Performance and Capacity analysis of MIMO system at 5 GHz and 60GHz in Indoor Environment

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Abstract:- The Millimeter Wave (MMW) band much useful for wireless indoor communications as it offers a large amount of license free spectrum. Blockage by walls and furniture limits the range indoors, the link range for indoors being 10m and outdoors 100m in the case of spatial reuse. The idea of dual-band integration of 5GHz/60GHz conceived by IST-Broadway is considered. The physical link layer throughput achievable in 5GHz would be limited by the available bandwidth while the huge bandwidth available for 60GHz would make it feasible for multi-gigabit link. Spatial multiplexing can offer large capacity gains if the spatial correlation is low. In this work, MIMO channel for 5 GHz and 60 GHz is modeled and the channel capacity is determined. The Triple Saleh Valenzuela model (desktop environment) is chosen as suitable channel model for Millimeter Wave while IEEE 802.11n channel model B (small offices) is chosen for 5GHz. The power delay profile obtained on simulation gives the Rician factor and the RMS delay spread indicating multipath fading and time-dispersive channel. The performance is analysed with respect to bit error rate (BER) for various antenna configurations with transceiver distance of 3m. Consideration of Line –of-Sight (LOS) component shows reduced BER in lower E_b/N_o range of 1 to 4 dB for 60 GHz compared to 5 GHz radio. This result makes MMW suitable for integration with 5 GHz, whose link is weak for short range communication. The bit error rate (BER) is compared for 2x2, 4x4, and 8x8 for different equalization techniques namely Zero Forcing (ZF), Maximum Likelihood (ML) and Minimum Mean Square Error (MMSE) for the two cases, which in turn had reinforced the fact of better performance of MMW. ML detection offers optimal error performance for 60 GHz. The channel capacity is found to be 2 Gbps for 60GHz and 600 Mbps for 5GHz. The link budget for MMW is also analyzed.

Key-Words:- Millimeter Wave, Time of Arrival (ToA), Angle of Arrival (AoA), Cluster arrival rate, Ray arrival rate, Spatial correlation.

1. Introduction

Uncompressed multimedia data transfer between wireless devices is expected to grow exponentially requires large bandwidth. This requirement would only be satisfied by millimeter wave technology especially in the unlicensed spectrum centered at 60GHz. For the efficient use of this spectrum necessitous the detailed study on channel performance and characteristics. The data rates have been increasing constantly from 1 Mbps in first generation to 600 Mbps with 802.11n MIMO products. IEEE 802.11n working group began a Very High Throughput Study Group (VHT SG) to investigate technologies giving multi-gigabit link throughput [1][2]. The achievable throughput in 2.5 GHz and 5 GHz bands would be limited by the bandwidth limitation in these two bands. The usage models of WLAN cover environments like sync-and-go, downloading movies or pictures from camera needs increasingly higher throughput as the quality and resolution increases. The growing uses like internet telephony, music, gaming, and in-home video transmission have in turn increased the number of WLAN users. This has started to strain the existing Wi-Fi networks which therefore, needs a frequency band that gives huge bandwidth and less interference [3][4].

The Millimeter Wave (MMW) being an attractive option for designing the multi gigabit links as they offer 7 GHz bandwidth of spectrum spanning from 57 -64 GHz. The MMW has made the possibility of usage of Wireless USB, Wireless Gigabit Ethernet. The large available bandwidth and O_2 absorption present at 60GHz and other intrinsic atmospheric attenuation make the MMW useful for high data rates and spatial reuse [5]. The range is limited by the blockage of waves by walls and furniture, the link range for indoors being 10m and outdoors 100m in the case of spatial reuse. This produces fast and fading statistics in channel. At 60 GHz, free space path loss is much higher. This property has led to the solution of integrating the existing 5 GHz network with the 60 GHz band.

The issues regarding the use of MMW initiate with the physical layer [6][7]. Channel capacity for indoor LOS spatial multiplexing was maximized by considering the singular values of the channel matrix [8][10]. Also degrees of freedom increased with more number of high singular values, which led to independent channels thus increasing the data rate. Antenna array with uniform linear configuration was accounted to deal with high propagation loss inherent with MMW. The limit on the array length without compromising channel capacity was studied [9][10]. The channel considered in the above work was 2-ray and 6-ray model accounting for the LOS and NLOS path [10].

The primary challenge is to cover the range for WLAN. The blockages occurring due to the environment decrease the coverage range of the MMW. This can be reduced by high gain antennas, high transmit power and sensitive receiver [11]. As the wavelength of the MMW is small, number of antennas can be packed on a small platform. This will increase the gain and hence there will be an increase in the link budget characteristics. Care should be taken to decrease the side lobes in the undesired directions [12]. Another key challenge in the Medium Access Layer (MAC) lies in providing the link robustness. As MMW is susceptible to high attenuations through obstructions, link is easily broken. In addition, the use of directional antennas makes the link sensitive to slight movement of the objects. To combat this, multipath MAC and efficient contention based schemes needs to be designed for the MMW propagation [13] [14].

