray in $l^{th}$ cluster, $\Psi_l$ is the angle of arrival of the $l^{th}$ cluster, $\Psi_{l,m}$ is the angle of arrival of $m^{th}$ ray in the $l^{th}$ cluster. $\alpha_{l,m}$ the complex amplitude of each ray given by,

$$|\alpha_{l,m}|^2 = \Omega_0 e^{\frac{T_l}{\Gamma}} e^{-\tau_{l,m}(1-k[1-\delta(m)])} \sqrt{G_r(0, \Psi_l + \Psi_{l,m})} \tag{4.8}$$

$$\angle \alpha_{l,m} \propto Uniform(0,2\pi) \tag{4.9}$$

where $\Omega_0$ is the mean value of amplitude of the first coming wave of the delay wave, and $k$ is the coefficient used to take the Rician-factor for each cluster into account.

Figure 4.2: Two ray model with antenna directivity
The impulse response gives the information of the relative power of the first ray that arrives to that of the last received signal component. The amplitude factor of this impulse response in TSV model is determined by the distance between the millimeter device positions and the heights of the antennas. The uncertainty and high vulnerability of the device position and the fading caused is modeled in TSV by the random variables generated by Poisson and Laplace distributions.

The PDP is defined by performing autocorrelation function of the impulse response \( h(t) \) by letting the time delay to zero can be pictorially explained as shown in Figure 4.3.

\[
\begin{align*}
\text{Relative Power} & \quad \Phi \quad \Omega \\
\sqrt{\Omega} & \quad \text{LOS (Two-path response)} \\
\Delta \tau & \quad T_0 \\
\text{Delay Time} & \quad \text{NLOS (SV model response)} \\
\text{Decay of amplitude of ray in each cluster}
\end{align*}
\]

Figure 4.3: Power Delay Profile of the TSV model

In Figure 4.3, \( \Omega \) is the average power of the first ray of the first cluster, \( \Delta \tau \) and \( T_0 \) is the ToA of the specular ray and first cluster. The PDP in Figure 4.3 is influenced by the transmit (Tx) and receive (Rx) antenna beams. Considering vertical polarized antenna with different radiation patterns, that is omni-directional, fan-beam and pencil beam, three cases of PDP for indoor system has been analyzed (Yang, H, et al., 2007). In the first case, with perfect alignment between Tx/Rx beam under the LOS condition, the PDP consists of direct ray and
an exponentially decaying part. The second case, with misalignment between Tx/Rx beam under LOS case, the PDP consists of a constant part before the exponentially decaying part. The duration of the constant part is governed by the antenna misalignment and antenna beam pattern. The third case, under NLOS condition, the PDP will have an exponentially decaying part without the constant part as they become independent of the antenna pattern. In general, accounting for all the three cases, the indoor channel PDP can be modeled as a function of ToA that consists of a specular ray, constant part and an exponential decay part.

\[
P(\tau) = \begin{cases} 
0, & \tau < 0 \\
|\alpha_0|^2 \delta(\tau), & \tau = 0 \\
\Pi, & 0 < \tau < \tau_c \\
\Pi e^{-\gamma(\tau - \tau_c)}, & \tau > \tau_c 
\end{cases}
\]

(4.10)

Where \(\alpha_0\) is the amplitude of the specular path, \(\sqrt{\Pi}\) is the amplitude of the specular path of duration \(\tau_c\) and \(\gamma\) is the decay exponent. The PDP in Figure 4.3 is evident from equation (4.10).

The parameters used in TSV model is summarized as follows:

- \(PL_0\), PL at 1m distance
- \(n\), PL exponent
- \(\sigma_s\), shadowing standard deviation
- \(\Lambda\), inter-cluster (cluster) arrival rate
- \(\lambda\), intra-cluster (ray) arrival rate
- \(\Gamma\), inter-cluster (cluster) decay rate
- \(\gamma\), intra-cluster (ray) decay rate
- \(\sigma_c\), cluster lognormal standard deviation
- \(\sigma_\gamma\), ray lognormal standard deviation
- \(\sigma_\phi\), angle spread
- \(\bar{L}\), average number of clusters
- \(d\), Tx-Rx separation, \(h_I\), Tx height, \(h_2\) Rx height, \(G_T\), Tx gain, \(G_R\), Rx gain, \(K\), Rician factor, \(\Omega\), average power of the first ray of the first cluster (for combined two path and S-V model)
The cluster and ray arrival rates, cluster and ray decay rates as a function of ToA and AoA are represented in Figure 4.4. The generation of ray and cluster are governed by equation (4.2), equation (4.3) and angular distribution is given by equation (4.5).

