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Beamforming Performance Analysis for OFDM Based IEEE 802.11ad Millimeter-Wave WPANs

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Abstract—This paper exploits the performance of three types of beamforming techniques over the 60 GHz orthogonal frequency division multiplexing (OFDM) based wireless personal area networks (WPANs). The effective SNR over typical IEEE 802.11ad channel models is used as the criterion to compare the beamforming performance. Symbol-wise beamforming reduces the complexity considerably compared to subcarrier-wise beamforming with some performance loss, while hybrid beamforming provides much less performance degradation at a reasonable cost. In order to verify the results, the bit error rate (BER) performance is simulated. In addition, the system throughput over range is presented in the paper.

Keywords- WPAN; 60 GHz; IEEE 802.11ad; OFDM; Beamforming; Codebook

I. INTRODUCTION

Recently, there has been increasing interest in millimeter-wave WPANs for delivering high quality multimedia and data services. The IEEE 802.11ad task group is currently working on standardizing the 60 GHz spectrum on both physical (PHY) and medium access control (MAC) layers [1], and it will build on the existing successful wireless local area networks (WLANs). To support high performance applications on frequency selective channels, the OFDM scheme is proposed in the standard. A key advantage of using the 60 GHz band is the small sizes of radio frequency components, so it is possible to employ multiple antennas on a small portable device. Considering both hardware cost and throughput performance, the beamforming technique is the optimal choice for millimeter-wave [2] compared to other multiple antenna technologies, such as spatial multiplexing and spatial diversity.

In a multiple-input multiple-output (MIMO) OFDM system, the transmit and receive beamforming can be carried out by two generic types, namely, subcarrier-wise beamforming and symbol-wise beamforming [3]. The first type is the optimal beamforming since each subcarrier selects the best weight vector. However, the hardware complexity is considerable because a FFT processor is required for each antenna element. On the other hand, the second type only need one FFT processor at each terminal, but all subcarriers apply the same weight vector, so a performance degradation is inevitable. A hybrid beamforming, which employs symbol-wise beamforming at the transmitter and subcarrier-wise beamforming at the receiver, is proposed in [2]. Although symbol-wise and hybrid beamforming 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 [4], the authors proposed a codebook design to support the 60 GHz WPANs, and the scheme has been accepted by IEEE 802.15.3c [5], which is the earlier IEEE 60 GHz task group.

In this paper, we will analyze the performance of the three different beamforming schemes over typical IEEE 802.11ad channel models. The BER performance will be simulated using our IEEE 802.11ad PHY simulator. The link throughput and operation range results will be also investigated.

II. SYSTEM MODEL

We consider an OFDM system with a 1-D uniform linear array consisting of $M_t$ and $M_r$ antenna elements at the transmitter and the receiver respectively. The antenna element spacing is half wavelength $\lambda$. Let $y_m$ be the received decision baseband signal for the $m$th subcarrier, which can be expressed as

$$y_m = \tilde{H}_m x_m + n_m, \quad m = 1, ..., N$$

where $x_m$ is the transmitted data symbol, $n_m$ is the Gaussian noise vector with zero mean and variance $\sigma^2$, $N$ is number of subcarriers, and $\tilde{H}_m$ represents the frequency response of the equivalent channel matrix for the $m$th subcarrier after beamforming, which is given by

$$\tilde{H}_m = c^H M_m w, \quad m = 1, ..., N$$

where $w$ and $c$ are the transmitter and the receiver beam steering vector respectively, and $M_m$ represents the response of the MIMO channel for the $m$th subcarrier. Assume the total transmitted power of all antenna elements is normalized to 1, then we have $w^H w = M_t$ and $c^H c = M_r$.

