# Low Complexity Codebook-Based Beamforming for MIMO-OFDM Systems in Millimeter-Wave WPAN

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***Abstract*—In this paper, we consider a beamforming system in millimeter-wave wireless personal area networks (WPAN), where transmit and receive weight vectors are jointly derived by exchanging a training sequence repeatedly with different combinations of transmit and receive weight vectors. We propose a low complexity codebook-based beamforming scheme that consists of multiple levels and level-adaptive antenna selection in order to reduce the beamforming setup time. For each level, 1) the transmit and receive antennas are selected according to pre-determined inter-element spacings, 2) the training sequences are sent with different weight vectors from a pre-defined codebook and 3) the receiver selects the best transmit and receive weight vectors in order to optimize an effective signal-to-noise ratio (SNR) and these vectors are used to determine the codebook for the next following level. Even with low complexity, we show from the numerical results that our proposed scheme can provide an effective SNR gain and an average spectral efficiency approaching those of the codebook-based beamforming with exhaustive search.**

***Index Terms*—Codebook-based beamforming, MIMO-OFDM, millimeter-wave wireless personal area networks.**

## I. Introduction

DUE to the demand for high-speed short-range wireless communication, millimeter-wave communication with abundant bandwidth has received considerable interest in the standardization activity such as IEEE 802.15.3c for 60 GHz wireless personal area network (WPAN) [1]. The ultimate advantage of millimeter-wave communication is its capability to achieve a Gbps-order system throughput [2]. However, when the line-of-sight (LOS) path is blocked by stationary or moving objects, millimeter-wave communication suffers from tremendous performance degradation due to a high propagation loss at 60 GHz channels. To compensate the performance degradation, beamforming for millimeter-wave communication is highly encouraged to increase the transmission range and the system throughput. Since multiple antenna elements can be packed onto the small devices due to the short wavelength, it is obvious that beamforming with multiple antennas is applicable to millimeter-wave communication systems. However, for 60 GHz communication systems, the conventional baseband beamforming strategies are infeasible due to the high power consumption from multiple radio frequency (RF) chains including multiple digital-to-analog converters (DACs) or analog-to-digital converters (ADCs) since the multiple DACs and ADCs should operate at several gigasamples per second [2], [3]. Hence, by adopting beamforming in the RF domain as considered in [2], which consists of only a single RF chain and applies weight vectors to the signals in the RF domain, the system overhead can be notably reduced.

When beamforming in the RF domain is applied to multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) systems at 60 GHz, the following two issues need to be considered. Firstly, obtaining channel state information (CSI), i.e. a set of channel matrices for all narrowband subchannels, is impracticable since the channel sounding procedure based on transmission and reception between all pairs of individual elements is not always possible due to the high propagation loss at 60 GHz channels [4]. Secondly, it is undesirable to apply the weight vectors with exact amplitude and phase to the signals as it requires higher power consumption and complexity since the RF devices, including phase shifter and gain controller, are more complicated to cover a wider range of phases and amplitudes. [5]. The authors in [5] proposed a codebook design to be applied to 60 GHz WPAN systems, which can minimize the power consumption of the RF devices since all the elements of codebook are specified by only one of four phase shifts (0, 90, 180, and 270 degrees) without any amplitude adjustment. Therefore, we consider beamforming in the RF domain which is based on training with four phase codebook in [5] rather than on explicit channel estimation and weight vector optimization as a beamforming setup.

In this paper, we propose a low complexity codebook-based beamforming with multi-level training and antenna selection which can reduce the beamforming setup time significantly. For each level, 1) the transmit and receive antennas are selected according to pre-determined inter-element spacings, 2) the training sequences (TS) are sent with different weight vectors from a pre-defined codebook set and 3) the receiver selects the best transmit and receive weight vectors to optimize a cost function. Compared to the conventional schemes with one or two level training [1], in our proposed scheme, we define the codebook set for each level, which is a subset of four phase codebook set [5]. The codebook set for each level is derived by maximizing the array factor correlation between the vector from the four phase codebook and the best weight vector for the previous level. The cardinality of codebook set for each level is limited to two, which can drastically decrease the total number of TS transmissions without loss of performance.