The TSV model considered in this work for desktop environment has the following specifications for obtaining the PDP.

The PDP obtained using Table 4.1 and cluster/ray arrival/decay rates can be used to measure channel parameters mean excess delay, RMS delay spread, maximum excess delay, received power and Rician factor ($K$). The specification in Table 4.1 give the room dimensions, the transmit and receive antenna height used, the room superstructure in the form of number of clusters, the distance between the transmitter and receiver in desktop environment.
Table 4.1 Layout geometry for CM7 (desktop model) contributed by NICT (www.ieee802.org)

In general, Table 4.1 is the layout geometry considered in the experimental setup by NICT to study and analyze the indoor channel propagation characteristics.

4.3 Spatial Multiplexing in LOS

The Shannon’s capacity theorem states that channel capacity increases with increase in bandwidth or increase in signal power.

\[ C = B \log_2 (1 + SNR) \text{ bps} \]

(4.11)

Where \( C \) is the channel capacity, \( B \) is the bandwidth and \( SNR \) is the signal power to noise ratio. \( SNR \) is computed as follows

\[ SNR = EIRP + G_r - PL(d_0) - PL(d) - I_L - 10 \log_{10}(kTB) \]

(4.12)

\( EIRP = P_t G_t \) is the equivalent isotropic radiated power, \( P_t \) is the transmit power and \( G_t \) is the transmit antenna gain.

In equation (4.12) \( G_r \) is the receive antenna gain, \( PL(d_0) \) is the FSPL, \( PL(d) \) is the path loss at \( d \), \( I_L \) the implementation loss, \( kTB \) is the noise power, where \( k \) is the Boltzmann constant, \( T \) is the equivalent noise temperature. Capacity increase is bounded by limitations in bandwidth and interference free increase in signal power. This holds good for a single input single output (SISO) system. These limitations are overcome by increasing the number of antenna from one to many, which takes advantage of the multipath fading environment.

Having multiple transmit (\( M_T \)) and receive antenna, (\( M_R \)) so called Multi Input and Multi Output (MIMO) system, the capacity in independent and identically distributed (i.i.d) channel is \( M_T \) times the SISO capacity. MIMO system can be realized as a combination of \( M_T \) parallel SISO system. Thus channel capacity is expected to increase with independent
MIMO channels and reduces to a minimum value called outage capacity when the MIMO channel has high spatial correlation.

At MMW frequencies, SM for MIMO links is found to be available with moderate antenna spacing without rich scattering (Torkildson, E., Zhang, H. and Madhow, U., 2010). This is possible with directional antenna as propagation loss at smaller wavelength is high with omni-directional case. In this work, as discussed in section 4.2, vertical polarized pencil beam antenna is assumed in both transmitter and receiver. The PDP when Tx/Rx beam are facing each other under LOS case, includes direct ray which contributes to maximum signal power and hence increase in multiplexing gain. Multiplexing gain is defined as the capacity gain at no additional power or bandwidth consumption obtained through the use of multiple antennas at both sides of a wireless link (Jankiraman, M. 2004). The objective of the spatial multiplexed systems as opposed to space-time diversity coding is to maximize the transmission rate.

Figure 4.5 MIMO system with directional antenna setup
In Figure 4.5, the symbols are modulated using Phase Shift keying (PSK) due to low power requirement in the transmitter and reduced phase noise in receiver. The modulated stream is then demultiplexed into $M_T$ streams depending on the number of transmit antenna. Accordingly, the $M_T$ independent data symbols are transmitted per symbol period. The time varying impulse response between $j^{th}$ $(1, 2, \ldots, M_T)$ transmitter antennas and $j^{th}$ $(1, 2, \ldots, M_R)$ receiver antenna is denoted as $h_{i,j}(t, \varphi)$, which are the TSV channel coefficients. The channel response is given by $H(t, \varphi)$ with dimension $M_R \times M_T$ matrix (Paulraj, A.J et al., 2004). The channel coefficients in equation (4.13) have the characteristics described in equation (4.6). Accounting for reduced spatial correlation, by maintaining $\lambda/2$ antenna spacing, the TSV channel matrix equation (4.13) is found to have full rank, which enables increase in data rate.

