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Modeling of 60 GHz High Speed Communication Beam forming for Wireless Personal Area Networks (WPAN)

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Abstract

The current systems of networking in the industrial, scientific and medical (ISM) band are experiencing some challenges like the designing of a power amplifier with fast switching ADC, less power consumption and inherent low latency in 2.4/5GHz RF end [1][2]. Other challenges are data achievement in multi-gigabits with operation below 20 meters, high speed multi-file transfer, wireless gaming and wireless gigabit Ethernet that permit bidirectional multi-gigabit Ethernet traffic as well as cable replacement for uncompressed HDTV. From the above limitations of the existing systems, there is a need for a wireless solution with higher data rate and improvement in reliability of the link. The proposed 60 GHz beam forming model which utilizes Orthogonal Frequency Division Multiplexing (OFDM) based short-range communication system for Wireless Personal Area Networks (WPAN) has been subjected to various cases of analysis in both line of sight (LOS) and non-line of sight (NLOS) scenarios. In order to utilize the bandwidth allocated to this system, this research analyses the proposed beam forming model performance using three types of beam forming techniques i.e. hybrid, subcarrier wise and symbol wise beam forming. The effective SNR gain was computed for the typical channel models developed by IEEE 802.15.3c for both LOS and NLOS scenarios. In the case of LOS, it is observed that the gap between the bound and both subcarrier-wise BF and hybrid BF gain is approximately 1dB while the one between bound gain and symbol-wise BF gain is approximately 1.5 dB. It is also observed that subcarrier-wise beam forming provides the best results with a gap of 3 dB in comparison with the bound in NLOS although it has hardware complexity with a requirement of one FFT/IFFT per antenna and a SVD processor per subcarrier whereas hybrid beam forming (HBF) is the next with performance gap of 5 dB while maintaining reasonable hardware complexity by employing symbol-wise BF at the transmitter which requires only one FFT/IFFT processor at each terminal and applies same weight vectors to each subcarrier; and symbol wise BF is the worst with performance gap of 10 dB in comparison with the bound. For verification of the results, BER performance for various SNR values was simulated for LOS and NLOS scenarios. In the case of LOS, it is observed that a BER of about 10^{-4} is achieved when the subcarrier-wise BF give a gain of 15 dB over single antenna system, which is the accepted minimum SNR to establish a connection, while both hybrid BF and symbol-wise BF achieves about 10^{-3} for the same gain. The simulation results in the case of NLOS scenario shows that a BER of 10^{-4} is achieved when the subcarrier-wise BF gives a gain of 15 dB over single antenna system while hybrid BF achieves 10^{-3} for the same gain and symbol-wise achieves 10^{-2}.

The results demonstrate that all three beam forming schemes increase the system performance significantly over the single antenna system through improved link reliability due to beam forming gain. It is seen that subcarrier-wise BF provides the best performance in both LOS and NLOS scenarios although with high hardware complexity while symbol-wise BF is the worst although with low hardware complexity. A trade-off between good performance and low hardware complexity shows that hybrid beam forming provides considerable improvement while maintaining reasonable hardware complexity from the results above.

Keywords: Beam-forming, WPAN, 60 GHZ, OFDM, HBF, BER, SNR.

INTRODUCTION

In recent years, millimetre-wave (mm-wave) technology has been one of the most important emerging wireless technologies. In comparison with the current communications systems, 60 GHz offers more advantages. Huge unlicensed bandwidth is one of the major reasons that have attracted interest in the 60GHz technology in recent times. There is availability of 5 GHz continuous bandwidth in many countries [3][4]]. The 60 GHz is comparable to unlicensed bandwidth allocated for the ultra-wideband (UWB) purposes though the 60 GHz has a continuous bandwidth and its power limits are less restrictive. The huge unlicensed bandwidth allocated at the 60 GHz band is one of the largest bandwidths ever allocated. This huge bandwidth has represented great potential when it comes to flexibility and capacity, making the 60 GHz technology more attractive for the gigabit wireless applications [3][5]. Multiple-antenna solutions are viable at user terminals because of the 60 GHz compact size; this is difficult or even impossible at lower frequencies. Compared to 5 GHz systems, the form factor of the 60 GHz systems is about 140 times smaller and therefore can be integrated more easily into the consumer electronic products. This band has therefore attracted a great deal of interest from academia, industry and standardization bodies.

