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Joint Relay-Spectrum Selection in Hybrid Millimeter-Microwave Cooperative (HMMC) Network Using Fall-Back Approach

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ABSTRACT The microwave (μWave) spectrum or low-frequency spectrum has become overcrowded due to the ever-increasing demand in bandwidth-intensive applications, such as video streaming and gaming. Owing to the fact that the spectral efficiency of μWave links is approaching its fundamental limits, there is a growing consensus in both industry and academia that millimeter wave (mmWave) will play an important role in increasing data rate and scarcity of spectrum. To redress the predicament and to ensure adequate availability of bandwidth, increasing attentions have been paid to the use of mmWave spectrum for future broadband wireless networks. The mmWave spectrum offers wider bandwidth compared to the μWave spectrum and a promising solution to overcome the scarcity of spectrum while providing gigabits per second (Gb/s) of data rates. To fully exploit the high potential rates of mmWave in mobile networks, a number of technical problems must be addressed. The mmWave signal transmission suffers from the issues of blockage and deafness. The former challenge is characterized by the loss of Quality of Service (QoS) in non-line-of-sight (NLOS) conditions, while the latter is characterized by the misalignment between the main lobe of transmitter and the receiver beam. Two strategies can be adopted to deal with the issues:1) relaying, use of another path with the help of relay(s) providing line-of-sight (LOS) link(s) and b) fall back, in the case of service interruption, switch back to the μWave spectrum-based transmission switching between mmWave and μWave frequency bands can support higher rates and QoS requirements. However, a tradeoff exists in employing any of the aforementioned strategies. In this paper, we study the joint spectrum allocation and relay selection problem to maximize the weighted sum rate relay selection (using resource block and time slot) along with a fallback approach for spectrum allocation in an HMMC network. A fallback approach is introduced to enable the hybrid transmission of μWave and mmWave, and an iterative bipartite relay-spectrum selection algorithm is proposed to solve the problem. The performance evaluation results show that the proposed fallback approach outperforms the conventional μWave or mmWave transmission schemes in terms of data rate, transmit power, and the number of users.

INDEX TERMS Relay selection, resource allocation, millimeter wave, microwave, cooperative communication.

I. INTRODUCTION

Bandwidth intensive applications have taken over the cellular network. The μWave spectrum is becoming scarce and is unable to completely fulfill the requirements of the network users. Sophisticated and complex resource allocation techniques have been adopted to effectively reuse the spectrum [1]–[3]. Even with complex allocation algorithms, the increasing data rate requirement of the next generation networks need more spectrum.

Recently, an increasing interest in millimeter-wave (mmWave) operating in frequency band ($10 - 300$ GHz) is

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gaining momentum. Utilizing the large bands of mmWave helps to mitigate the scarcity of spectrum and provide gigabit-per-second data rates for future next generation network. Thus, mmWave network offers an abundant of unexploited and is expected to significantly increase the average data rate per user. It is therefore an attractive solution for vehicular networks, mobile offloading and mobile front hauling and in-band back-hauling [4], [5]. However, in order to utilize the mmWave spectrum, a few issues to be addressed [6]–[9] can be broadly classified as:

- Path loss sensitivity: the LOS nature of mmWave resulting in the severe signal attenuation with long distance,
- Blockage: the signal suffers from high penetration loss due to solid material(s) present in its path, and
- Deafness: the quality of the signal deteriorates if the main beam of the transmitter and receiver are misaligned.

The issue of attenuation can be dealt by employing cooperating nodes or relays [10]. Relays reduce the transmission distance between the transmitter and the receiver, as a result, transmitter can transmit at lower power levels [11]. Similarly, blockage can also be addressed with the use of LOS relay path. The selection of a LOS relay path is another issue when considering the use of relay to address blockage. Alternatively, a fall-back strategy can be adopted to combat this problem. In the fall-back strategy, the transmitter switches back from mmWave spectrum to μWave spectrum in case of blockage. Lastly, the problem of deafness can be addressed with the use of highly directional antennas [12].

To address these scheduling challenges, a number of recent works have been discussed. The literature of this study can be broadly classed into two categories: a) allocation of mmWave and μWave spectrum; and b) joint relay selection and resource allocation. mmWave network is an active research area as it is integral part of the 5G network.

In [8], the authors have identified fundamental challenges faced by employing mmWave cellular network at Medium Access Control (MAC) layer. Design aspects of control channel architecture, initial access, mobility management, handover, resource allocation and interference are discussed. In [7], the authors have proposed context-aware resource allocation in joint mmWave and μWave network. The authors have taken into consideration the delay constraints of different user applications. The problem is formulated as a matching game and a distributed algorithm is proposed to solve the formulated problem. In [6] authors proposed context aware scheduling problem as an optimization problem to maximize the number of satisfied user applications. The Proposed algorithms finds an effective solution for both mmWave and μWave in polynomial time. Issues pertaining to spectrum access in 20GHz – 30GHz along with pooling at 70GHz are discussed in [13].