The feasibility of the MMW is much higher than 5 GHz band for short-range communication. The data rate of more than 1 Gbps can be achieved easily in MMW band with lower order modulation schemes like BPSK without the use of many antennas, whereas in 5GHz , the transmit and receive antennas has to be increased and higher modulation schemes like QAM has to be used [15] . Various parameters like the link budget, channel capacity and its comparison with the Shannon limit was performed varying the communication range from 5 -20 m for 60 GHz system [16]. The EIRP achieved by the MMW is nearly 4dB higher than that achieved in the 5 GHz band. This is possible for MMW because a number of antennas can be integrated which increases the gain of the link.

Modeling indoor propagation environment is complicated by large variability in building layout and construction materials. 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 [17]. The wideband of waves used in indoor applications increase the sensitivity to delay spread. Site-specific and site-general modeling are the two general types of propagation modeling. As the path loss combines with other channel impairments like delay spread, there arises a necessity to use directional antennas to obtain reliable communications [18][19]. 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.

Performance analysis of 60 GHz using Triple Saleh Valenzuela (TSV) was carried in the earlier work for MIMO system [20]. The analysis and results of the above work are used in this paper. MIMO system performance for 60 GHz and 5 GHz is studied and analyzed [21]. The channel model used for the MMW propagation is the TSV which is a modified form of Saleh Valenzuela (SV) model. This is a merger of two-path model and SV model. This model was contributed by NICT, Japan to 802.15.3c [22]. The complex impulse response obtained from this model contains the Time of Arrival information (ToA), Angle of Arrival information (AoA), and amplitude of each ray in the cluster[20]. For 5 GHz, IEEE 802.11n channel model B is used. The performance of the systems with respect to BER in lower and higher SNR ranges, the channel capacity and link budget for MMW is analyzed. In this paper, section 2 and 3 discusses the channel models used for 60 GHz and 5 GHz, section 4 discusses MIMO system for indoor environments using TSV model, which is a cluster based model newly attempted in this work as opposed to ray tracing technique along with the various equalization techniques and section 5 discusses the results with respect to BER performance, computation of channel capacity of 60 GHz and 5 GHz and the link budget analysis for MMW system.

2. Triple Saleh Valenzuela Model for 60 GHz

Indoor channel modeling is found to be difficult by the large number of obstructions, variations in layout of the building and movements of people. To satisfy all these, site-general models are preferred. As the frequency of operation for millimeter waves is very high, large bandwidths are available for the link but this high frequency also leads to high path loss [22][23].

The TSV is a site-general model that merges S-V and two-path models. 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 [17].

The impulse response of the modified SV model accounted for the antenna effects such as angle spread in the transmitter and receiver antenna [14]. MMW being high frequency waves, both LOS and NLOS components tend to dominate. Hence the complex impulse response (CIR) of the TSV model is given [7] as

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

where β is the direct wave component that holds the information about the heights of the transmitter and receiver antenna, distance between the antenna, reflection co-efficient and the wavelength at the center frequency[17], $\alpha_{l,m}$ 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, $\psi_{l,m}$ 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.

The direct path component is generated by using a two-path model as shown in [7]

$$\beta=\frac{\mu_D}{D}\left|G_{t1}G_{r1}+G_{t2}G_{r2}\,\Gamma_0\,\exp\left[j\frac{2\pi}{\lambda_f}\frac{2h_1h_2}{D}\right]\right| \tag{2}$$

where D is the distance between the transmit and receive antennas and h_1 , h_2 are the antenna heights λ_f, Γ_o, and μ_D are the wavelength at the centre frequency, the reflection coefficient, and the average distance distribution respectively. G_{t1} and G_{r1} are the transmitter and receiver gains for the direct path, and G_{t2} and G_{r2} are the transmitter and receiver gains for the reflected path. The value of β is very sensitive to small antenna movements [22]. The arrival rate of clusters and rays are defined by the Poisson process as following

$$P(T_l \mid T_{l-1}) = \Lambda \exp\{-\Lambda (T_l-T_{l-1})\} \qquad l > 0 \tag{3}$$

$$P(\tau_l \mid \tau_{l,(m-1)}) = \lambda \exp\{-\lambda (\tau_l-\tau_{l,(m-1)})\} \qquad m > 0 \tag{4}$$

where Λ and λ are the cluster and ray-arrival rate respectively.

3. Channel model for 5 GHz

The channel used is IEEE 802.11n B that uses 5GHz as the centre frequency and 48 MHz bandwidth. The IEEE 802.11n group has developed channel models applicable for indoor WLAN systems. These models are developed by the cluster models given by the Saleh-Valenzuela channel models. The number of clusters considered for the models varies from 2 to 6. Angle of Arrival (AoA), Angle of Departure (AoD), Angular Spread (AS) vary for each cluster models. Cluster angular spread was found to be between 20^0 and 40^0 range and mean AoA had uniform distribution. The channel correlation matrix can be obtained from all these values of AoD, AS, AoA. The size of the channel matrix depends on the number of transmitter and receiver antennas. If the number of transmit antenna is n_t and that of receiver antenna is n_r the size of the channel would be n_t x n_r [18][19].