To support high performance applications on frequency selective channels, the OFDM scheme is implemented for WPAN standard. Considering both hardware cost and throughput performance, the beam forming technique is the optimum choice for mm-wave compared to other multiple antenna technologies, such as spatial multiplexing and spatial diversity [3]. In a multiple-input multiple-output (MIMO) OFDM system, transmit and receive beam forming can be implemented using three different configurations, namely, subcarrier-wise beam forming, symbol-wise beam forming and hybrid beam forming. Subcarrier-wise beam forming is optimal since each subcarrier selects the best weight vector. However, there is an increase in the hardware complexity because an FFT processor is required for each antenna element. The symbol-wise beam forming only needs one FFT processor at each terminal. In this type all the subcarriers apply the same weight vector and therefore performance degradation is inevitable [6]. The hybrid beam forming (HBF) employs symbol-wise beam forming at the transmitter and subcarrier-wise beam forming at the receiver [7]. Although symbol-wise BF and HBF can reduce the complexity, it is still complex to apply them directly in practice, because obtaining the estimated channel state information (CSI) introduces high overhead and power consumption. In [8], the authors proposed a codebook design to support the 60 GHz WPANs and the scheme has been accepted by IEEE 802.15.3c [9], which is the earlier IEEE 60 GHz task group.

In this paper, the performance of the proposed system model when implemented using the three different beam forming schemes over line of sight (LOS) and non-line of sight (NLOS) scenarios, is analyzed. In section II brief discussion on the system model is given. In section III, the model implementations using the various beam forming techniques are discussed and in section IV the simulation results supporting the proposed models are presented. Finally, results and discussion are presented in section V and conclusions drawn in section VI.

SYSTEM MODEL

Consider a 1-D uniform linear array of OFDM system having M_t number of antenna elements at the transmitter and M_r at the receiver. The spacing between the antenna elements is half wavelength λ. Let y_m represent the decision baseband signal received at the receiver side for the m^{th} subcarrier, its expression [7] can then be given as

$$y_m = \widetilde{H_m}\, X_m + n_m, \qquad m = 1, \dots N \qquad (1)$$

Where N is the number of subcarriers, X_m the data symbol transmitted, $\mathbf{n_m}$ the Gaussian noise vector having zero mean with variance σ^2, and $\widetilde{H_m}$ is the frequency response after the beam forming for equivalent channel matrix at m^{th}subcarrier given as [10]

$$\widetilde{H_m} = c^H H_m w, \qquad m = 1, \dots N \qquad (2)$$

Where H_m is MIMO channel response for m^{th} subcarrier, $\boldsymbol{w}$ is the transmitter beam steering vector, c is the receiver beam steering vector and $(\,)^H$ denotes operation of transpose and complex conjugate. Assuming that we normalize the total power transmitted by all the antenna elements to 1, then we have $c^H c = M_r$ and $w^H w = M_t$.

Beam forming aims at choosing the optimal weight vectors for the transmitter and receiver based on a selected criterion. In this work, the effective SNR is selected as that criterion and its definition can be given as the average SNR across all the subcarriers. This is computed as [10]

$$\gamma_{eff} = -\beta \ln\left(\frac{1}{N}\sum_{m=1}^{N} \exp\left(-\frac{\gamma_m}{\beta}\right)\right) \qquad (3)$$

Where β is a parameter which is dependent on the modulation scheme, coding rate and the size of information block, γ_m is the experienced SNR of the symbol on the m^{th} subcarrier. This can be given as [10]

$$\gamma_m = \frac{E||C^H H_m w x_m|^2|}{E||n_m|^2|} = \frac{|c^H H_m w|^2}{M_t M_r \sigma^2} \qquad (4)$$

BEAM FORMING TECHNIQUES

In this paper the implementation of the transmit and receive beam forming to an OFDM system have been done using three different types of configurations, namely, subcarrier-wise beam forming, symbol-wise beam forming and hybrid beam forming.