The aim of the beamforming is to choose the optimal transmit and receive weight vectors according to a selected criterion, and in this work, effective SNR is chosen as that criterion. The effective SNR defined as the average SNR across all subcarriers can be computed as [6]

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

where $\gamma_m$ is the symbol SNR experienced on the $m$th subcarrier, $\beta$ is a parameter dependent on the coding rate, the modulation
and the information block size. The SNR of the \( m \)th subcarrier can be calculated as
\[
\gamma_m = \frac{E[|c^H H_m w_m|^2]}{E[|n_m|^2]} = \frac{|c^H H_m w|^2}{M_t H_r \sigma^2}
\]
(4)

III. OFDM BASED BEAMFORMING

When implementing the beamforming technique to an OFDM system, three different configurations are considered in this work. Subcarrier-beamforming is the optimal solution, which maximizes the average received SNR on each subcarrier. As shown in Fig. 1, subcarrier-wise beamforming requires one FFT/IFFT processor per antenna. In addition, estimated channel matrix must be sent back to the transmitter, and the weight computation need a singular value decomposition (SVD) processor per subcarrier.

As defined in [7], the beam codebook is created with 4 shifts per antenna element without amplitude adjustment. It is determined by both the number of antenna elements \( M_r \), and the desired number of beams \( K \). For a 1-D phased antenna array, the column vector of the following matrix gives the codebook beam vector when \( K \geq M_r \)
\[
W(m, k) = j^{\text{floor} \left[ \frac{m \times \text{mod}(k+1, K)}{K/K} \right]} \tag{6}
\]

For a MIMO system with 2 antenna elements and 2 beams, the beam codebook generates the following beam vector
\[
C = \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \tag{7}
\]

Fig. 3 shows the beam pattern of the corresponding codebook \( C \).

![Figure 1: Block diagram of subcarrier-wise beamforming](image)

Under the effective SNR criterion, the problem for subcarrier-wise beamforming can be represented as
\[
\gamma_{\text{eff, subcarrier}} = -\beta \ln \left( \frac{\sum_{m=1}^{M_r} \exp \left( -\frac{\max_{c \in \mathcal{E}} |c^H H_m w|^2}{\beta M_t M_r \sigma^2} \right) \right) \tag{5}
\]

This maximization can be achieved by finding the first entry of SVD of the channel matrix.

In practice, this type of beamforming is not employed because of the high complexity. The complexity can be reduced by performing beamforming in the time domain as shown in Fig. 2. Symbol-wise beamforming requires only one FFT processor at each terminal, and each subcarrier applies the same weight vector. However, in order to find the optimal weight vector, we have to compare the effective SNR by calculating the SVD for each individual subcarrier. It results in intensive computations, and in order to avoid these calculations, a set of pre-defined beam codebook is used for rapid processing in 60 GHz systems [5].

![Figure 2: Block diagram of symbol-wise beamforming](image)

Then, the problem for symbol-wise beamforming becomes to find the best pair of codebook \( C \)
\[
\gamma_{\text{eff, symbol}} = \max_{c \in \mathcal{E}} (-\beta) \ln \left( \frac{\sum_{m=1}^{M_r} \exp \left( -\frac{|c^H H_m w|^2}{\beta M_t M_r \sigma^2} \right) \right) \tag{6}
\]

Compared to subcarrier-wise beamforming, symbol-wise beamforming will introduce a performance loss because only the maximum effective SNR for overall subcarriers can be satisfied. [2] proposed a hybrid beamforming technique, in which the symbol-wise beamforming is employed at the transmitter to minimize the complexity, and the receiver is configured with subcarrier-wise beamforming to optimize the performance. The structure is shown in Fig. 4.

![Figure 4: Block diagram of hybrid beamforming](image)
The beam codebook is also applied in this configuration, so the effective SNR can be calculated by the following equation

$$Y_{\text{eff, hybrid}} = \max_{\mathbf{w} \in \mathcal{C}} (-\beta) \ln \left( \frac{1}{N} \sum_{n=1}^{N} \exp \left( - \frac{\| y_n \mathbf{w}_{\text{opt}} \|^2}{\beta M_s M_r \sigma^2} \right) \right)$$

(9)

where $w_{\text{opt}}$ is the optimal transmitter beam steering vector obtained from receiver vector $\mathbf{c}$.

