Max-Min Fair Hybrid Precoding for Multi-group Multicasting in Millimeter-Wave Channel

Fawwaz Alsubaie

Abstract—The potential of using millimeter-wave (mmWave) to encounter the current bandwidth shortage has motivated packing more antenna elements in the same physical size which permits the advent of massive multiple-input-multiple-output (MIMO) for mmWave communication. However, with increasing number of antenna elements, the ability of allocating a single RF-chain per antenna becomes infeasible and unaffordable. As a cost-effective alternative, the design of hybrid precoding has been considered where the limited-scattering signals are captured by a high-dimensional RF precoder realized by an analog phase-shifter network followed by a low-dimensional digital precoder at baseband. In this paper, the max-min fair problem is considered to design a low-complexity hybrid precoder for multi-group multicasting systems in mmWave channels. The problem is non-trivial due to two main reasons: the original max-min problem for multi-group multicasting for a fully-digital precoder is non-convex, and the analog precoder places constant modules constraint which restricts the feasible set of the precoders in the design problem. Therefore, we consider a low complexity hybrid precoder design to tackle and benefit from the mmWave channel structure. Each analog beamformer was designed to maximize the minimum matching component for users within a given group. Once obtained, the digital precoder was attained by solving the max-min problem of the equivalent channel.

Index Terms—Multicasting, Limited RF chains, Hybrid precoding, Low complexity algorithm.

I. INTRODUCTION

The event of common data targeting a mass of users or relay stations, in the case of relay networks, has become popular in current wireless systems. Services like video/audio streaming, news, common clips and messages are expected to further grow in next-generation wireless systems [1]. In a scenario where a group of users demand the same information, i.e. single-group multicasting (SGM) or broadcasting, the base station (BS) can provide the service by a point-to-multipoint connection. In the case of multi-group multicasting (MGM), groups with disjoint sets of users are entitled to different common messages. In the case of a single user per group, the scenario is known as multi-user (MU) downlink beamforming. The provision of multicasting services, both SGM and MGM, has been introduced by the Global System for Mobile communication (GSM) and Universal Mobile Telecommunications System (UMTS) as a form of multimedia broadcast/multicast service [2, 3]. In addition, a form of multicasting has been proposed by the Worldwide Interoperability for Microwave Access (WiMAX) [4].

When considering a serving-network where users can request same common messages (multicasting), the support of such services can be provided under a wired network. However, from a cost and feasibility prospective, it is impossible to extend cables to every user or a relay station. The solution is to utilize the wireless medium to perform multicasting. The apparent wireless nature as a broadcast medium causes cross-talk or co-channel interference among users scheduled at the same time and frequency slots, not mentioning fading and shadowing. Then, to mitigate interference, users used to be scheduled among the orthogonal resources, e.g. time and frequency. This resulted in increasing network traffic and decreasing spectral efficiency.

To address this issue, in MU-beamforming, smart antenna array with adjustable antenna weights has been implemented at the transmitter to beamform, or precode, to the served users. Hence, users can be simultaneously scheduled at the same time-frequency slot while experiencing minimal interference. The later technique utilizes the third degree of freedom (DoF) in the system, i.e. space, and formally called spatial division multiple access (SDMA). Techniques to perform SDMA to design optimal and sub-optimal precoders and with various scenarios have been extensively studied in the literature [5–10]. When considering multicasting, the concept of physical-layer multicasting (PHY-multicasting) was firstly introduced in [11] for SGM and in [12] for MGM. Moreover, the discussed design problems were far from trivial compared to MU-beamforming and are detailed later in this paper.

In addition to the future need for multimedia/multicasting services, the demand for low-latency application and delivery of high-quality multimedia content is a genuine challenge. With the rapid growth of smartphones, available carrier frequency slots have become ever more scarce. To overcome the bandwidth shortage, the underutilized millimeter wave (mmWave) has been strongly suggested for the next-generation frequency spectrum use [13]. The mmWave signal experiences orders-of-magnitude path loss due to a ten-fold carrier frequency increase. With this difficulty comes the interesting feature of mmWave that is packing more antennas at the same physical size of the original microwave antenna. Large antenna array offers beamforming gain to overcome path loss and allows spatial multiplexing which could improve the overall system spectral efficiency [14–16].