The MIMO matrix formulation is done by the equation as follows:

$$H=\sqrt{P}\left[\sqrt{\frac{K}{K+1}}H_{Rician}+\sqrt{\frac{1}{K+1}}H_{Rayleigh}\right] \tag{5}$$

$$H=\sqrt{P}\left[\sqrt{\frac{K}{K+1}}\begin{bmatrix}e^{j\varphi 11} & e^{j\varphi 12}\\ e^{j\varphi 21} & e^{j\varphi 22}\end{bmatrix}+\sqrt{\frac{1}{K+1}}\begin{bmatrix}X_{11} & X_{12}\\ X_{21} & X_{22}\end{bmatrix}\right] \tag{6}$$

where $\sqrt{\frac{K}{K+1}}H_{Rician}$ is the LOS component of the channel and $\sqrt{\frac{1}{K+1}}H_{Rayleigh}$ is the fading component. K is the Rician factor, and P is the power of each tap. X_{ij} (i-th receiving and j-th transmitting antenna) are correlated zero-mean, unit variance, complex Gaussian random variables considered as coefficients of the variable NLOS (Rayleigh) matrix $H_{Rayleigh}$, $e^{j\varphi}$ are the elements of the fixed LOS matrix H_{Rician}. It is assumed that each tap consists of a number of individual rays so that the complex Gaussian assumption is valid. P in (5) represents the sum of the fixed LOS power and the variable NLOS power (sum of powers of all taps). Parameters in the 5GHz channel model are as follows:

Table 1: Channel B parameters for IEEE 802.11n

Model Name	**Condition**	**Rician factor K (dB)**	**RMS delay spread(ns)**	**No. of clusters**
B	LOS and NLOS	∞/0	15	2

4. MIMO Transceiver for 5 GHz and 60 GHz

Considering a MIMO structure containing $\{1,2,\ldots M_T\}$ transmitter antennas and $\{1,2,\ldots M_R\}$ receiver antennas , the discrete time channel is modeled using the equation,

$$Y = HX + N \quad (7)$$

Where, Y is the (M_R x 1) channel output, X is the (M_T x1) transmitted data. H is the (M_R x M_T) impulse response of the channel which contains the Time of Arrival (ToA) and AoA information and N is the (M_R x 1) Additive White Gaussian Noise (AWGN). The work contributed by us (Savitha Manojna et.al[20]), has analysed the MIMO transceiver performance for 60 GHz. The influence of TSV and channel B on the multiplexed data stream and equalization of complex channel co-efficient due to time-dispersive channel are presented in the following two sections.

4.1 Spatial Multiplexing

The multipath fading is considered to be that of the near-field effect, as the system is designed for indoor environment. With dominance of LOS component, spatial multiplexing is considered to improve the channel capacity. By providing multiple transmit and multiple receive antennae, spatial dimension increases and this leads to the increase in degree-of-freedom [21] [24][25]and [26]. The MIMO concept can be shown in the diagram as follows;

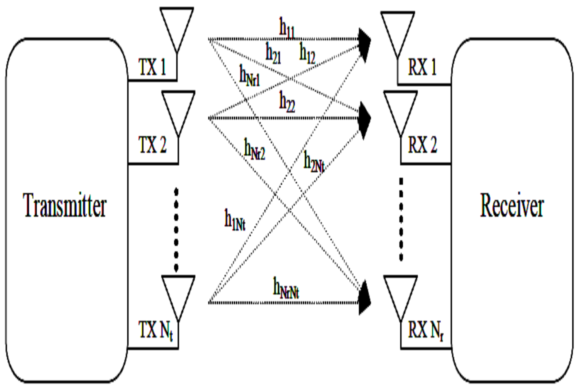

Fig. 1 MIMO Transceiver

The multiplexed data stream X, has both training and data. The training symbols train the receiver in identifying the spatial signatures, which is attenuated due to interference from the adjacent channel. This is evident from the Fig.1, receive antenna 1 (RX1), receives data from all transmit antenna TX 1,TX 2....TX N_t. The recovery of the spatial signature is performed using linear estimation techniques [27]. MIMO system is considered to be a set of parallel SISO systems. The singular value decomposition (SVD) of the channel matrix H results in independent SISO channel [28].

In any case for MIMO spatial multiplexing the number of receive antenna must be equal to or greater than the number of transmit antenna. To take advantage of the additional throughput offered, MIMO wireless systems utilize a matrix mathematical approach [29][30]and [31].