Subcarrier-wise beam forming

Subcarrier-wise beam forming is found to maximize, on each subcarrier, the received average SNR and is therefore the optimal solution. One IFFT/FFT processor is required per antenna in subcarrier-wise as we can see in Fig.1 [6].

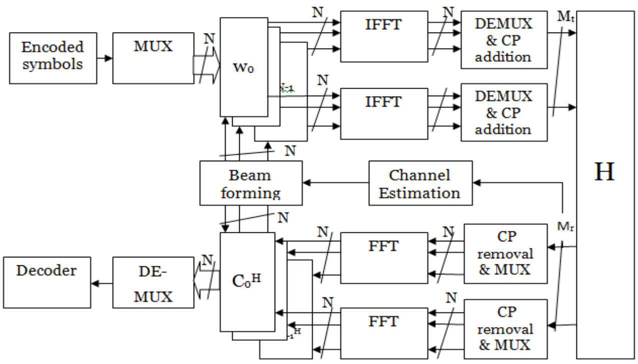

Figure 1: Subcarrier-wise beam forming

Additionally, the transmitter needs to have the knowledge on the estimated channel matrix, and a singular value decomposition (SVD) processor is required as per the subcarrier for computation of weights. For subcarrier-wise beam forming, its effective SNR $\gamma_{eff,subcarrier}$ can be represented [10] as

$$= -\beta \ln\left(\frac{1}{N}\sum_{m=1}^{N} exp\left(-\frac{max_{c,w}|c^H H_m w|^2}{\beta M_t M_r \sigma^2}\right)\right) \quad (5)$$

To achieve this kind of maximization we need to find the first entry of the SVD as per the channel matrix. Due to the increased hardware complexity of the subcarrier-wise, it is not recommended for practical implementation. As shown in Fig. 2, through the performance of beam forming in time domain, hardware complexity can be reduced.

Symbol-wise beam-forming

In the case of Symbol-wise beam forming, at each terminal there is a requirement of one FFT processor whereby the same weight vector is applied for each subcarrier. The optimal weight vector can be obtained through the comparison of effective SNR by finding the SVD for each subcarrier. This will result in intensive computations which are avoided in 60 GHz systems [8] by the use of a set of pre-defined beam codebook for rapid processing.

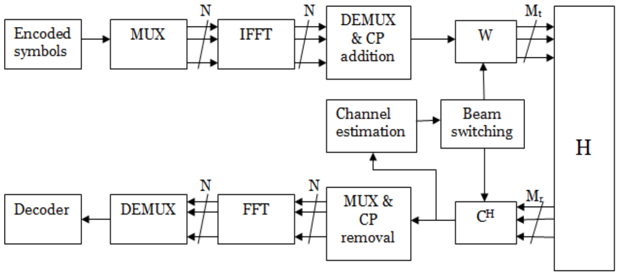

Figure 2: Symbol-wise beam forming

Without amplitude adjustment, four shifts per antenna element are used to create the beam codebook as defined in [6]. This is determined by K, the desired number of beams, and M number of antenna elements. The codebook beam vector for the 1-D phased antenna array is given by the column vector of the matrix in (6) when K ≥ M

$$W(m,k) = j^{floor\left\{\frac{M\times mod[k+k/2]k}{k/4}\right\}}$$

$$m = 0,\dots,M-1; k = 0,\dots K-1 \quad (6)$$

For a MIMO system having 2 beams and 2 antenna elements, equation (7) gives the beam vector as generated by the beam codebook.