So far, the adaptive antenna array permits flexible configuration in the RF domain of both magnitude and phase. However, in mmWave channels, the BS is equipped with a large antenna array and it is rather infeasible to dedicate a single RF-chain per antenna element [17]. Therefore, precoding has been divided into two stages: digital low-dimensional baseband precoding followed by high-dimensional RF-precoding realized by an analog phase shifter network. Since the introduction of hybrid precoding in [18], it has been a strong candidate for the next-generation wireless system [19]. In the hybrid structure, the RF-precoding has a fewer number of RF-chains...
fully or partially-connected with all antennas whereas the digital-processing is done at the baseband. The Full analysis of the minimal number of RF chains to realize a fully-digital precoder is given in [20]–[22]. Works on designing a hybrid precoder in mmWave channels for various systems are given in [23]–[28] while a low-complexity hybrid precoder design under independent and identically distributed (i.i.d) Rayleigh fading channel is considered in [29].

II. RELATED PREVIOUS WORK

In multicasting, SGM or MGM, the existing work have addressed various frameworks to specify what-called the optimal precoder. Herein, we mention the existing design problems for multicasting systems:

- Quality of Service (QoS): the QoS problem considers a minimum service level for each individual user in the multicasting system. The goal is to minimize the total transmit power subject to the minimum service levels for all users in the multicasting system. The optimal precoder in the QoS sense provides the minimum service level(s) with the minimum power consumption.

- Max-min fair (max-min): the max-min fair problem is concerned with a fair performance in a multicasting system. The goal is to maximizes the minimum QoS level(s) for all users in the multicasting system subject to a total transmit power. Conceptually, this is achieved by reducing the power for the good-condition-channel users compared to the worst channel(s). The optimal precoder in the fairness sense ensures a fair performance among users and satisfies the total transmit power constraint with equality.

- Sum-Rate Maximization (SR): the SR problem considers the optimal precoder for which the multicasting system experiences the ultimate throughput. Along this line, the SR problem doesn’t consider fairness among users or groups. For example, in the case of MGM, low-channel-condition group can be set to service unavailability. In other words, the power is not consumed to compensate for channel conditions.

One or more of the above problems could be solved under Per Antenna Constraint (PAC). The motivation of investigating such a constraint comes from a practical system implementation aspect. Power flexibility is not always feasible at the transmitter due to different antennas having individual amplifiers and hence the need to specify the power consumed by each antenna element. Also, different antenna amplifiers can have different power range, i.e. different saturation power levels, and thus PAC problem can help in controlling the power of each antenna element.

A. Single-group multicasting (SGM):

In SGM, the cell performance characterized by total transmission power or overall throughput is constrained by the worst-condition user in the group. In SGM, a single common message addresses a group of co-channel users and thus cross-talk is not an issue. While SGM can be a special case of MGM and a work on MGM would generally apply on SGM, we mention specific works on SGM systems.

Physical layer multicasting was firstly introduced by Lopez in [30], where the sum of signal-to-noise ratio (SNR) was maximized for all users. The optimization was equivalent to maximizing an average SNR not considering individual users which boiled down to a simple eigenvalue problem. However, the work in [30] has inspired the development of various algorithms and design problems concerning multicasting systems.

The QoS problem for SGM has been firstly introduced in [11], where the problem is formulated as a non-convex Quadratically Constrained Quadratic Program (QCQP) and shown to be an NP-hard problem. The problem is relaxed, new variables are introduced, and reformulated as a semi-definite relaxation program (SDR) [31]. Following that, if the solution is not rank-one, Gaussian randomization with scaling are used to find the optimal precoder. The max-min problem has also been addressed in [11], and the solution is found following the previous strategy.

In [32], the max-min fair problem has been formulated to find a sub-optimal hybrid precoder design under mmWave channel. The RF-precoder and baseband precoder are decoupled. The RF-precoder is designed based on a codebook to maximize an upper bound assuming a fixed baseband precoder. Once obtained, the digital precoder is obtained following the strategy in [11].

B. Multi-group multicasting (MGM):

A fundamental difference in MGM compared to SGM: is the existing of disjoint sets of users demanding different common messages and hence interference becomes an issue. However, the problem is very general where it includes many scenarios, SGM, for example. In addition, the SGM design problems are always feasible, whereas for MGM systems, the design problems can be infeasible. On the other hand, some of the MGM design problems are more flexible in which the service levels for different groups can be adjusted to fulfill some optimization goals.