Spatial Multiplexing assumes full rank channel matrix i.e. the spatial correlation arising due to the scatterers, spacing between the antenna elements and antenna array geometry is low. Hence, M_T independent data symbols are transmitted per symbol period [10][28]. Considering no temporal inter-symbol interference (ISI), that is made possible with high directive antenna, the channel matrix has a dominant LOS. This contributes to improvement in performance in lower E_b/N_o range. With TSV being a two-ray model, one formed by LOS and the other one being the ground reflected path, the signal propagation is dominated by LOS [8]. In 5 GHz radio, multipath fading contributes to the major part of the signal propagation. Hence the channel impulse response in equation (7) is given by M_R x M_T matrix H (t,φ)

$$H(t,\varphi)=\begin{pmatrix} h_{1,1}(t,\varphi) & .... & h_{1,M_T}(t,\varphi) \\ . & . & . \\ . & . & . \\ h_{M_R,1}(t,\varphi) & .... & h_{M_R,M_T}(t,\varphi) \end{pmatrix} \tag{8}$$

The time varying impulse response between j^{th} (1,2,… M_T) transmitter antenna and i^{th} (1,2,….M_R) receiver antenna is denoted as $h_{i,j}(t,\varphi)$. The MIMO channel capacity can be calculated for TSV and channel B by performing SVD on H.

The MIMO channel capacity with M_t inputs and M_r output signals with equal power allocation in the transmitter as the channel state index (CSI) is unknown at the transmitter is represented as

$$C = E\left[\log_2\left(\det\left[I_{M_r} + \frac{SNR}{M_T} HH^H\right]\right)\right] \tag{9}$$

with I_{M_R} being the identity matrix of size M_R x M_T, where SNR is the signal to noise ratio and H is the channel matrix and H^H is the hermitian transpose.

Assuming perfect channel estimation, the received signal is sent to the different equalization schemes to estimate the transmitted signal and to reduce the noise. Three equalization schemes i.e. Zero Forcing, Minimum Mean Square Error and Maximum Likelihood are compared and the bit error rate is determined [20].

4.2 Equalization of channel effects

The following analysis is performed to reduce the channel impairments and reduce the ISI along with the noise.

A) Minimization of ISI using Zero Forcing technique

The time-dispersive nature of the channel within the cluster leads to ISI. The effect of ISI is reduced by using the ZFE. The channel matrix H is a function of delay spread, angle spread and doppler spread. The effect of doppler spread in indoor environment is too low and hence neglected.

With perfect channel estimation, the elements in the channel matrix can be equalized by multiplying the received signal with $W_{zf} = (H^*H)^{-1} H^*$. where H is the (M_R x M_T) impulse response of the channel which contains the ToA and AoA information and H^* is the conjugate of H.

As a comparison of 60 GHz and 5 GHz with respect to ZFE, distance of propagation is a matter of concern. In MMW, oxygen absorption limits the propagation and with directional antenna the effect of ISI will not be felt [10][32]. When LOS component is fully blocked, the received signal power goes below the receiver sensitivity and is left undetected. Hence directional antenna with moderate half power beamwidth is preferred, for which ZFE is required. In 5 GHz, ISI effect is pre-dominant and is effectively neutralized with one-tap filter.

B) Maximization of SNR using Maximum Likelihood Receiver (ML)

Due to multipath fading and noise, the received signal appears as a cloud of points around the desired signal. ML performs a comparison of these points with the desired signal and the optimum signal is determined. The optimum signal is the most likely signal with least error probability [27].

The ML principle is given as

$$m = \underset{x_k \, \varepsilon \, \{y_1, y_2 .... y_N\}}{\arg\min} \| y - x \|^2 \tag{10}$$

The noise effect in the received signal is taken into account on computing the most likely path. MMW and 5 GHz radio gain advantage with this ML.

C) Minimization of ISI and noise using Minimum Mean Square Error Receiver

Compared to ZFE, MMSE minimizes ISI and noise. With full rank channel, the channel correlation HH^* results in identity matrix. But, in reality, this cannot be achieved. The antenna array geometry, scatterer location and antenna polarization can be considered such that the uncorrelated channels are obtained.

MMSE computes the channel correlation R_h and effect of noise as $W_{MMSE} = \left(R_h + \frac{1}{SNR} I\right)^{-1} H^*$, in the received signal in (7).

5. Results and Discussion

The results obtained in the channel modeling and the spatial multiplexing of 2x2, 4x4, 8x8 antennae with 5 GHz and 60 GHz channel models are analyzed. The bit error rate of this configuration is computed and compared for various equalization techniques i.e. Zero Forcing, Minimum Mean Square Error and Maximum Likelihood. Also, the capacity and link budget is presented. At high SNR, the channel capacity increases with SNR as min $\{M_T, M_R\}$ log SNR (bps/Hz), in contrast to log SNR for single channels [21] .Thus multiple antenna channels are min $\{ M_T, M_R \}$ parallel spatial channels, which accounts hence it is the total number of degrees of freedom to communicate.