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## II. System Model

We consider a MIMO-OFDM system with $M_t$ transmit antennas, $M_r$ receive antennas, and $N$ subcarriers. At the transmitter, the signal after baseband processing is up-converted to the RF band. The RF signal is phase-shifted by applying the transmit weight vector and is transmitted via the MIMO channel. At the receiver, the received RF signal is phase-shifted by the receive weight vector and combined in the RF domain. Then the combined signal is down-converted for baseband processing. Note that the transmit and receive weight vectors are selected from the pre-defined transmit and receive codebooks, respectively, in order to optimize a cost function as a performance metric. As a cost function, we adopt the effective signal-to-noise ratio (SNR) derived by an exponential effective SNR mapping (EESM) which can provide the link error performance for the OFDM system without exhaustive link-level emulation [6], [7].

After combining, the baseband signal representation for the $m$-th subcarrier is expressed as [8]

$$y_m = \mathbf{c}^{\mathsf{H}}\mathbf{H}_m\mathbf{w}x_m + \mathbf{c}^{\mathsf{H}}\mathbf{z}_m, \ \ m = 1, ..., N, \tag{1}$$

where $\mathbf{H}_m \in \mathbb{C}^{M_r \times M_t}$ represents the MIMO channel matrix for the $m$-th subcarrier and $\mathbf{z}_m$ is the noise vector with independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and variance $\sigma^2$. Throughout the paper, since we consider beamforming in the RF domain, it requires only one pair of transmit and receive weight vectors for the entire OFDM symbol so that it can be classified as a codebook-based symbol-wise beamforming system [8]. In (1), we denote the transmit and receive weight vectors as $\mathbf{w}$ and $\mathbf{c}$, respectively.

We adopt the codebook generation method introduced in [1] which enables beamforming in the RF domain without a high power consumption by using only specific phase shifts. This codebook generation method is to be used at both the transmitter and the receiver. Denoting the codebook set as $\mathcal{F}$, the $(u, v)$-th element of the codebook set for $u = 0, 1, \cdots, U-1$ and $v = 0, 1, \cdots, K-1$ is defined as

$$[\mathcal{F}]_{(u,v)} = j^{\left\lfloor \frac{u \times \mathrm{mod}(v+(K/2),K)}{K/4} \right\rfloor} \tag{2}$$

where $u$ and $v$ denote the antenna and beam indices, respectively, and $j = \sqrt{-1}$. In (2), $U$ and $K$ are the total number of antenna elements and beams, respectively and the function $\mathrm{mod}(x, y)$ returns $x - n \cdot y$ where $n$ is an integer smaller than or equal to $x/y$. Since all the elements of $[\mathcal{F}]_{(u,v)}$ have unit magnitudes, we obtain $\mathbf{w}^{\mathsf{H}}\mathbf{w} = M_t$ and $\mathbf{c}^{\mathsf{H}}\mathbf{c} = M_r$. The transmitted signal, $x_m$, has the power of $\mathrm{E}[|x_m|^2] = 1/M_t$ to normalize the total transmitted power over all transmit antennas to 1.

From (1), the SNR of the $m$-th subcarrier is given by

$$\gamma_m = \frac{E[|\mathbf{c}^{\mathsf{H}}\mathbf{H}_m\mathbf{w}x_m|^2]}{E[|\mathbf{c}^{\mathsf{H}}\mathbf{z}_m|^2]} = \frac{|\mathbf{c}^{\mathsf{H}}\mathbf{H}_m\mathbf{w}|^2}{M_t M_r \sigma^2}. \tag{3}$$

The effective SNR, $\gamma_{\text{eff}}$, from the EESM function can be written as [6]

$$\gamma_{\text{eff}} = -\beta \ln\left(\frac{1}{N}\sum_{m=1}^{N} e^{-\gamma_m/\beta}\right), \tag{4}$$

where $\beta$ is an adjustment constant which can be calibrated by a sufficiently large number of independent channel realizations. By substituting (3) into (4), we can obtain the effective SNR as

$$\gamma_{\text{eff}} = -\beta \ln\left(\frac{1}{N}\sum_{m=1}^{N} e^{-\frac{|\mathbf{c}^{\mathsf{H}}\mathbf{H}_m\mathbf{w}|^2}{\beta M_t M_r \sigma^2}}\right). \tag{5}$$

## III. Codebook-Based Beamforming

In this section, we briefly investigate conventional codebook-based beamforming schemes. Subsequently, we describe our proposed scheme, which is a codebook-based beamforming with multi-level training and antenna selection. Finally, we compare the overhead of the proposed scheme with the conventional codebook-based beamforming schemes.