In [14], the design and architecture of 5G using mmWave and μWave in heterogeneous network are studied and a service driven resource management scheme is proposed correspondingly. Existence of both technologies increase the system potential gains in terms of capacity and delay. In [15], the authors investigated resource allocation of mmWave in a device-to-device network with underlay mode and the reuse of the resource blocks. To satisfy the QoS requirements an accurate propagation analysis is carried out to achieve the trade-off between performance and complexity. An analysis of coverage probability of a hybrid scheme is discussed in [16]. The Proposed hybrid scheme outperforms in terms of coverage and Area Spectral Efficiency (ASE) due to reduced interference and robustness.

Relay selection is a well investigated topic in the field of wireless cellular network. mmWave suffers from propagation loss over long distances and hence, a promising way to resolve the issue is to deploy relays in the network. In [17], [18], the authors have investigated the benefits of deploying relay in mmWave network in terms of coverage probability. Results show that deployment of relays in mmWave increases the coverage probability and transmission capacity of the network. Mobile relay selection is studied for a mmwave heterogeneous cellular network in [19]. Authors in [19] proposed a proportional switching algorithm that switches between mobile relays based on a coalition game. The coverage probability and transmission capacity of the system is enhanced with the use of relay. A distance based relay selection algorithm is studied in [20]. Proposed schemes in [20] significantly improve outage probability and system throughput. In [21], [22], authors propose an outage probability based on amplify-and-forward (AF) cooperative communication to address power allocation minimization problem and attain a closed-form outage probability expression. A distributed relay selection along with power allocation for an OFDMA mmWave network is studied in [9]. A relay selection for N number of non-Line-of-sight (NLOS) links is studied in [23] with an objective to maximize the total throughput of the NLOS links. However, maximizing the total throughput of the NLOS links does not guarantee good quality of service for individual links. With an addition of the constraint of the quality of the service in the problem, the problem becomes infeasible if none of the link paths are able to satisfy the quality of service requirement of the users. As seen employing mmWave spectrum for relay based cooperative transmission has also seen quite some attention in recent years. However, this contour comes with a unique set of problems. One of the most important issue is the selection of relay(s) [10], [24]. In [10], the authors have discussed a relay placement strategy for the transmission over mmWave. In [24], a distributed algorithm is proposed to solve the problem of joint association and relaying. Load balancing at the access point is considered while using auction theory to solve the problem. In [25], a trade-off between using a relay and a fall-back strategy in the mmWave system is studied. It is shown that the choice between relaying and fall-back approach depends on the payload size, beam training overhead and blockage probability. They separately analyzed the strategies under different traffic conditions. However, the fall-back strategy is yet to be studied jointly with relay selection.

Challenges pertaining to resource allocation and relay selection in mmWave are excluded as they are somehow dependent on each other for performance consideration. In view of these challenges, to the best of our knowledge the problem of relay selection in hybrid mmWave-μwave network with fall back strategy is not yet studied.

A. OUR CONTRIBUTION

This work provides useful insights to the joint selection of relays and spectrum in a HMMC network. The main contributions are as follows:

- We formulate a joint relay-spectrum selection problem with the objective of maximizing the Weighted Sum Rate (WSR) in a HMMC network. Based on the spectrum (mmWave and μWave) selected, the optimization formulation also considers resource block and time slot allocation variables,
- The formulated problem is then modified and a sub-hybrid problem is formulated such that the mmWave is given higher priority and μWave is only used as a fall-back strategy,
- An iterative bipartite relay-spectrum allocation algorithm is also proposed.

Detailed analysis is carried out to study and compare the performance of our proposed scheme. Simulation results show improvement in performance of HMMC as compared to μWave and mmWave only.

B. ORGANIZATION OF THE PAPER

The rest of the paper is organized as follows: Section I discusses Introduction and the state-of-the-art related work and Section II gives the detail of the system model of a cooperative network. In Section III, we present the problem formulation and develop an algorithm to solve the problem in Section IV. Section V shows the performance evaluation and Section VI concludes the paper.

II. SYSTEM MODEL

Downlink of a macrocell base station (BS) is considered with $\mathcal{R}$, a set of stationary relay stations (RSs), and $\mathcal{U}$, a set of macrocell user equipment (UEs). The coverage of BS is a planar area with radius L centered at $(0, 0) \in \Re^2$. All the users operate in the cooperative mode. They receive data from both the BS and the selected relay. The users are distributed in an area outside the planar with radius $\frac{1}{3}L$. We have considered $\frac{1}{3}L$ as the QoS, outside this region the QoS falls below the required threshold. The set of relays is uniformly distributed in the planar area with radius $\frac{1}{3}L$ to assist the transmission of the users. The relays work on decode-and-forward (DF) strategy. To bound latency in the network only two-hop path is considered, i.e., employing only one relay. Figure 1 shows the system model with both the LOS and NLOS links.

The BS operates in dual mode, i.e., it operates at both mmWave and μWave frequency bands [12]. Both frequency bands are divided into equal size, frequency symbols of size w. A total number of K^{mm} and K^{μ} symbols of mmWave and μWave are available respectively, where, $K^{mm} \gg K^{\mu}$. The resource to be allocated is the frequency with priority given to mmWave transmission. Moreover, a certain amount of μWave frequency is allocated for the downlink transmission, which is to be used for the purpose of fall-back strategy when the mmWave is unable to satisfy the downlink rate of that user. Table 1 gives the explanation of the system parameters used in the model.