5.1 Power delay profile analysis for MMW

Power delay profile (PDP) denotes the average power that is associated with the given multipath delay. Using (1), the channel is modeled with the range being 3m and number of clusters considered to be 3. The LOS desktop parameters provided by NICT, Japan are used as part of two path statistical model [22]. The following parameters are used in modeling the channel.

Path loss = $(4\pi/\lambda)^2 d^n$ where d= 3m, λ=0.005m, n=2
Therefore, Path loss = 77.56 dB

Table 2: Parameters used in the TSV channel model

Channel model	Desktop – CM 7
Distance between transmitter and receiver	3m
LOS component path loss	77.54 dB
Average number of clusters	3
Cluster power level	- 92 dB
Small Rician effect	2.53
Cluster arrival angle in deg	34.6
Cluster arrival rate (Cluster per ns)	27
Ray arrival rate (Ray per ns)	1.56
Cluster decay rate (ns)	21.1
Ray decay rate (ns)	8.85
Standard deviation for lognormal variable for cluster fading	3.01
Standard deviation for lognormal variable for Ray fading	7.69

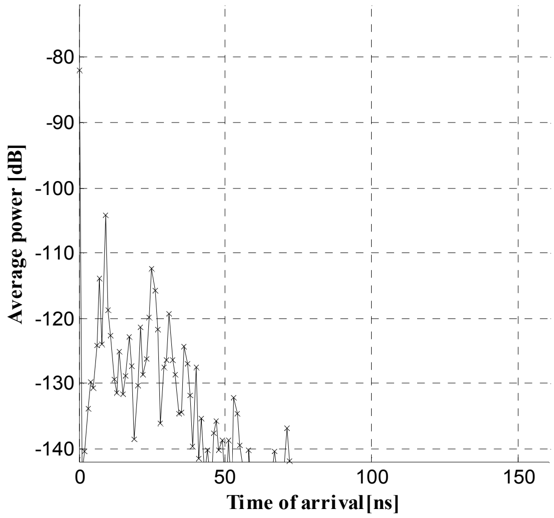

Fig. 2 PDP of the TSV channel

From Fig 2, the following parameters are calculated

Table 3: Simulation results of the TSV model used for MMW

Average RMS delay	1.28 [ns]
Maximum RMS delay	0.004 [ns]
Minimum RMS delay	0.015 [ns]
Average Rician factor	38.51 [dB]
Maximum Rician factor	72.99 [dB]
Minimum Rician factor	1.18 [dB]

The PDP in Fig.2 shows the presence of direct component having the average power of -80 dB. As the number of reflections per ray increases, the corresponding amplitude of the ray decreases because of both reflection losses and higher free space losses.