### A. Conventional Codebook-Based Beamforming

In codebook-based beamforming, system performance depends on the selection of a pair of transmit and receive weight vectors before data transmissions. Throughout the paper, we assume that the best beam pair, i.e. the best transmit and receive weight vectors, is determined by exchanging training sequences with specific combinations of transmit and receive weight vectors from the transmit and receive codebooks. We consider two conventional codebook-based beamforming schemes: 1) codebook-based beamforming with exhaustive search (CBF-ES) and 2) codebook-based beamforming with two-level training (CBF-2T). Let us assume that the numbers of beams for transmitter and receiver are $K_t$ and $K_r$, respectively. In CBF-ES, while the transmitter sends the training sequence with one transmit weight vector from the transmit codebook, the receiver attempts to listen to it with $K_r$ different receive weight vectors from the receive codebook. The procedure is repeated until the transmitter has tried $K_t$ transmit weight vectors for the transmission of the training sequence. As a result, CBF-ES requires $K_t \times K_r$ TS transmissions to select the best beam pair.

To reduce the beamforming setup time of CBF-ES, CBF-2T is introduced in [1], which consists of sector level and beam level training. In the sector level training, a subset of antenna elements is activated to generate wider sector patterns. Denoting $S_t$ and $S_r$ as the numbers of sectors for the transmitter and the receiver, respectively, $S_t \times S_r$ TS transmissions are required in the sector level training. Similarly, denoting the numbers of beams per sector for the transmitter and receiver as $B_t = K_t/S_t$ and $B_r = K_r/S_r$, respectively, $B_t \times B_r$ TS transmissions are required since only the beam patterns corresponding to the selected sector are involved in the beam level training. Therefore, CBF-2T requires $S_t \times S_r + B_t \times B_r$ TS transmissions to select the best beam pair.

### B. Proposed Codebook-Based Beamforming

Let us assume that the system adopts an uniform linear array with inter-element spacing as half carrier wavelength $\lambda/2$. Denoting the total number of levels for our proposed codebook-based beamforming with multi-level training and level-adaptive antenna selection (CBF-MTAS) as $n = \max(n_t, n_r)$, where $n_t = \lceil \log_2 M_t \rceil$ and $n_r = \lceil \log_2 M_r \rceil$, we develop the simple level-adaptive antenna selection scheme as follows. Let $q$ be the level index, then the numbers of selected antennas for the $q$-th level at the transmitter and receiver are given by

$$M_{t,q}=\begin{cases}2^q & \text{, if } q<n_t\\ M_t & \text{, if } q\geq n_t\end{cases},\ M_{r,q}=\begin{cases}2^q & \text{, if } q<n_r\\ M_r & \text{, if } q\geq n_r\end{cases}, \tag{6}$$

respectively. The inter-element spacings between selected antennas for the $q$-th level at the transmitter and the receiver are given by

$$d_{t,q}=\begin{cases}2^{n_t-(q+1)}\lambda & \text{, if } q<n_t\\ 2^{-1}\lambda & \text{, if } q\geq n_t\end{cases}, \tag{7}$$

$$d_{r,q}=\begin{cases}2^{n_r-(q+1)}\lambda & \text{, if } q<n_r\\ 2^{-1}\lambda & \text{, if } q\geq n_r\end{cases}, \tag{8}$$

respectively.