$$C = \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \quad (7)$$

Finding the best pair of codebook (C) becomes a problem in symbol-wise beam forming and its effective SNR $\gamma_{eff,symbolwise}$ can be represented [10] as.

$$= max_{c,w\epsilon C}(-\beta)\ln\left(\frac{1}{N}\sum_{m=1}^{N} exp\left(-\frac{|c^H H_m w|^2}{\beta M_t M_r \sigma^2}\right)\right) (8)$$

There is an introduction of performance loss in the case of symbol-wise beam forming in comparison to the subcarrier-wise beam forming and this is because of the satisfaction of the maximum effective SNR only for overall subcarriers.

Hybrid beam forming (HBF)

In HBF technique, the hardware complexity is minimized through configuring the transmitter using symbol-wise beam forming while subcarrier-wise beam forming is employed at the receiver for optimization of performance as shown in Fig. 3[7]. In this configuration the beam codebook is also used and therefore the effective SNR_$\gamma_{eff,hybrid}$ can be represented [10] as

$$= max_{c,c\epsilon C}(-\beta)\ln\left(\frac{1}{N}\sum_{m=1}^{N} exp\left(-\frac{\left|c^H R_m w_{opt}\right|^2}{\beta M_t M_r \sigma^2}\right)\right) (9)$$

Where w_{opt} is the transmitter optimal beam steering vector attained from receiver vector ***C***

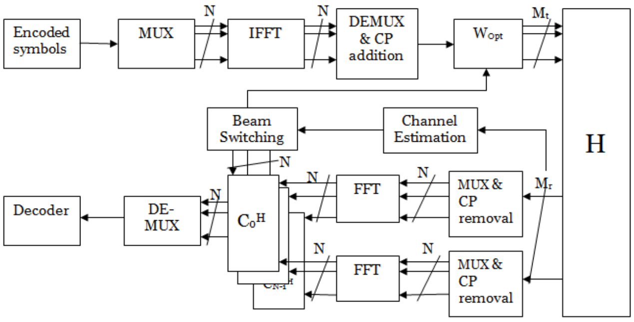

Figure 3: Hybrid beam forming

RESULTS AND DISCUSSION

Beam forming Gain

The beam forming gain was evaluated using the 60 GHz channel models generated by isotropic radiators in a conference room environment and LOS and NLOS scenarios are considered. For simplicity, it was assumed in this research that the numbers of antenna elements at the transmitter and receiver are equal, with $M = M_t = M_r$. For the evaluation of beam forming performance [7] through the utilization of the parameters shown in Table 1, the effective SNR of different beam forming techniques were calculated in comparison to the single antenna system (SISO) and using the formula

$$G_{beamforming} = \frac{\gamma_{eff,beamforming}}{\gamma_{eff,SISO}} \qquad (10)$$

Where $\gamma_{eff\ beam\ forming}$ is defined as an effective SNR given in equations (5), (8) or (9), while $\gamma_{eff\ SISO}$ is obtained using equation (3). In Fig. 4, 60 GHz beam forming gain of different number of antenna elements with LOS for the three different beam forming schemes together with a bound is shown. The bound is the theoretical beam forming gain achieved when the MIMO channel is totally correlated in a special situation where all the antenna elements are placed in one single point and only one single path exists between the transmitter and the receiver. The bound gain can be calculated as [7],

$$G_{bound}[dB] = 10log_{10}(\,M_t\ M_r) \qquad (11)$$

The beam forming gain of the three beam forming schemes is compared to the bound gain. In the case of LOS, it is observed that the gap between the bound and both subcarrier-wise BF and hybrid BF gain is approximately 1dB while the one between bound gain and symbol-wise BF gain is approximately 1.5 dB. It is also noteworthy that the gains for the subcarrier-wise beam forming and HBF are identical while the one for the symbol-wise beam forming is lower, this is due to the existence of the LOS where the channels of different links are more correlated, and also the smallness of the gain loss at the beam pattern intersection and hence the difference in performance is not significant. In Fig. 5, when the LOS does not exist, there is degradation on the beam forming performance. It is observed that the gap between the bound gain and subcarrier-wise beam forming gain is approximately 3 dB, the one between bound gain and hybrid BF gain is approximately 5 dB while between bound gain and symbol-wise beam forming gain is approximately 10 dB.