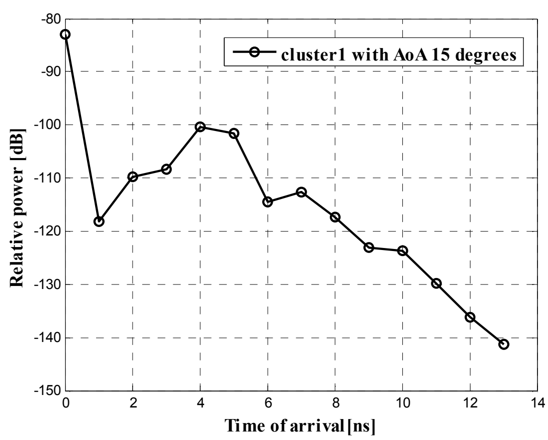

Fig. 3 PDP of cluster1 as a function of ToA with AoA 15^o

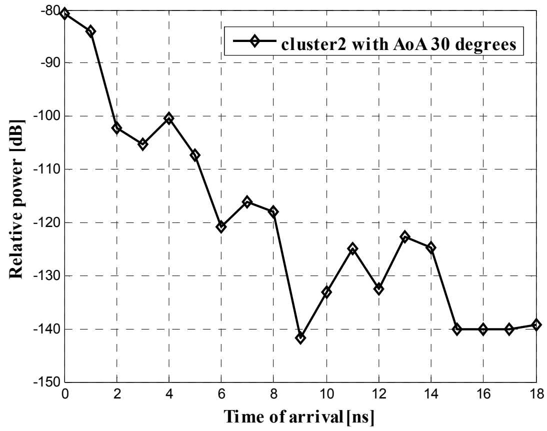

Fig. 4 PDP of cluster2 as a function of ToA with AoA 30^{o}

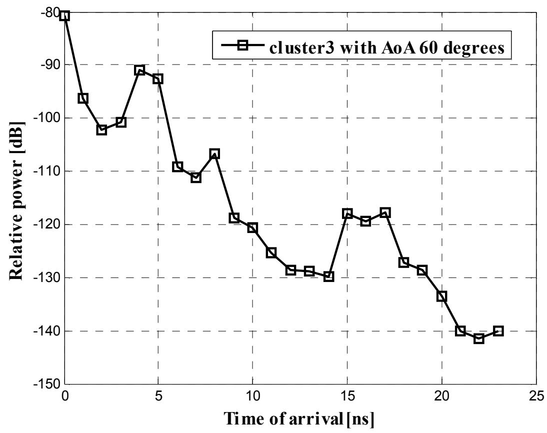

Fig. 5 PDP of cluster3 as a function of ToA with AoA 60^{o}

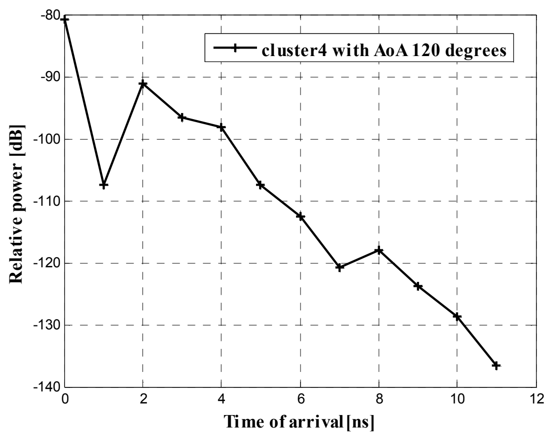

Fig. 6 PDP of cluster4 as a function of ToA with AoA 120^{o}

The exponential PDP is evident from Fig. 3, Fig. 4, Fig. 5 and Fig. 6, as the various clusters have a maximum LOS component and power decaying as a function of distance travelled by the signal. Cluster is formed by scattering and the start and end of cluster depends on the geometry of the scattering obstacle. From the above figures, arrival rates and decay factors of the cluster and ray are determined for computing the impulse response of the channel as discussed in section 2 for two path model. Also the angular spread required to analyze the wide-sense stationary uncorrelated scattering (WSSUCS) characteristics of the channel and antenna directivity can be determined. In this, the ray clustering is evidenced by the peaks in the PDP. The LOS component path gain is also computed [22]. Likewise the delay spread and the rician factor K can be calculated from ToA and power in the LOS and NLOS components. Cluster1, 2, 3 and 4 contribute significantly to the multipath components at the receiving end. The angular spread of the clusters is 110^{o}.

5.2 Bit error rate comparison using ZF, MMSE and ML equalization for TSV channel

The various equalization techniques are used to analyze the bit error rate for different MIMO configurations using TSV channel. MIMO system is simulated using the BPSK modulation scheme, the distance of separation between the transmitter and receiver being 3m and the parameters in Table 2 are considered for modeling the channel.

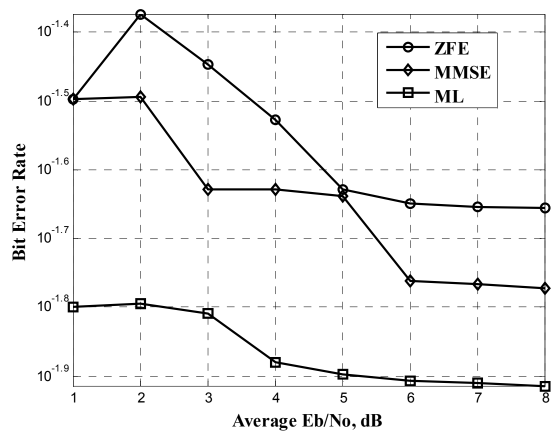

Fig. 7 Comparison of BER for 2x2 MIMO system using ZFE, MMSE and ML technique.

From Fig.7, it can be inferred that the ML receiver is optimal in reducing the error probability and estimates better as it compares the received signal with all the possible transmitted vectors while the ZF receiver has the advantage of complexity reduction, but as the multipath components are large, the noise components are not suitably taken care of by ZF, hence ZF shows a reduced performance. MMSE technique is able to reduce both the interference and noise components as compared to ZF even though it has a slight edge in performance with 2x2 system, as the number of antennas increase, they perform almost equally.

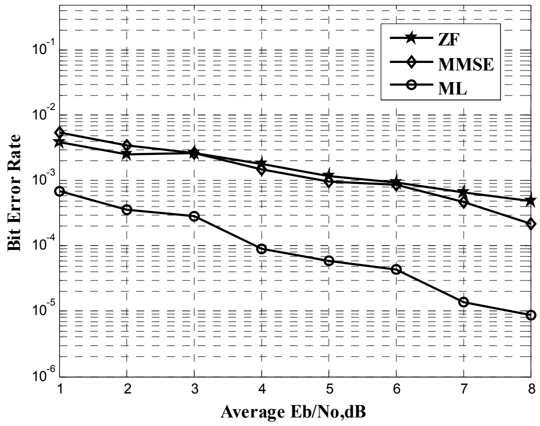

Fig. 8 Comparison of BER for 4x4 MIMO system using ZFE, MMSE and ML technique.