$$H(t, \varphi) = \begin{pmatrix}
h_{i,1}(t, \varphi) & h_{i,2}(t, \varphi) & \cdots & h_{i,M_T}(t, \varphi) \\
h_{2,1}(t, \varphi) & h_{2,2}(t, \varphi) & \cdots & h_{2,M_T}(t, \varphi) \\
\vdots & \vdots & \ddots & \vdots \\
h_{M_R,1}(t, \varphi) & h_{M_R,2}(t, \varphi) & \cdots & h_{M_R,M_T}(t, \varphi)
\end{pmatrix} \tag{4.13}$$

Given that $x_j(t)$ is launched from $j^{th}$ transmitter antenna, the signal received $y_i(t)$ at $i^{th}$ receiver antenna is

$$y_i(t) = \sum_{j=1}^{M_T} [h_{i,j}(t, \varphi)x_j(t)] + n_i(t) \tag{4.14}$$

The receiver processes equation (4.14) with perfect CSI known at the receiver. The dominant path generated by the two-path model is considered and the reflected paths in clusters contribute insignificant power to the receiver. The atmospheric and thermal noise is modeled as $n(t)$ in equation (4.14). The effect of noise and other channel impairments are equalized. The in-phase and out-phase component are separated in demodulation and the binary stream decoded in the final stage in the receiver. The remainder of this section focuses on receiver
structures for spatial multiplexing and the corresponding performance complexity tradeoff. For the sake of simplicity the number of receiver antennas is considered to be equal to transmitter antennas. Simple receiver structures are chosen for channel equalization owing to their less computational complexity. In addition to this fact, the MIMO channel for 60 GHz is found to possess the following characteristics (i) The $h_{ij}$ component when $i = j$ is the desired and has more value compared to $i \neq j$. (ii) The delay spread being low, the MMW signal experiences flat fading and (iii) The channel matrix is close to diagonal matrix. Owing to the above factors conventional linear equalizers i.e ZF, MMSE are selected for MMW 60 GHz system.

A. Zero Forcing Receiver (ZF)

Considering the MIMO channel model given in equation (4.13), where the $M_T$ data sub streams are mixed by the channel matrix. The ZF equalizer can be applied to decouple the $M_T$ substreams (Jiang, Yi. et al., 2011).

$$W_{zf} = (H^*H)^{-1}H^*$$

(4.15)

where $H$ is channel matrix whose co-efficient are obtained using equation (4.6) and $H^*$ is the conjugate transpose of $H$. The product of channel matrix and its conjugate transpose is performed for non-square channel matrix, that arises when $M_T \neq M_R$. Multiplying the received signal vector $y$ given in equation (4.14) by $W_{zf}$, $M_T$ decoupled substreams is obtained with output SNRs given as

$$\rho_{zf,n} = \frac{\text{snr}}{[(H^*H)^{-1}]_{nn}}, \quad 1 \leq n \leq M_T$$

(4.16)

The snr in equation (4.16), is the input signal to noise ratio, where the signal power $E\{XX^*\} = \sigma^2 I$ is uniform across all the antennas and noise is white Gaussian with normal distribution of zero mean and unit variance. The ZF receiver converts the joint decoding problem into single stream decoding problems thereby significantly reducing receiver complexity. This leads to the trade-off between complexity reduction and performance degradation since only the channel impairments are equalized and without accounting for noise.

B. Minimum Mean Square Error (MMSE)

Considering the MIMO channel model given in equation (4.13), where the $M_T$ data
substreams are mixed by the channel matrix. The MMSE equalizers can be applied to decouple the $M_T$ substreams (Jiang, Yi. et al., 2011).

$$W_{MMSE} = \left( H^* H + \frac{1}{\text{snr}} I \right)^{-1} H^*$$  \hspace{1cm} (4.17)

Multiplying the received signal vector $y$ in equation (4.14) by $W_{MMSE}$, $M_T$ decoupled substreams is obtained with output SNRs given as,

$$\rho_{\text{mmse},n} = \frac{\text{snr}}{[(H^* H + \frac{1}{\text{snr}} I)^{-1}]_{nn}} - 1, \quad 1 \leq n \leq M_T$$  \hspace{1cm} (4.18)