Assuming that the number of beams is the same as the number of antennas at the $q$-th level, we define the mother codebook sets for the transmitter and the receiver as $\mathcal{F}_{(t,q)}$ and $\mathcal{F}_{(r,q)}$, respectively, which are generated by (2). Denoting the $v_t$-th transmit weight vector and the $v_r$-th receive weight vector at the $q$-th level as $\mathbf{f}_{(t,q),v_t}\in\mathbb{C}^{M_{t,q}\times 1}$ and $\mathbf{f}_{(r,q),v_r}\in\mathbb{C}^{M_{r,q}\times 1}$, respectively, the mother codebook sets for the transmitter and receiver can be expressed as

$$\mathcal{F}_{(t,q)}=\left\{\mathbf{f}_{(t,q),1}\ ,\ \mathbf{f}_{(t,q),2}\ ,\ \cdots\ ,\ \mathbf{f}_{(t,q),M_{t,q}}\right\}, \tag{9}$$

$$\mathcal{F}_{(r,q)}=\left\{\mathbf{f}_{(r,q),1}\ ,\ \mathbf{f}_{(r,q),2}\ ,\ \cdots\ ,\ \mathbf{f}_{(r,q),M_{r,q}}\right\}, \tag{10}$$

respectively. However, in the proposed CBF-MTAS, the subsets of the mother codebook sets are adopted in order to reduce the total number of TS transmissions. To derive the subset for each level, we consider an array factor that can describe the beam patterns resulting from the codebook. The array factor for the linear array is determined by the positions of the individual antenna elements and their coefficients of weight vector, which is given by [9]

$$AF(\mathbf{f},\theta)=\sum_{u=1}^{U}[\mathbf{f}]_u\exp\left(j2\pi/\lambda(u-1)d\cos(\theta)\right), \tag{11}$$

where $[\mathbf{f}]_u$ is the $u$-th element of arbitrary weight vector $\mathbf{f}$, $d$ is the inter-element spacing, and $\theta$ is the direction of departure (DoD) or the direction of arrival (DoA). From (11), by letting $\mathbf{g}(\mathbf{f})=[AF(\mathbf{f},0),\cdots,AF(\mathbf{f},2\pi-360/2\pi)]^{\mathsf{T}}$, we can define the array factor correlation between the best transmit/receive weight vector to optimize an effective SNR for the $(q-1)$-th level and the $v_t/v_r$-th transmit/receive weight vector from (9)/(10) for the $q$-th level as

$$|\mathbf{g}(\mathbf{f}_{(t,q-1),i_{(t,q-1)}})^{\mathsf{H}}\mathbf{g}(\mathbf{f}_{(t,q),v_t})|\ ,\ v_t=1,2,\cdots,M_{t,q}, \tag{12}$$

$$|\mathbf{g}(\mathbf{f}_{(r,q-1),i_{(r,q-1)}})^{\mathsf{H}}\mathbf{g}(\mathbf{f}_{(r,q),v_r})|\ ,\ v_r=1,2,\cdots,M_{r,q}, \tag{13}$$

respectively, where $i_{(t,q-1)}$ indicates the index of the best transmit weight vector for the $(q-1)$-th level and $i_{(r,q-1)}$ indicates the index of the best receive weight vector for the $(q-1)$-th level. Consequently, we can derive the codebook set for the $q$-th level at the transmitter as