IV. NUMERICAL RESULTS

A. Beamforming Gain

In this section, we use 60 GHz channel models, which were proposed in IEEE 802.11ad standard [8], to evaluate the beamforming gain. These channel models are generated with isotropic radiators in the conference room environment, and both line-of-sight (LOS) and non-line-of-sight (NLOS) cases are considered. In this paper, we assume the transmitter and the receiver have the same antenna elements where $M = M_t = M_r$. The channel model is generated at carrier frequency of 60 GHz, bandwidth of 1.76 GHz, and transceiver distance of 5m. For the OFDM parameters, the number of subcarrier is 512 and the cyclic prefix length is 64 samples. The exponential effective SNR parameter $\beta$ equals 2, which is a typical value for QPSK modulation [6].

In order to evaluate the beamforming performance, we measure the effective SNR of the different beamforming schemes compared to single antenna system (SISO), which is given by

$$G = \frac{Y_{\text{eff, beamforming}}}{Y_{\text{eff, SISO}}}$$

(10)

where $Y_{\text{eff, beamforming}}$ is the effective SNR defined in equation (5), (8) or (9), and $Y_{\text{eff, SISO}}$ can be obtained by (3).

Fig. 5 shows the effective SNR gain over the single antenna system with LOS. It can be seen that the beamforming gain has a bound when the single path exists [2]. The subcarrier-wise beamforming is shown to be the best, the hybrid beamforming is the next and the symbol-wise beamforming is the worst. However the performance difference is not noticeable, because the LOS component exists and the gain loss at the intersections of the beam pattern is very small. On the other hand, it can be seen that in Fig. 6 when no LOS exists, the beamforming performance degrades. It is shown that when the number of antenna elements is 2, the subcarrier-wise beamforming give 5.7 dB gain over the single antenna system, compared to only 1 dB with symbol-wise beamforming. The hybrid beamforming gain is 3.5 dB, which distinctly improves the performance over symbol-wise beamforming. The improvement is even higher when the number of antenna elements is larger.

B. Bit Error Rate (BER) Performance

To verify the numerical results of the beamforming systems, we simulate the BER performance using our IEEE 802.11ad PHY MATLAB simulator and channel models described in the previous section. Based on the assumption of perfect CSI, the BER performance of the SISO system is also plotted on the same graph as a reference. We assume there are two antenna elements at each transceiver side, and zero-forcing equalization is used at the receiver. Fig. 7 shows the simulated BER versus SNR for QPSK modulation with LDPC (672, 336) code in LOS scenario, and Fig. 8 presents the results in NLOS scenario.
It is shown that to achieve a BER at $10^{-3}$ in LOS scenario, the beamforming techniques give around 5-6 dB gain over the single antenna system. The BER performance difference of the three beamforming schemes is not distinct, but it still can be seen that at the same SNR level, the BER of subcarrier-wise beamforming is lowest, symbol-wise beamforming is highest, and hybrid beamforming is in the middle. In NLOS scenario, the simulation results show that the symbol-wise beamforming provides very little gain compared to the single antenna system, while the optimum subcarrier-wise beamforming gives about 6-6.5 dB gain. It is worth mentioning that around 4 dB gain can be achieved by hybrid beamforming. So when transmission path is blocked by obstacles, the superiority of hybrid beamforming is obvious. If systems with higher MIMO order are considered, the performance advantage of hybrid beamforming over symbol-wise beamforming will be more significant. It can be observed that the simulation results are very close to the theoretical analysis.

### C. Link Throughput and Ranges

In this section, we study the beamforming impact on the link throughput and operation range. As specified in the IEEE 802.11ad standard [1], the OFDM mode is designed for high performance applications and the modulation and coding schemes (MCSs) we consider in the paper are listed in Table I.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Coded Bits/Symbol</th>
<th>Data Bits/Symbol</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>672</td>
<td>336</td>
<td>1386.00</td>
</tr>
<tr>
<td>QPSK</td>
<td>5/8</td>
<td>672</td>
<td>420</td>
<td>1732.50</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>672</td>
<td>504</td>
<td>2079.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>1344</td>
<td>672</td>
<td>2772.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>5/8</td>
<td>1344</td>
<td>840</td>
<td>3465.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>1344</td>
<td>1008</td>
<td>4158.00</td>
</tr>
<tr>
<td>16-QAM</td>
<td>13/16</td>
<td>1344</td>
<td>1092</td>
<td>4504.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/8</td>
<td>2016</td>
<td>1260</td>
<td>5197.50</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>2016</td>
<td>1512</td>
<td>6237.00</td>
</tr>
<tr>
<td>64-QAM</td>
<td>13/16</td>
<td>2016</td>
<td>1638</td>
<td>6756.75</td>
</tr>
</tbody>
</table>