The QoS and MMF problems for MGM have been firstly introduced in [12]. Due to interference and possible infeasibility, the QoS problem for MGM is different from the SGM one presented in [11]. The SDR method is proposed to solve the QoS problem similar to [11]. However, the randomization is more involved since the scaling can enhance the interference. Therefore, a power control program is solved to provide the right scaling factors. For the max-min problem, the SDR program is non-linear and is solved, if feasible, by a bisection method followed by a multi-group power control program. In the case of Vandermonde channels, which is the case in line-of-sight (LoS) scenarios, the channel matrices are shown to be rank-one and the relaxation is tight. Hence, if the problem is feasible, the optimal solution is always obtainable [33].

To account for practical system limitation, the MGM sum-rate problem with PAC has been presented in [34], while the max-min fair problem with PAC has been discussed in [35], [36].

In order to mitigate SDR complexity, specially as number of users increases, Successive Convex Approximation (SCA) has
been proposed to solve the QoS problem in [37] and max-min fair problem in [38]. Also, the max-min sum rate and max-min with PAC have been investigated in [39] and [40], respectively. Similar to SGM, the solution might not be optimal but it is a low-complexity design compared to SDR.

Recent works have considered hybrid precoding for MGM systems under mmWave channels [41]–[44]. In this paper, we consider the problem for MGM systems with hybrid precoding introduced in [13] under mmWave channels. We give a low complexity max-min fair hybrid precoding design for MGM systems under mmWave channels. System performance is simulated and discussed.

Notations: We use the following notation throughout this paper: $A$ is a matrix; $a$ is a vector; $a$ is a scalar; $I_N$ is the $N \times N$ identity matrix; $\| \cdot \|_2$ is the Frobenius norm; $(\cdot)^T$ is the transpose operator; $(\cdot)^H$ is the conjugate transpose operator; $\text{tr}(\cdot)$ is the trace operator; $\mathbb{E} [\cdot]$ is the expectation and $\arg(\cdot)$ is the phase of the entries for matrix or vectors.

III. SYSTEM MODEL

Consider a single-cell system where the base station (BS) is equipped with $N$ antenna elements and $N_{RF}$ RF-chains communicating with $M$ single-antenna users. Further, let there be a total of $1 \leq G \leq N_{RF}$ multicastring groups where the multicast group index set writes as $\mathcal{G} = \{G_1, \ldots, G_G\}$ and $G_k$ is the set of users belonging to the $k$th multicast group, $k = \{1, \ldots, G\}$. Each user can belong to one group only and hence, $G_i \cap G_j = \emptyset$, $\forall i, j \in \{1, \ldots, G\}$ and $\bigcup_{k=1}^{G} G_k = M$.

We assume a single RF chain is dedicated to each group and there are as many groups as number of chains at a given time instant and thus $N_{RF}^G = G$.

On the downlink, the base station applies the $N_{RF} \times G$ digital baseband precoder $W = [w_1, w_2, \ldots, w_G]$ to the sampled transmitted data $s \in \mathbb{C}^{G \times 1}$ and up-converts the processed signal to the carrier frequency by applying the $N \times N_{RF}$ RF precoder $F = [f_1, f_2, \ldots, f_{N_{RF}}]$. The precoded transmitted signal $x \in \mathbb{C}^{N \times 1}$ writes as:

$$x = FWs,$$

where $\mathbb{E}[ss^H] = I_G$. The RF precoder $F$ is implemented using an analog phase shifter network and its entries has the constant modulus constraint such that $|F(i,j)| = e^{j\theta_{i,j}}$ and $|F(i,j)|^2 = 1$. The total transmission power $P$ is allocated such that $\|FW\|_F^2 = P$.

For simplicity, we focus on the narrow-band block fading channel model in which the $m$th user, belonging to the $k$th group, observes the following received signal:

$$y_m = h_{mk}^{H}Fw_k s_k + \sum_{i \neq k, i = 1}^{G} h_{mk}^{H}Fw_i s_i + n_m,$$

where $h_{mk} \in \mathbb{C}^{N \times 1}$ is the mmWave channel response vector between the BS antenna elements and the $m$th single-antenna user. We adopt a geometric finite-scattering channel model with $L$ propagation paths between the BS and a mobile terminal. The mmWave channels are expected to have finite scattering for a single propagation path and hence we assume that each scatter contribute a single path between the BS and a mobile user. Additionally, we consider an Uniformally-Linear-Array (ULA) structure at the BS. Then, the channel for the $m$th user is written as:

$$h_m = \sqrt{\frac{\pi}{N}} \sum_{l=1}^{L} \beta_{ml}\alpha_l(\phi_{ml}),$$

where $\alpha_l(\phi_{ml}) \in \mathbb{C}^{N \times 1}$ is the array response vector at the base station due to the transmitted (beamformed) signal at the $\phi_{ml}$ angle of departure (AoD) and can be expressed as:

$$\alpha_l(\phi_{ml}) = \frac{1}{\sqrt{N}} \left[ 1, e^{2\pi j \sin(\phi_{ml})}, \ldots, e^{(N-1)2\pi j \sin(\phi_{ml})} \right]^T,$$

and $\beta_{ml}$ is the channel gain of the $m$th user in the direction of the steered signal. The term $n_m$ is an Additive White Gaussian Noise (AWGN) at the $m$th receiver such that $\mathbb{E}[n_m n_m^H] = \sigma_n^2$, and we assume without the lose of generality $\sigma_1^2 = \sigma_2^2 = \cdots = \sigma_M^2 = \sigma_n^2$. The Signal to Interference plus Noise Ratio (SINR) experienced by the $m$th is given by:

$$\text{SINR}_m \triangleq \frac{|h_{mk}^{H}Fw_k|^2}{\sum_{i \neq k, i = 1}^{G} |h_{mk}^{H}Fw_i|^2 + \sigma_n^2},$$

Assuming i.i.d Gaussian input-streams, the instantaneous rate experienced by the $m$th user writes as:

$$R_m = \log_2(1 + \text{SINR}_m)$$

IV. PROBLEM FORMULATION

The main objective is to design a low-complexity hybrid precoder for multi-group multicasting systems in mmWave channels. In this work, we consider the max-min fairness problem to design the hybrid precoder to ensure minimum service level for all users regardless to the group they belong to. The max-min fair problem is formally defined as:

$$\min_{F, W} \max_{m \in \mathcal{G}} \min_{k \in \{1, \ldots, G\}} \frac{|h_{mk}^{H}Fw_k|^2}{\sum_{i \neq k} |h_{mk}^{H}Fw_i|^2 + \sigma_n^2},$$

subject to:

$$F \in \mathcal{F},$$

$$\|FW\|_F^2 \leq P,$$

where $\mathcal{F}$ is the set of $N \times G$ matrices with constant modules entries and $W$ is the $N_{RF} \times G$ digital precoder. The total transmission power constraint is explicitly specified in (6). In the fully digital system, i.e., when $FW = V_D$ where $V_D \in \mathbb{C}^{N \times G}$, the problem in (6) has been shown to be non-convex (NP-hard) and thus cannot be solved efficiently using convex optimization solvers, e.g., interior-point method [12]. Moreover, restricting the search space by adding the special structure of the RF precoder results in an even more difficult problem. In addition, the baseband precoder $W$ needs to be jointly designed with the RF precoder $F$ and the optimization is often found intractable [25]. Therefore, it is often advised to decouple the problem into two parts. First, we design the
RF precoder $F$ by assuming a fixed baseband precoder $W$ and then $F$ is fixed and $W$ is designed [28]. Assuming $F^\ast$ is attained, and for clarity we denote it as $F$, the program in (6) can be re-written as:

$$W^\ast = \arg \max_W \min_{k \in \{1, \ldots, G\}} \min_{m \in \mu_k} \frac{\left| h_{\text{eff},m}^H w_k \right|^2}{\sum_{i \neq k} \left| h_{\text{eff},m}^H w_i \right|^2 + \sigma_n^2}$$

s.t. : $W \in \mathbb{C}^{N_{RF} \times G}$,
$$\|FW\|_F^2 \leq P,$$

where $h_{\text{eff},m}^H = h_{\text{eff},m}^H F$. The program in (7) can be equivalently written as a Semi-Definite Program (SDP). Defining $\{Q_{\text{eff},m} = h_{\text{eff},m}^H h_{\text{eff},m}^H\}_{m=1}^{m=M}$ and $\{X_k = w_k w_k^H\}_{k=1}^{k=G}$.