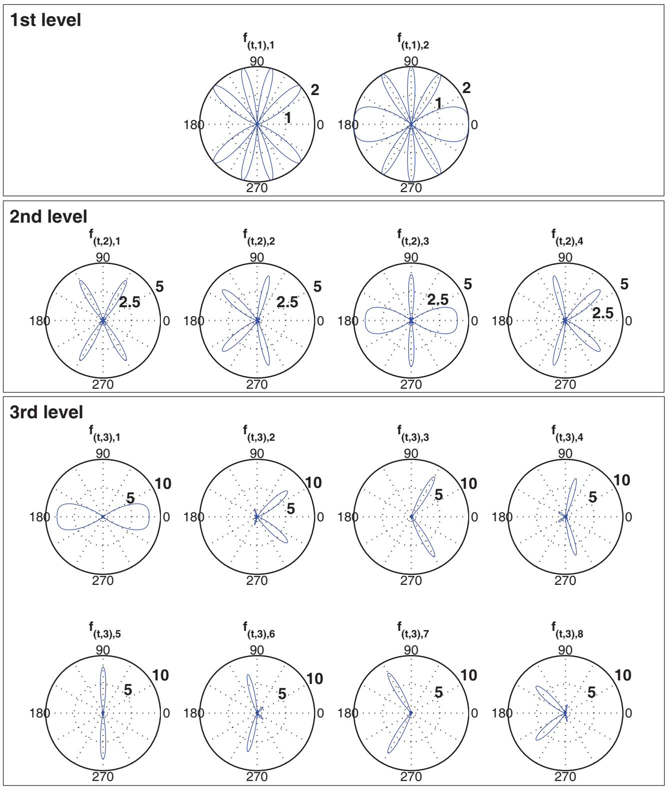


Fig. 1. Transmit beam patterns in the polar coordinate plane for CBF-MTAS when $M_t=K_t=8$. The first, second and third boxes include the beam patterns of the first, second, and third levels, respectively. We adopt the different scaling between angle and amplitude, where the number in bold-face indicates the amplitude. Note that the beam patterns for the fourth level are omitted since they are the same as those for the third level.

$$\tilde{\mathcal{F}}_{(t,q)}=\begin{cases}\left\{\mathbf{f}_{(t,q),1}\ ,\ \mathbf{f}_{(t,q),2}\right\} & \text{, if } q=1\ ,\\ \left\{\mathbf{f}_{(t,q),v_1}\ ,\ \mathbf{f}_{(t,q),v_2}\right\} & \text{, if } 1<q\leq n_t\ ,\\ \left\{\mathbf{f}_{(t,q),i_{(t,q-1)}}\right\} & \text{, if } q>n_t\ ,\end{cases} \tag{14}$$

where $\mathbf{f}_{(t,q),v_1}$ and $\mathbf{f}_{(t,q),v_2}$ denote the largest and the second largest arguments to maximize the array factor correlation given by (12). We note for $1<q\leq n_t$ that the codebook $\tilde{\mathcal{F}}_{(t,q)}$ is a subset of (9). Analogous to (14), we can also derive the codebook set for the $q$-th level at the receiver as

$$\tilde{\mathcal{F}}_{(r,q)}=\begin{cases}\left\{\mathbf{f}_{(r,q),1}\ ,\ \mathbf{f}_{(r,q),2}\right\} & \text{, if } q=1\ ,\\ \left\{\mathbf{f}_{(r,q),v_1}\ ,\ \mathbf{f}_{(r,q),v_2}\right\} & \text{, if } 1<q\leq n_r\ ,\\ \left\{\mathbf{f}_{(r,q),i_{(r,q-1)}}\right\} & \text{, if } q>n_r\ ,\end{cases} \tag{15}$$

where $\mathbf{f}_{(r,q),v_1}$ and $\mathbf{f}_{(r,q),v_2}$ denote the largest and the second largest arguments to maximize the array factor correlation given by (13). For illustrative purpose, we consider a simple example to explain how to derive the codebook sets for our proposed scheme.

*Example:* Assuming $M_t=K_t=8$ and $M_r=K_r=16$, we obtain $n_t=3$, $n_r=4$, and $n=4$. From the level-adaptive antenna selection, we can obtain the transmit beam patterns in the polar coordinate plane by using (11) for the first, the second, and the third levels as depicted in Fig. 1. Note that we

**- Definitions**

- $q$ : the level index

**- Functions**

- Updateparam($q$) : Update $M_{t,q}$, $M_{r,q}$, $d_{t,q}$, and $d_{r,q}$ for the $q$-th level according to (6), (7) and (8)
- Antsel($q$) : Activate transmit and receive antennas for the $q$-th level with output of Updateparam($q$)
- Training($q, v_t, v_r$) : TS transmission with the $v_t$-th weight vector of codebook set $\tilde{\mathcal{F}}_{(t,q)}$ and the $v_r$-th weight vector of codebook set $\tilde{\mathcal{F}}_{(r,q)}$ as transmit and receive weight vectors, respectively
- $[i_{(t,q)}, i_{(r,q)}]$ = Calculate($q$) : Calculate (16) after TS transmissions for the $q$-th level and output the best beam indices