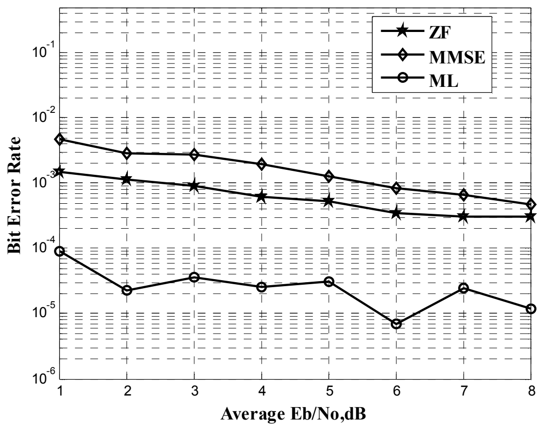

Fig. 9 Comparison of BER for 8x8 MIMO system using ZFE, MMSE and ML technique.

The results obtained for 2x2, 4x4 and 8x8 using TSV channel model indicate an increase in data rate as ($n_t.n_r$) increase. A BER of 10^{-5} at SNR = 8 dB for 4x4 and 8x8 indicates any further increase in transmit/receive antenna may not provide performance improvement.

5.3 Bit error rate comparison using ZF, MMSE and ML equalization for channel B

The following parameters of 2x2, 4x4 and 8x8 are used for channel B

Table 4: Simulation parameters for 5 GHz System

Modulation used	BPSK
Number of bits	10^6
Average Energy per bit to Noise power spectral density (E_b/N_o)	1 to 8 dB
Channel model	IEEE 802.11n, Channel Model B
Centre frequency	5 GHz

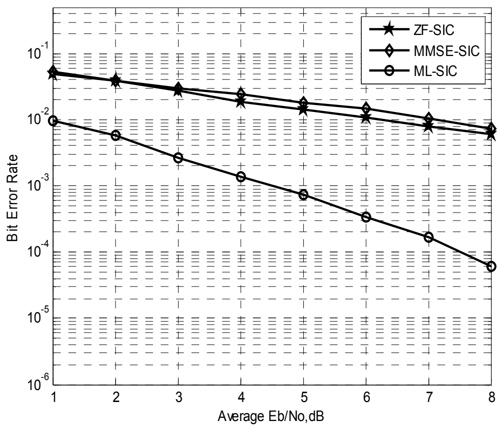

Fig. 10. BER for a 2x2 spatial multiplexed system

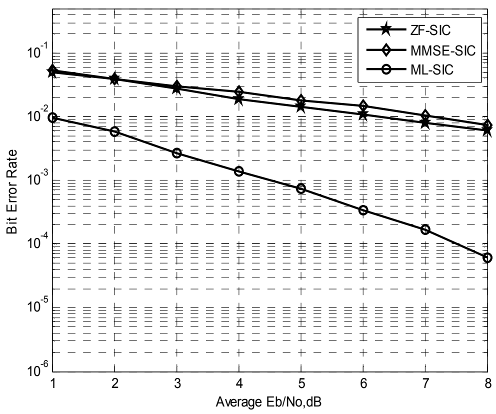

Fig.11 BER for a 4x4 spatial multiplexed system

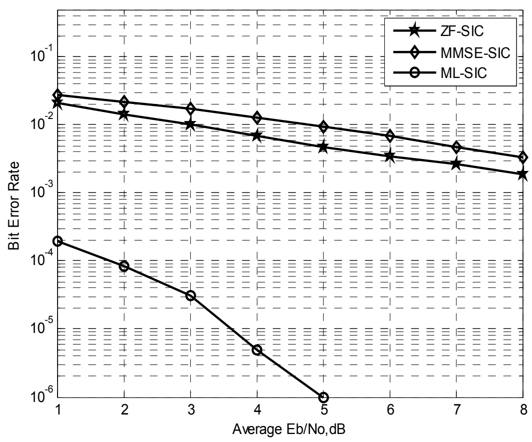

Fig. 12 BER for a 8x8 spatial multiplexed system

Thus the BER improves with increase in E_b/N_o. The performance of 5GHz using channel B was studied for indoor environment. ZF and MMSE achieves a BER of $10^{-2.5}$ at 8 dB, while ML achieves BER of 10^{-6} at 5dB.

5.4 Comparison of BER for 60GHz and 5 GHz using TSV and IEEE 802.11n channel B

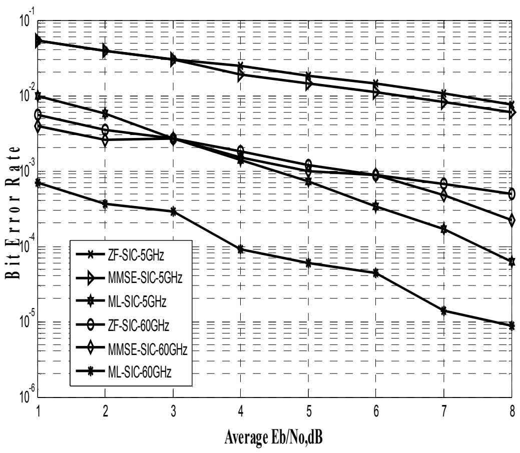

Fig.13 Bit Error Rate of 4x4 system using TSV and Rayleigh channel models for indoor environment with transceiver separation of 3m.