Thus, $\left| h_{\text{eff},m}^H w_k \right|^2 = \text{tr}(Q_{\text{eff},m} X_k)$, $X_k \geq 0$ and noting $\|FW\|_F^2 = \sum_{k=1}^{G} \text{tr}(FX_kF_k^H)$, (7) is then reformulated as:

$$\{X_k^G\}_{k=1} = \arg \max_{\{X_k\}_{k=1}^G} t$$

s.t. : $\sum_{i \neq k} \text{tr}(Q_{\text{eff},m} X_i) + \sigma_n^2 \geq t$,
$$\sum_{k=1}^{G} \text{tr}(FX_kF_k^H) \leq P,$$
$$X_k \geq 0, t \geq 0,$$
$$\text{rank}(X_k) = 1,$$
$$\forall k \in \{1, \ldots, G\}, \forall m \in \{1, \ldots, M\}.$$

where (8) is reminiscent of the max-min fairness problem discussed in [12] where the non-convex rank-one constraints are dropped and the problem is solved, if feasible, by bisection to yield an upper bound for the maximum SINR experienced by all users. The relaxed problem is re-casted as:

$$P_{\text{main}} : \max_{\{X_k\}_{k=1}^G} t$$

s.t. : $\text{tr}(Q_{\text{eff},m} X_k) - t \left( \sum_{i \neq k} \text{tr}(Q_{\text{eff},m} X_i) + \sigma_n^2 \right) \geq 0$,
$$\sum_{k=1}^{G} \text{tr}(FX_kF_k^H) \leq P,$$
$$X_k \geq 0, t \geq 0,$$
$$\forall k \in \{1, \ldots, G\}, \forall m \in \{1, \ldots, M\}.$$

Therefore, in this paper, we aim to design a low-complexity hybrid precoder design for multi-group multicasting systems to approach the upper bound achieved by the fully-digital precoder bearing in mind the special structure of the channel, namely, sparse multipath channels or mmWave channels.

V. PROPOSED SOLUTIONS

Problem $P_{\text{main}}$ can be solved to attain a local optimal digital baseband precoder $W^\ast$. However, prior solving for $W^\ast$, we need to design the RF precoder and construct the effective channel(s) $Q_{\text{eff}}$. Fortunately, the nature of the mmWave suggests a way in selecting the RF precoder and here we could indicate the following remarks:

- In the case of a mmWave channel between the BS and a served user and as number of transmit antenna increases, the dependence on other paths becomes less important compared to the strongest path [25]. Thus, we consider single path mmWave channels.
- In single path mmWave channels and as number of transmit antenna increases, different users with distinct AoD's from the BS exhibit orthogonal channel vectors, thanks to the asymptotic orthogonality property of mmWave channels [24].
- In order to realize a fully-digital precoder under any channel structure, [18], [26] have shown that two RF-chains are needed per a digital precoder, i.e, $G = 2N_{RF}$. In addition, in order to modulate $G$ streams, it is necessary to have at least $G$ RF-chains and hence $N_{RF,\text{min}} = G$. Therefore, we consider a single RF-chain per group, $N_{RF} = G$.
- In single path mmWave channels of users with distinct angles from the BS and as $N \to \infty$, the conjugate analog beamformer per user, $N_{RF} = M$, is optimal [43].
- In connection of the last mentioned remarks, we propose to design the RF precoder as in the following program:

$$\max_{f_k \in \mathbb{C}^{M \times 1}} \min_{m \in \mu_k} |h_{\text{eff},m}^H f_k|^2$$

s.t. : $|f_k(i)| = 1, \forall k \in \{1, \ldots, G\}, \forall i \in \{1, \ldots, M\}.$

However, the program in (9) is NP-hard due to the non-convex constant modules constraint. Therefore, we opt to relax the constraint as shown in (10).

$$\max_{u_k \in \mathbb{C}^{M \times 1}} \min_{m \in \mu_k} |h_{\text{eff},m}^H u_k|^2$$

s.t. : $|u_k|^2 = N, \forall k \in \{1, \ldots, G\}, \forall m \in \{1, \ldots, M\}.$

where $u_k$ is now entirely digital and (10) is equivalently written as:

$$F_{\text{main}} : \max_{Y_k} t$$

s.t. : $\text{tr}(Q_m Y_k) \geq t, \text{tr}(Y_k) = N, \forall k \in \{1, \ldots, G\}, \forall m \in \{1, \ldots, M\}.$

where $Y_k = \text{tr}(u_k u_k^H)$ and $Q_m = \text{tr}(h_{\text{eff},m}^H)$. Problem $F_{\text{main}}$ represents a set of single group max-min fairness multicasting problems where the problem is always feasible [11]. In addition, if the solution is optimal, $F_{\text{main}}$ outputs a rank-one solution. In fact, Problem $F_{\text{main}}$ always outputs a rank-one solution since the channels are all rank-one. Hence, the principle component vectors of $(Y_k)_{k=1}^G$ gives the optimal digital precoders $(\tilde{u}_k^\ast_{k=1}^G)$. Once $(\tilde{u}_k^\ast_{k=1}^G)$ is obtained and denoted $U = [\tilde{u}_1^\ast, \ldots, \tilde{u}_M^\ast], \ast \text{RF-precoder has a closed-form solution}$