In equation (4.18), $I$ is the identity matrix and $[.]_{nn}$ denotes the nth diagonal element. The MMSE receiver suppresses both the interference and noise components, whereas the ZF receiver removes only the interference components. Some of the important characteristics of MMSE detector are simple linear receiver, superior performance to ZF and at low SNR, MMSE performance equals that of the matched filter. The linear ZF and MMSE equalizers are classic functional blocks and are ubiquitous in digital communications. They are also the building blocks of more advanced communication schemes such as the decision feedback equalizer (DFE) or equivalently, the V-BLAST (Vertical Bell Labs layered Space-Time) architecture and various other MIMO transceiver designs. It is commonly understood that ZF is a limiting form of MMSE as SNR tends to infinity.

C. Maximum Likelihood Receiver (ML)

The signals $x_j(t)$ from the multiple transmitter are influenced by the TSV channel matrix $H$. These signals form a constellation in the signaling space. The received signal in equation (4.14) is decomposed to its components in the signal space. The ML receiver performs optimum vector decoding and is optimal in the sense of minimizing the error probability (Tse, D. and Viswanath, P. 2005). ML receiver is a method that compares the received signals $y_1, y_2, y_3, ..., y_{M_T}$ with all possible transmitted signal vector which is modified by channel matrix $H$ and estimates transmit symbol vector $x$ according to the ML principle given by,

$$\hat{x} = \arg \min_{x \in \{x_1, x_2, ..., x_{M_T}\}} \|y - Hx\|^2$$  \hspace{1cm} (4.19)

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where the minimization is performed over all possible transmit symbols $x$. The ML receiver selects signal $y$ that is close to the signal point $x$ in the signal space. Although ML detection offers optimal error performance, it suffers from complexity issues. The complexity increases exponentially with increase in constellation size i.e the receiver has to consider $|A|^M_T$ possible symbols where $A$ is the modulation constellation and $M_T$ is the transmitter antenna system.

4.4 Results and discussion

4.4.1 Power delay and angle profile analysis of TSV channel

The statistic two path model proposed by Shoji, Sawada was based on device-position dependent fading specific for MMW WPAN (Sawada, H. et al., 2006). This was then combined with the SV model which was the model used in IEEE 802.15 standardization groups. Thus this TSV model as discussed in section 4.2 is analyzed considering LOS desktop environment. The directional antenna in both transmitter and receiver having half power beamwidth $30^0$ with the layout geometry listed in Table 4.1 is considered. The PDP of the channel is analyzed with the channel parameters i.e cluster and ray arrival rate, cluster and ray decay rate with the experimental setup (Sawada, H. et al., 2006 ; Sato, K. et al., 2007).

![Figure 4.6 Power delay profile of TSV channel in desktop environment](image)

Figure 4.6 Power delay profile of TSV channel in desktop environment

PDP in Figure 4.6 shows the presence of LOS and NLOS components as is evident from equation (4.10). The significant contribution of LOS is due to the directional transmit and receive antenna. Perfect alignment between them is also one of the reasons for high LOS and
reduced power in NLOS. Desktop environment is chosen to guarantee dominant LOS channel given in equation (4.6) with few clusters between transmit and receive and this is ensured using TSV discussed in detail in section 4.2. The average power owes to the fact that the four clusters that comprise the channel has been accounted and averaged. From Figure 4.6, the rician factor \( K \), root mean square delay spread \( \text{RDS} \) can be calculated.

From the average power delay profile, the RDS can be defined by (Yang, H. et al., 2007)

\[
\sigma_s = \sqrt{\sum_{n=0}^{N} P(\tau_n) (\tau_n - \bar{\tau})^2}
\]

(4.20)

where \( \tau_n \) is the delay component and \( \bar{\tau} \) is the mean excess delay and \( P(\tau_n) \) is the received power of signal.

With the mean excess delay \( \bar{\tau} \) given by

\[
\bar{\tau} = \sum_{n=0}^{N} \tau_n P(\tau_n)
\]

(4.21)

where \( P(\tau_n) \) is the received power of the signal.

Rician \( K \)-factor is the ratio between the powers contributed by the direct path and the reflected paths (Yang, H., et al., 2007).

\[
K = \frac{E\left(\left|\alpha_n\right|^2\right)}{2\sigma^2}
\]

(4.22)

Where \( 2\sigma^2 \) is the mean power of the scattered path.