From the results, it is observed that subcarrier-wise BF achieves performance levels closer to those of the theoretical beam forming gain, hybrid BF is the next and symbol-wise BF is the last one.

Table 1: System Parameters

Frequency	60 GHz
Bandwidth	1.76 GHz (59.12-60.88 GHz)
Modulation	QAM
No. of. Subcarriers	512
Transceiver distance	5m
Cyclic Prefix length	64 samples
Data Rate	3-4 Gbps

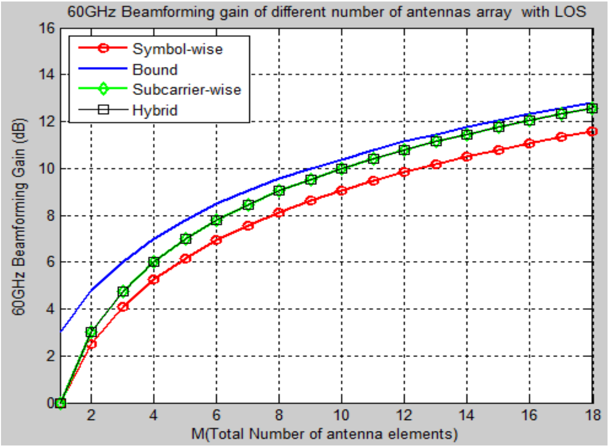

Figure 4: Beam forming gain vs Number of antennas in **LOS**

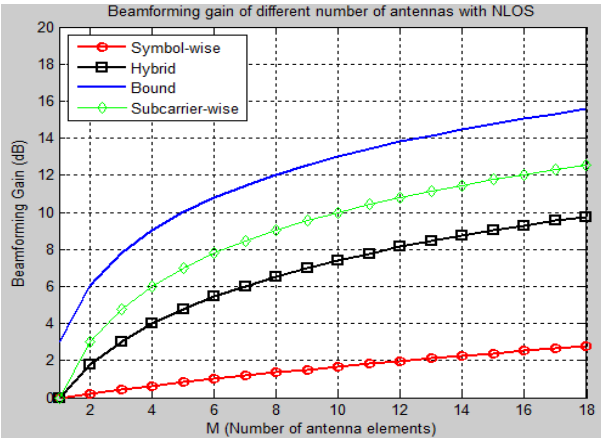

Figure 5: Beam forming gain vs Number of antennas in NLOS

Bit Error Rate (BER) Performance

For verification of the beam forming systems numerical results, BER performance was obtained through simulation. As a reference, SISO system BER performance is plotted on the same graph with the assumption of perfect CSI. In this case we assumed that we have two antenna elements at both the transmitter and the receiver sides. At the receiver side we used the zero-forcing equalization due to its simplicity in hardware.

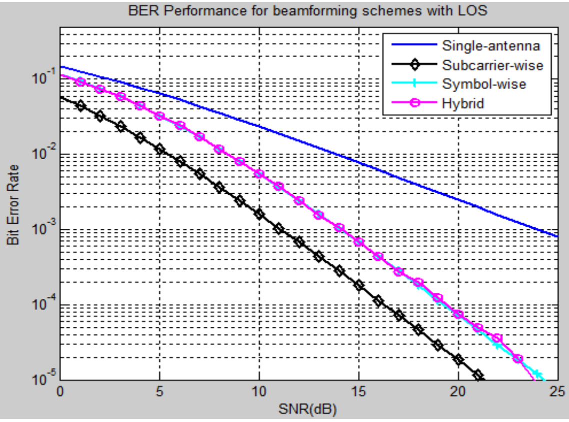

Figure 6: BER performance of the single antenna system and beam forming schemes in LOS condition