$$\arg(F) = \arg(U)$$
from a uniform random variable defined as \( \phi_m \sim U(0, 2\pi) \). The angle of departure (AoD) of the \( m \)th user, \( \phi_m \), is drawn from a uniform random variable defined as \( \phi_m \sim U(0, 2\pi) \). In addition the channel gain of the \( m \)th user, \( \beta_m \), is drawn from a circularly symmetric Gaussian random variable defined as \( \beta_m \sim CN(0,1) \). The noise variance of the receivers is assumed as \( \sigma_n^2 = \sigma_1^2 = \cdots = \sigma_{10}^2 = 1 \). The transmit power at the BS is varied from \(-10\)dB to \(50\)dB with \(5\)dB increment.

Fig. 1 shows the performance of the hybrid proposed algorithm versus the fully-digital system algorithm for a single user-group distribution. As can be seen in Fig. 1, both systems with different \( N \) values have the same slope of 1 at high SNR values which indicates an interference-free stream experienced by all users in the system. The proposed algorithm performance is close to the fully-digital system at low SNR values and with constant gap at high SNR values. As \( N \) increases, the rate increases for both systems which is a result of the array gain offered by the MISO channel.

Fig. 2 shows the performance of the hybrid proposed algorithm versus the fully-digital system algorithm for a single user-group distribution. As can be seen in Fig. 2, the performance of the proposed algorithm is close to the fully-digital system algorithm at low SNR values. However, the gap increases as the transmit power increases. At high SNR values, the interference between different users becomes more dominant compared to the noise level and thus degrades the overall performance of the proposed algorithm. The interference causes the slope of the rate curve to gradually decrease as SNR value increases until it saturates. Conversely, at low SNR values, the interference is neglected compared to the noise level and hence the performance of both algorithms are relatively similar.

Fig. 3 shows the performance of both systems for a multi-user beamforming system with \( G = 3 \), \( N_{RF} = 3 \), and \( M = 6 \). Users are equally distributed among groups, i.e. 2 users per group. Number of antennas \( N \) is varied to evaluate the performance of both systems. As seen in Fig. 3 at low SNR values the performance of both algorithms are extremely close. However, at high SNR, the rate curves for the proposed algorithm with different \( N \) values saturates while the fully-digital system experiences no saturation effect. The saturation is due to inter-group interference experienced by users belonging to different groups. The fully-digital system doesn’t suffer from the interference due to the minimal adequate amount of antennas at the transmitter to fully null-out the interference. In specific, for equal user-group distribution, the minimum number of antennas at the transmitter to null-out the inter-group interference is \( 1 + M - |G| \). Figure 4 illustrates the performance for an asymmetric distribution specified in the figure caption compared to the symmetric distribution (equal user-group distribution). As can be seen in Fig. 4 with an asymmetric distribution, the rate curve slope is larger compared to the symmetric case. Saturation occurs in both cases but it would happen later in the asymmetric scenario and the reason could attribute to the less interfering users in the groups with smaller number of users compared to the group
with largest number of users.

In Fig. 3 the performance of the two systems are shown for a multi-group multicasting system with \(N = 8\), \(G = 3\), \(M = 6\) and different number of paths per user’s channel. The goal is to evaluate the performance at an extreme mmWave case when \(L = 1\) and a moderate case when \(L = 15\). For the fully-digital system, the extra paths in the channel allows for an increase in the rate for all users. In contrast, for the proposed system design and at high SNR values, the extra paths result in an early saturation effect compared to the single path channel performance. Because the design only accounts for the dominant path of each user, increasing number of paths per user creates a greater inter-group interference and eventually results in a saturation effect. At low SNR values, the interference is minimal and a larger rate is observed when \(L = 15\) compared to the performance when \(L = 1\).

VII. CONCLUSION

In this paper, a low complexity max-min fair hybrid precoder design was proposed for multi-group multicasting systems. The design extended to multi-user systems as well as broadcasting systems. The design was motivated by the special structure of the channel, namely, single-path mmWave channel for each user. The RF precoder consisted of \(G\) analog beamformer(s). Each analog beamformer was designed to maximize the minimum matching component for users within a given group. Once obtained, the digital precoder was attained by solving the max-min problem of the equivalent channel. The performance of the fully-digital system and the proposed system design were shown by simulations for multi-group multicasting, broadcasting and multi-user systems.

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