**- Algorithm**

```
q := 0,  n = max(n_t, n_r)
repeat
    q := q + 1
    Updateparam(q)
    Antsel(q)
    Training(q, 1, 1)
    if q ≤ n_r then
        Training(q, 1, 2)
    if q ≤ n_t then
        Training(q, 2, 1)
        if q ≤ n_r then
            Training(q, 2, 2)
    [i_(t,q), i_(r,q)] = Calculate(q)
until q == n
```

Fig. 2. Pseudo code of proposed CBF-MTAS algorithm.

omit the beam patterns for the fourth level which are identical to those for the third level. In Fig. 1, we can observe that one beam pattern of the $(q-1)$-th level can be mapped onto two beam patterns of the $q$-th level that exhibit larger array factor correlations than the other beam patterns of the $q$-th level. Since the number of candidates for each level to attempt the training is limited to 2 for $q \leq n_t$, it leads to the reduction of the total number of TS transmissions. In case of $q > n_t$, the beam patterns of the $(q-1)$-th level are the same as those of the $q$-th level since same antennas are selected with the same inter-element spacing, which implies that all antenna elements of the array are activated. ■

Using (5), we can formulate the best beam pair selection problem for the $q$-th level in the proposed CBF-MTAS as

$$(\hat{\mathbf{w}}_{(q)}, \hat{\mathbf{c}}_{(q)}) = \arg \max_{\substack{\mathbf{w}_{(q)} \in \tilde{\mathcal{F}}_{(t,q)} \\ \mathbf{c}_{(q)} \in \tilde{\mathcal{F}}_{(r,q)}}} -\beta \ln \left( \frac{1}{N} \sum_{m=1}^{N} e^{-\frac{|\mathbf{c}_{(q)}^{\mathrm{H}} \mathbf{H}_{(q),m} \mathbf{w}_{(q)}|^2}{\beta M_{t,q} M_{r,q} \sigma^2}} \right) \tag{16}$$

where $\mathbf{w}_{(q)}$ and $\mathbf{c}_{(q)}$ are the weight vectors from the codebook sets $\tilde{\mathcal{F}}_{(t,q)}$ and $\tilde{\mathcal{F}}_{(r,q)}$ for the $q$-th level, respectively, and $\hat{\mathbf{w}}_{(q)}$ and $\hat{\mathbf{c}}_{(q)}$ are the weight vectors of the transmitter and the receiver corresponding to the best beam pair for the $q$-th level, respectively. Note that $\mathbf{H}_{(q),m}$ indicates the $m$-th subcarrier channel matrix between the selected transmit and receive antennas for the $q$-th level. Based on (6)-(8) and (14)-(16), we can summarize the proposed CBF-MTAS as pseudo code in Fig. 2.

### *C. Overhead Comparison*

As a measure of the system protocol overhead, we consider the number of TS transmissions during a beamforming setup.

TABLE I
OVERHEAD COMPARISON FOR CODEBOOK-BASED BEAMFORMING SCHEMES

| | Number of TS transmissions |
|---|---|
| CBF-ES | $K_t K_r$ |
| CBF-2T | $S_t S_r + (K_t/S_t)(K_r/S_r)$ |
| CBF-MTAS | $4 \lceil \log_2 \min(M_t, M_r) \rceil +$ $+2 \left( \lceil \log_2 \max(M_t, M_r) \rceil - \lceil \log_2 \min(M_t, M_r) \rceil \right)$ |

| | Number of complex multiplications per subcarrier |
|---|---|
| CBF-ES | $K_t K_r \times (M_r {M_t}^2)$ |
| CBF-2T | $S_t S_r \times S_r {S_t}^2$ $+(K_t/S_t)(K_r/S_r) \times \left( (K_r/S_r)(K_t/S_t)^2 \right)$ |
| CBF-MTAS | $4 \times \lceil \log_2 \min(M_t, M_r) \rceil \times 2^3$ $+2 \times (\lceil \log_2 \max(M_t, M_r) \rceil$ $- \lceil \log_2 \min(M_t, M_r) \rceil) \times 2^3$ |