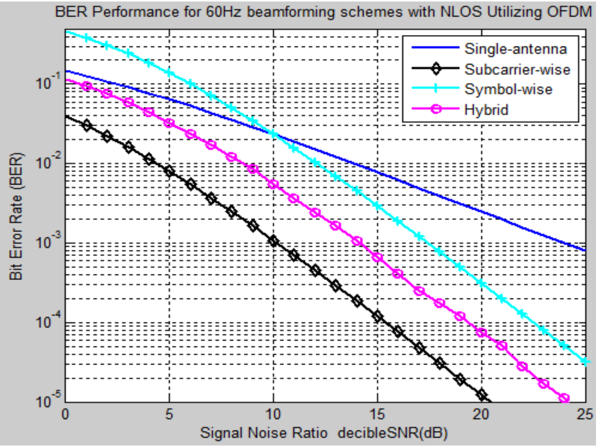

Figure 7: BER performance of the single antenna system and beam forming schemes in NLOS condition

Fig. 6 shows the BER performance for beam forming schemes with LOS scenario where BER versus SNR have been simulated for QAM modulation while Fig. 7 shows the results in the case of NLOS scenario. In Fig.6, it is observed that in LOS scenario, a BER of about 10^{-4} is achieved when the subcarrier-wise BF give a gain of 15 dB over single antenna system, which is the accepted minimum SNR to establish a connection, while both hybrid and symbol-wise BF achieves about 10^{-3} for the same gain. In Fig.7, the simulation results in the case of NLOS scenario shows that a BER of 10^{-4} is achieved when the subcarrier-wise BF gives a gain of 15 dB over single antenna system while hybrid BF achieves 10^{-3} for the same gain and symbol-wise achieves 10^{-2}.

CONCLUSION

This paper considered modeling of 60 GHz beam-forming system which utilizes Orthogonal Frequency Division Multiplexing (OFDM) based short-range communication for Wireless Personal Area Networks (WPAN). When implementing beam forming technique for an OFDM system, three different configurations were considered. Performance evaluation of these three types of beam forming techniques over the OFDM based 60GHz communication system for WPAN's was then carried out. The effective SNR gain was computed for the typical channel models developed by IEEE 802.15.3c for both LOS and NLOS scenarios. In the case of LOS, it is observed that the gap between the bound and both subcarrier-wise BF and hybrid BF gain is approximately 1dB while the one between bound gain and symbol-wise BF gain is approximately 1.5 dB. It is also observed that subcarrier-wise beam forming provides the best results with a gap of 3 dB in comparison with the bound in NLOS although it has hardware complexity with a requirement of one FFT/IFFT per antenna and a SVD processor per subcarrier whereas hybrid beam forming (HBF) is the next with performance gap of 5 dB while maintaining reasonable hardware complexity by employing symbol-wise BF at the transmitter which requires only one FFT/IFFT processor at each terminal and applies same weight vectors to each subcarrier; and symbol wise BF is the worst with performance gap of 10 dB in comparison with the bound. For verification of the results, BER performance for various SNR values was simulated for LOS and NLOS scenarios. In the case of LOS, it is observed that a BER of about 10^{-4} is achieved when the subcarrier-wise BF give a gain of 15 dB over single antenna system, which is the accepted minimum SNR to establish a connection, while both hybrid BF and symbol-wise BF achieves about 10^{-3} for the same gain. The simulation results in the case of NLOS scenario shows that a BER of 10^{-4} is achieved when the subcarrier-wise BF gives a gain of 15 dB over single antenna system while hybrid BF achieves 10^{-3} for the same gain and symbol-wise achieves 10^{-2}.

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