The values in Table 4.2 are those obtained from Figure 4.6 and using equation (4.20), equation (4.21) and equation (4.22).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space pathloss</td>
<td>-81.9842[dB]</td>
</tr>
<tr>
<td>RMS delay spread</td>
<td>1.290 [ns]</td>
</tr>
<tr>
<td>Maximum delay spread</td>
<td>2.657 [ns]</td>
</tr>
<tr>
<td>Minimum delay spread</td>
<td>0.693 [ns]</td>
</tr>
<tr>
<td>Average Rician factor</td>
<td>27.023 [dB]</td>
</tr>
<tr>
<td>Maximum Rician factor (K)</td>
<td>35.799 [dB]</td>
</tr>
<tr>
<td>Minimum Rician factor</td>
<td>14.737 [dB]</td>
</tr>
</tbody>
</table>

Table 4.2 Model parameters calculated from Power Delay Profile

In Table 4.2, for four cluster desktop environment, the delay spread ranges between 0.693 ns and 2.657 ns. The minimum delay spread is the difference in time between the LOS and the
first arrived path while the maximum delay spread is the difference in time between the LOS and the last arrived path. RDS is analyzed to study the maximum data rate that could be achieved in the system without equalization. In general for directive configurations, delay spread less than 1.5 ns and rician factor greater than 10 leads to less time dispersive channel characteristics and accounts for larger coherence bandwidth (Yang, H. et al., 2007). As the achieved RMS delay spread is less than 1.5 ns and Rician factor is greater than 10 listed in Table 4.2, the TSV channel appears to be less time dispersive. The less time dispersive channel indicates frequency flat fading channel characteristics. As RDS and coherence bandwidth are inversely proportional, the channel is ISI free, that is evident from the equation $B_c=1/50\sigma$ (Rappaport, T.S. 2002).

The free space path loss in Table 4.2 is used to compute the received signal power which is a function of distance and frequency. The received signal power decreases with increase in distance and frequency. The received power and receiver sensitivity together decide the link margin.

$$\text{Link Margin} = \text{Received power} - \text{Receiver sensitivity}$$

(4.23)

The detailed analysis of the link budget for 60 GHz MMW is discussed in chapter 5.

![Figure 4.7 Power Delay Profile of individual cluster](image)

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The power in each cluster is depicted in Figure 4.7. As ToA increases the power decreases, since the signal has undergone multiple reflections and traversed longer path before reaching the receiver. This is evident from Friis expression

\[
P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}
\]

(4.24)

Where \( P_r \) is the received power, \( P_t \) is the transmitted power, \( G_t, G_r \) are the transmit and receive antenna gain, \( \lambda \) is the carrier wavelength and \( R \) is transmit and receive distance. From equation (4.10), the PDP unique to that of indoor channel is observed in Figure 4.6. This characteristic has been discussed in section 4.2. The LOS part, the constant part and exponential decay part is the general indoor channel profile.

Figure 4.8 Power Delay Profile and Power Angle Profile (PAP)
Power as a function of ToA and AoA is shown in Figure 4.8. The LOS is available at ToA=0 ns, constant signal level is clustered in ranges of 2 to 5 ns, 7 to 11 ns and 16 to 18 ns followed with decay as shown in Figure 4.7. Angle spread in Figure 4.8 gives the directional distribution of multipath components as discussed in section 4.2.

4.4.2 Spatial Multiplexing in LOS using TSV

The system in Figure 4.5 is considered for the analysis. The system is simulated using random samples drawn from the uniform distribution and noise signal is generated using normal distribution of zero mean and unit variance. The samples drawn from the distribution are taken to be equiprobable for simple and efficient decoding.

LOS links are well established with high directional narrow beam antenna and also with circular polarized antenna as this suppresses the multipath components. In this analysis, the first case is used. As SNR has to be maintained high, the effects of interference and noise are to be reduced. External and internal noise radiators contribute to atmospheric noise and thermal noise. The internal noise minimization is performed using suitable equalization techniques. BER metric is the evaluation parameter used to measure the performance of the equalization technique at low and high SNR. Spatial multiplexed system using Table 4.3 is analyzed for 2x2, 4x4 and 8x8 antenna configuration for MMW using TSV channel model.