In Fig 13 and Fig 14 performance of various equalization techniques assuming perfect channel estimate is analysed for 4x4 and 8x8 system. The ML equalizer shows performance improvement compared to ZF and MMSE in both 60 GHz and 5 GHz systems.

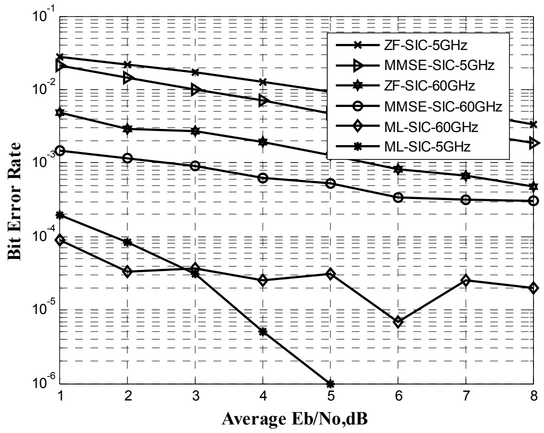

Fig.14 Bit Error Rate of 8x8 system using TSV and Rayleigh channel models for indoor environment with transceiver separation of 3m.

Comparing Fig.13 and Fig.14 a power gain of 3 dB is achieved in 60 GHz range using ML technique. The Rician factor K in Table 3 indicates the dominance of LOS component and hence improvement in performance of MMW system for short range communication.

5.5 Capacity calculation of 5 GHz and 60 GHz systems

Capacity calculation:

The capacity of 2x2 MIMO channel is given by

$$C = \sum_{i=1}^{r} \log_2\left(1 + \frac{E_s}{M_T N_0}\lambda_i\right) \qquad (11)$$

where r is rank of the channel matrix H obtained by SVD, E_s/M_TN_0 is the signal to noise power per transmit antenna with symbol period T= 1second and λ is the Eigen value representing the channel power gain. Applying SVD on H in (9), the r parallel SISO channels are obtained as in (11)

Table 5: Comparison of capacity for 60 GHz and 5 GHz spatial multiplexed systems

Center Frequency	Data Rate
60 GHz	2 Gbps
5 GHz	600 Mbps

5.6 Link budget analysis for MMW

To design a communication system for an intended environment, it is necessary to predict the system performance before deployment. The essential parameters that control the performance of each link are received signal strength, noise in the received signal and channel impairments. For this, link budget is prepared.

Link Margin Figure = Power Received – Receiver sensitivity (12)

Calculation of Power Received and Receiver Sensitivity

Data Rate R_b obtained from the simulation is 2 Gbps, and the noise bandwidth B is 1 GHz and let E_b/N_o be 8 dB with transmit and receive separation being 3m.

Carrier to Noise Ratio (CNR) is given as:

$$CNR = 10\log_{10}\left(\frac{E_b}{N_o} * \frac{R_b}{B}\right) \qquad (13)$$

$$= 11 \text{ dB}$$

$$Pathloss = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (14)$$

$= 77.54$ dB

Power Received=$P_{tx} + G_{tx} + G_{rx}$ - Path loss (15)

= 10 dBm + 6 dBi + 6 dBi – 77.54 (dB)

= -45.54 dBm

Calculation of noise power (at T=290 k and Noise Figure F = 8 dB)

$P_{noise} = 10\log_{10}(kTBF)$ (16)

= -174 dBm/Hz + 10 $\log_{10}$ (B) + 8 dB

= -136 dBm.

Calculation of receiver sensitivity

$$P_{rx} = CNR + P_{noise} \quad (17)$$

= 11 + (-136) = -105 dBm

Link Margin Figure = Power received - Receiver sensitivity

= - 45.54 – (-105) = 59.46 dBm

The receiver sensitivity of -105 dBm indicates the receiver can process signals with SNR as low as 11 dB.

6. Conclusion

The TSV model developed by NICT, Japan is considered for 60 GHz. The channel characteristics of the indoor environment using TSV model is studied and the PDP is shown. As the scatterers local to the transmitter contribute to multipath fading in MMW, the near-field effect is dominant compared to the far-field effect. The delay spread is reasonably low with average delay spread of 1.289 ns and the channel is considered flat –fading. This paves way for deploying multiple MMW transceivers in a single room. Performance of the spatial multiplexed system for 60 GHz and 5 GHz channel with 2x2, 4x4 and 8x8 were analyzed. With dominance of LOS component in 60 GHz, the bit error rate is reduced and the channel capacity is increased. ML is found to have reduced BER at low SNR which suggests that MMW can be the last mile solution of WLAN operating at 5 GHz. The drawback being if the LOS component is blocked, the system will incur loss of data increasing the bit error rate. The future work, is to consider schemes that will maintain the bit error rate even with loss of LOS component.

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