TABLE II
PERCENTAGE OF THE NUMBER OF TS TRANSMISSIONS REDUCTION OF OUR PROPOSED SCHEME COMPARED TO CBF-ES AND CBF-2T

| $M$ | **CBF-MTAS** vs **CBF-ES** | **CBF-MTAS** vs **CBF-2T** |
|---|---|---|
| 4 | 50.00% | - |
| 8 | 81.25% | 40.00% |
| 16 | 93.75% | 50.00% |
| 32 | 98.05% | 75.00% |
| 64 | 99.41% | 81.25% |

For the overhead comparison, we calculate the total number of TS transmissions for CBF-ES, CBF-2T, and CBF-MTAS as presented in Table I. For CBF-2T, $S_t$ and $S_r$ are determined as $\arg\min_{(S_t, S_r)} S_t S_r + (K_t/S_t)(K_r/S_r)$ such that the number of TS transmissions is minimized. Assuming that $M_t = M_r = K_t = K_r = M$ to facilitate the comparison of the system protocol overhead, Table II lists the percentage of the number of TS transmissions reduction by adopting the proposed scheme compared to CBF-ES and CBF-2T for $M = 4$, 8, 16, 32, and 64. It is clear that our proposed scheme requires much fewer TS transmissions than other schemes. We can see that the proposed scheme can further reduce the number of TS transmissions as $M$ increases so that the spectral efficiency can be increased.

We can also compute the number of complex multiplications per subcarrier during a beamforming setup for CBF-ES, CBF-2T, and CBF-MTAS as presented in Table I. This indicates that our proposed scheme can provide even more computational savings for larger $N$, which is a typical scenario for millimeter-wave WPAN systems with a large channel bandwidth over 2 GHz.

## IV. NUMERICAL RESULTS

In this section, we present some simulation results to illustrate the performance of the proposed CBF-MTAS compared to the conventional schemes, CBF-ES and CBF-2T. Throughout the simulations, the effective SNR from (5) is used as a cost function to determine the best beam pair for each level. For the performance comparison, we adopt the effective SNR gain over the single antenna system in [10], which is given by

$$G = \frac{\gamma_{\text{eff}}}{\gamma_{\text{single}}}, \tag{17}$$

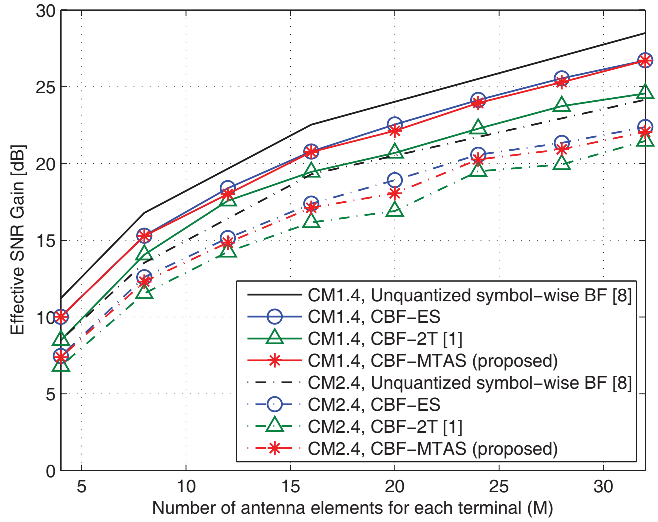


Fig. 3. Effective SNR gain versus the number of antenna elements for each terminal, $M$, over the LOS channel model (CM1.4.) and the NLOS channel model (CM2.4.) in [11]. In (18), we set $|H_{0,0}[m]|^2/\sigma^2 = 1$.