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bits</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Modulation Used</td>
<td>BPSK</td>
</tr>
<tr>
<td>Transmit and receive antenna beamwidth</td>
<td>$30^\circ$</td>
</tr>
<tr>
<td>$E_b/N_0$</td>
<td>1:8 dB</td>
</tr>
<tr>
<td>Channel Model</td>
<td>Triple Saleh Valenzuela</td>
</tr>
<tr>
<td>Environment Used</td>
<td>Desktop</td>
</tr>
<tr>
<td>Centre Frequency</td>
<td>60 GHz</td>
</tr>
<tr>
<td>MIMO configuration</td>
<td>2x2, 4x4 and 8x8</td>
</tr>
<tr>
<td>Equalization</td>
<td>ZF, MMSE and ML</td>
</tr>
</tbody>
</table>

Table 4.3 Parameters for 2x2, 4x4 and 8x8 spatial multiplexed system
In Table 4.3, parameters used in analyzing the performance of spatial multiplexing in line-of-sight condition are considered. Linear modulation technique BPSK is chosen as it has good spectral efficiency and also offers reduced probability of error. The indoor channel model TSV, discussed in section 4.2 is used to model the propagation characteristics for desktop environment listed in Table 4.1. To equalize the channel impairments, equalization techniques i.e ZF, MMSE and ML are used and their performance is evaluated.

The ML equalization results in reduced BER compared to ZF and MMSE as is evident in figure 4.9. ML evaluates the euclidean distance between the transmitted and the received signal which are BPSK modulated. The ML estimate for all data combinations are calculated and the combination that yields minimum distance is considered the best equalized signal. While MMSE has little improvement in BER compared to ZF in $E_b/N_0$ range 6 to 8 dB. The
MMSE from equation (4.17) and equation (4.18) indicates the reduction of noise along with the channel equalization, which is not the case with ZF.

![Graph showing Bit Error Rate (BER) performance for a 4x4 Spatial Multiplexed system](image)

Figure 4.10 Bit Error Rate performance for a 4x4 Spatial Multiplexed system

The probability of error calculated using the Q-function in (Jiang, Yi et al., 2011), shows marginal advantage of ZF over MMSE. As the path loss and reflection loss are the maximum in MMW system, the received signal power is minimum compared to noise power, hence MMSE shows drop in performance compared to ZF in low SNR in Figure 4.10. But MMSE performance is comparable to ZF in high SNR regime (Jiang, Yi et al., 2011). ML chooses the data combination that has minimum Euclidean distance, the complexity of ML increases with increase in transmit/receive antenna. The BER obtained for 4x4 using TSV is compared with Rayleigh channel proposed by Jiang, Yi et al., and is made available in Table 4.5 to demonstrate the performance improvement of equalization techniques for the indoor channel under consideration.
SM with 8x8 is attempted for MMW as the dimension of the antenna is of the order of millimeter for 60 GHz frequency and BER performance analyzed in Figure 4.11. High data rates are achieved with increase in MIMO configuration, which is discussed in chapter 5. The performance of the equalizers is the same even with increase in MIMO configuration as the targeted link is LOS.

Table 4.4 gives the performance comparison of equalization techniques used for spatial multiplexed line of sight millimeter wave system. In low and high $E_b/N_0$ region, ML is found to have reduced BER compared to ZF and MMSE in all MIMO configurations. ZF is the best technique in the absence of noise, to overcome the noise effects MMSE is used since the minimization of error accounts for the noise effects.
Table 4.4 Equalization performance comparison of 2x2, 4x4 and 8x8 spatial multiplexed line of sight system for Rician factor $K = 35.799$ dB

With MMSE, BER of $10^{-3.8}$ at 8 dB is achieved. Reduction in BER is achieved using ML, resulting in BER of $10^{-5.5}$ at 8 dB for 4x4 MIMO configuration. Table 4.4 indicates performance of the equalizers is the same even with increase in MIMO configuration as the targeted link is LOS. Thus MMSE and ML performance for 4x4 and 8x8 configuration is the same as seen in Table 4.4.