In order to enable the system to adapt the transmission mode to the link quality, the PHY modes with different MCSs are selected by a link adaptation scheme. When the data is not received correctly, the transmitter will retransmit the packet. The link throughput when retransmission is employed is given by [9]: $\text{Throughput} = R \times (1 - \text{PER})$, where $R$ and $\text{PER}$ are the peak data rate and packet error rate for a specific mode respectively. As shown in Fig. 9 and Fig. 10, the throughput envelop is the ideal adaptive MCS based on the optimum switching point. It is shown in Fig. 9 that the three beamforming schemes do not improve the peak error-free throughput, but at a certain SNR, beamforming systems offer higher throughput than the SISO system. The beamforming schemes achieve about 5-6 dB gain in comparison to the SISO system. In NLOS scenario, to maintain the same throughput, subcarrier-wise and hybrid beamforming provide about 6 dB and 4 dB gain compared to the SISO system respectively. However, the SISO system need even more SNR to achieve very high throughput (>4500 Mbps). It can be seen from Fig. 10 that subcarrier-wise and hybrid beamforming reach to the
maximum throughput at an average SNR of approximately 17 dB and 21 dB respectively.

The achievable operation range is derived from the path loss (PL) model. The 60 GHz conference room can be modeled as [8]:

\[
PL(\text{dB}) = A + 20 \log_{10}(f) + 10n \log_{10}(D)
\]

where for LOS scenario \(A = 32.5 \, \text{dB}, \, n = 2.0,\) and for NLOS scenario \(A = 51.5 \, \text{dB}, \, n = 0.6.\) \(f\) is the carrier frequency in GHz, and \(D\) is the distance between the transceivers in meter. Then the link budget can be described as:

\[
P_T - PL \geq kTB + NF + \text{ReceiverSNR}
\]

where \(P_T\) is the maximum transmit power (10dBm), \(k\) is Boltzmann’s constant, \(T\) is the room temperature (290K), \(B\) is the bandwidth, \(NF\) represents the noise figure (10dB) of such devices, and \(\text{ReceiverSNR}\) is the SNR required for the demodulation. Fig. 11 and Fig. 12 illustrate the maximum data rate that can be achieved over distance, based on equation (12) and the results of link throughput.

With the link adaption scheme applied, the system can operate at its maximum throughput when the devices are close, and adaptively switch to the lower speed when a device moves further away. It can be observed that the maximum tolerant distance for single antenna system in LOS scenario is about 12m, but in order to guarantee high throughput applications (>3000 Mbps), the transceivers distance should be within 4m. The beamforming schemes extend the operation range to about 18m, and almost increase 50% the tolerant distance to guarantee the high data rate. In the case of NLOS, the single antenna system could not provide service beyond 1m, but subcarrier-wise beamforming and hybrid beamforming extend the achievable operating range to 8m and 3.5m respectively.

\[\text{Figure 11: Operation range with LOS}\]

\[\text{Figure 12: Operation range with NLOS}\]

V. CONCLUSIONS

This paper has presented a performance evaluation of three types of beamforming techniques over the OFDM based 60 GHz millimeter-wave WPAN. The effective SNR gain has been computed for the typical channel models developed by IEEE 802.11ad. To verify the performance, BER results are evaluated using our PHY simulator. The adaptive link throughput are presented based on the simulated PER results. The achievable operation range is also investigated using the 60 GHz path loss model. The results demonstrate all three beamforming schemes increase the system performance significantly. When there is no LOS, hybrid beamforming provide considerable improvements while maintaining reasonable hardware complexity.

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