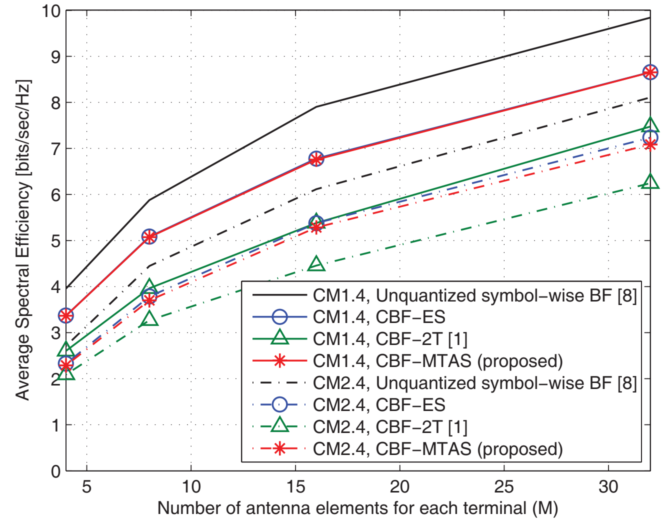


Fig. 4. Average spectral efficiency versus the number of antenna elements for each terminal, $M$, over the LOS channel model (CM1.4.) and the NLOS channel model (CM2.4.) in [11]. In (18), we set $|H_{0,0}[m]|^2/\sigma^2 = 1$.

where $\gamma_{\text{single}}$ is the effective SNR of the single antenna system which can be defined as

$$\gamma_{\text{single}} = -\beta \ln \left( \frac{1}{N} \sum_{m=1}^{N} e^{-|H_{0,0}[m]|^2/\beta\sigma^2} \right), \tag{18}$$

where $H_{u,s}[m]$ is the channel frequency response between the $s$-th transmit antenna and the $u$-th receive antenna. Note that we can select the channel gain between the first transmit and the first receive antennas to compute (18) since $H_{u,s}[m]$ for $u = 0, 1, \cdots, M_r - 1$ and $s = 0, 1, \cdots, M_t - 1$ can be regarded as identically distributed random variables. We assume that $\beta$ for both $\gamma_{\text{single}}$ and $\gamma_{\text{eff}}$ is set to 3, which is adjusted by the numerical simulations.

We consider the system parameters as a 60 GHz carrier frequency, an 1 GHz bandwidth, and a 5m distance between the transmitter and receiver. As the OFDM parameters, 512 OFDM subcarriers and 64 length of cyclic prefix are assumed. We consider a double directional channel model based on the Saleh-Valenzuela model, which includes the channel gain, the time delay, the DoA and the DoD [10]. Our simulations are conducted both in the non-line-of-sight (NLOS) model and in the LOS model which are specified in [11] as CM2.4 and CM1.4, respectively. The statistical characterization of the parameters for the channel model can be found in [11] in detail[1].

In Fig. 3, we illustrate the effective SNR gain over the single antenna system with respect to the number of antenna elements, $M$, for each terminal. As a benchmark, we consider the symbol-wise beamforming introduced in [8], which adopts only one pair of weight vectors for all subcarriers under the MIMO-OFDM transmit and receive beamforming system. Instead of the vector from codebook, a non-quantized weight vector is utilized so that we can see the performance gap between the unquantized symbol-wise beamforming in [8] and the other codebook-based beamforming schemes. As seen in both figures, we can confirm that the effective SNR gain of the proposed CBF-MTAS approaches that of CBF-ES and even outperforms that of CBF-2T, although CBF-MTAS significantly reduces the total number of TS transmissions as shown in Table II, i.e., more than $50\%$ and $40\%$ of reductions compared to CBF-ES and CBF-2T, respectively. We can also verify that the proposed scheme can provide substantial gain regardless of the existence of LOS components.

In Fig. 4, we present the average spectral efficiency with respect to the number of antenna elements, $M$, for each terminal [12]. Similar to the results of the effective SNR gain, we can observe that the proposed CBF-MTAS provides a negligible loss of the average spectral efficiency compared to CBF-ES with even lower complexity.

[1]Since the statistical characterization of the DoD has not been defined in [11], we assume that the statistical characterization of the DoD is the same as one of the DoA for simplicity.

## V. Conclusion

In this paper, we proposed a low complexity codebook-based beamforming scheme for MIMO-OFDM systems in millimeter-wave WPAN, which consists of multi-level training and level-adaptive antenna selection. Compared to the conventional codebook-based beamforming, the proposed scheme can reduce the beamforming setup time significantly by decreasing the number of TS transmissions without performance loss. We showed in simulation that the proposed scheme offers almost the same effective SNR gain and average spectral efficiency as CBF-ES even though it is using fewer TS transmission.

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