<table>
<thead>
<tr>
<th>Equalization</th>
<th>2x2</th>
<th>4x4</th>
<th>8x8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b/N_0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 dB</td>
<td>$10^{-2}$</td>
<td>$10^{-2.4}$</td>
<td>$10^{-2.6}$</td>
</tr>
<tr>
<td>8 dB</td>
<td>$10^{-2.3}$</td>
<td>$10^{-2.5}$</td>
<td>$10^{-2.6}$</td>
</tr>
<tr>
<td>BER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZF</td>
<td>$10^{-2.6}$</td>
<td>$10^{-3.3}$</td>
<td>$10^{-3.2}$</td>
</tr>
<tr>
<td>MMSE</td>
<td>$10^{-2.7}$</td>
<td>$10^{-3.8}$</td>
<td>$10^{-3.2}$</td>
</tr>
<tr>
<td>ML</td>
<td>$10^{-2.5}$</td>
<td>$10^{-4}$</td>
<td>$10^{-3.7}$</td>
</tr>
</tbody>
</table>

Table 4.5 Equalization performance comparison using TSV and Rayleigh for 4x4 system

In Table 4.5, comparing BER of 4x4 system using Rayleigh channel proposed by Jiang, Yi. et al., with that using TSV, reduction in BER is obtained using TSV owing to high Rician factor of 35.799 dB.

<table>
<thead>
<tr>
<th>Channel model</th>
<th>TSV</th>
<th>Rayleigh (Jiang, Yi. et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b/N_0$</td>
<td></td>
<td>5 dB</td>
</tr>
<tr>
<td>BER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZF Equalizer</td>
<td>$10^{-2.6}$</td>
<td>$10^{-3.3}$</td>
</tr>
<tr>
<td>MMSE Equalizer</td>
<td>$10^{-2.7}$</td>
<td>$10^{-3.8}$</td>
</tr>
</tbody>
</table>

4.5 Conclusion and contribution

The exponential PDP that is fitting best for the outdoor environment is replaced with specular ray, constant part and an exponential decay part for indoor environment. The indoor channel model TSV is cluster based model with dominant LOS and NLOS clusters with ray formed by reflection, scattering and diffraction effects. The parameters considered for the simulation of the TSV model is as contributed by NICT Japan to the TG3c group that complies with propagation conditions expected at 60 GHz. The simulation was performed for an indoor desktop environment having a distance of 3m considering the transmitter antenna...
beamwidth and receiver antenna beamwidth as 30°. The RDS from the PDP is found to be 1.29 ns, which is in perfect agreement with observations by Yang, H. et al. In general for directive configurations, delay spread less than 1.5 ns and rician factor greater than 10 leads to less time dispersive channel characteristics and accounts for larger coherence bandwidth (Yang, H. et al., 2007).

The low delay spread enables spatial multiplexing in LOS environment. Also, the diagonal elements of the channel matrix had relatively better signal strength than the off-diagonal reflected co-efficients. This validates spatial multiplexing can be implemented in LOS condition. The analysis of spatial multiplexed system with 2x2, 4x4 and 8x8 configurations were performed.

The path loss and reflection loss are the maximum in MMW system, the received signal power is minimum compared to noise power. This leads to reduction in link budget and hence increases the probability of error in signal detection. The reduction in signal strength is better compensated in the baseband subsystem apart from the signal strength improvements imparted by the RF, IF subsystems and the matched filter. This leads to the use of simple equalization techniques such as ZF, MMSE and ML. In low and high $E_b/N_0$ region, ML is found to have reduced BER compared to ZF and MMSE. ZF is the best technique in the absence of noise, to overcome the noise effects MMSE is used since the minimization of error accounts for the noise effects. With MMSE, BER of $10^{-3.8}$ at 8 dB is achieved.

Reduction in BER is achieved using ML, resulting in BER of $10^{-5.5}$ at 8 dB for 4x4 MIMO configuration. The BER obtained for 4x4 using TSV is compared with Rayleigh channel proposed by Jiang, Yi et al., and is made available in Table 4.5 to demonstrate the performance improvement of equalization techniques for the indoor channel under consideration.

Thus to understand the propagation characteristics of the physical layer at 60 GHz, a suitable channel model depicting the same has been performed. From the channel characteristics analyzed, means of achieving high date rate using spatial multiplexing in LOS was performed. In addition to this, the receiver baseband subsystem to reduce BER was also analyzed. The channel capacity, link budget of 60 GHz system is analyzed in the next chapter. Also performance comparison of 5 GHz and 60 GHz the probable frequency candidates for WPAN system is analyzed.