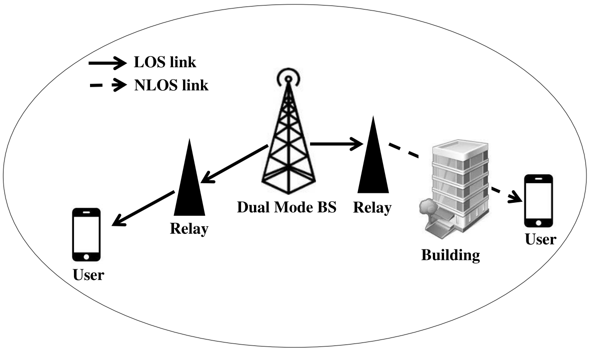

FIGURE 1. System model of a dual-mode BS with relays.

TABLE 1. System parameters.

Parameter	Description
$\mathcal{U}$	Set of mobile small cells
$\mathcal{R}$	Set of Relay
w^{mm}	Size of a resource block (RB) of mmWave
w^{μ}	Size of a RB of μWave
K^{mm}	Number of RBs in mmWave
K^{μ}	Number of RBs in μWave
τ^{mm}	Time slot duration in mmWave
τ^{μ}	Time slot duration in μWave
β_c^{mm}	Intercept of the fit for path loss under mmWave
α_c^{mm}	Slope of the fit under mmWave transmission
σ^{mm}	Signal-to-noise ratio (SNR) of mmWave
T	Total number of time frames formed in a time period

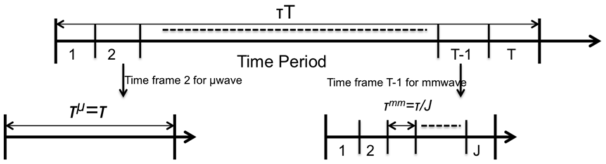

FIGURE 2. Allocation of time period for mmWave & μWave transmission.

To simplify the analysis, we assume that if a user is transmitting on mmWave, then the relay it associates itself with will also transmit on mmWave and the same is the case with μWave. Figure 2 shows the details of the time period, dividing it into a total of T time frames. We define τ as the duration of a time frame for which the transmission is scheduled. In case a user is transmitting on μWave, then the user will be transmitted on the completion time frame of duration τ. Whereas, for all users transmitting on mmWave, the time frame is divided between all the users and each will be allocated $\frac{\tau}{J}$ duration. Next, in this section, we will discuss the transmission models for both mmWave and μWave spectrum.

A. MMWAVE TRANSMISSION MODEL

A downlink cooperative transmission is considered for both mmWave and μWave. For mmWave, a spectrum of wK^{mm}Hz is considered centered at a frequency of 40GHz. A time division multiple access (TDMA) scheme is used as preferred access scheme for transmission as it is more flexible in handling the elastic demand of the downlink traffic and because of the transmission at high frequencies the channel coherence time of the mmWave is smaller than that of μWave [15].

As TDMA is considered, we divide the transmission time frame τ in equal time slots of duration τ^{mm}, where $\tau^{mm} = \frac{\tau}{J}$. Here, J is the total number of slots in a time frame. The link between the BS to relay and relay to the user can be both LOS and NLOS. The free space path loss for a user located at (x, y) is considered as best linear fit propagation model as given in [26].

$$L^{mm}(x, y) = \beta_c^{mm} + \alpha_c^{mm} 10 \log_{10}(\sqrt{x^2 + y^2}) + X_c \qquad (1)$$

where, $\beta_c^{mm} = 32.4 + 20 \log(f_c)$ is the fixed path loss (in dB scale) for 1 meter of distance. α_c^{mm} is the path loss exponent under mmWave transmission for a parameter c, here $c = [Lo, NL]$, Lo is representing LOS transmission and NL is representing NLOS transmission. X_c is the zero mean log normal random variable for set c.

The mmWave transceiver at the BS is equipped with an antenna array. An overall gain of $\psi(x, y)$ is achieved for a UE located at $(x, y) \in \Re^2$. Two links are created in the cooperative communication with DF strategy; the links are BS-UE and BS-RS-UE. The signal-to-noise ratio (SNR) experienced by a UE i from BS b over time slot j is given as,

$$\sigma_{b,i}^{mm}(j) = \frac{p_{b,i}^{mm}(j)\psi_r(x_i, y_i)|h_{b,i}(j)|^2 10^{\frac{L^{mm}(x_i, y_i)}{10}}}{N_0} \qquad (2)$$

where, $p_{b,i}^{mm}(j)$ is the transmit power from BS to UE i over time slot j, $h_{b,i}(j)$ is the channel gain experienced by user i over time slot j, $L(x_i, y_i)$ is the path-loss gain experienced by UE i located at $(x, y) \in \Re^2$. The channel gain $h_{b,i}(j)$ is modeled as Rician fading [27]. Similarly, the SNR from BS to RS and RS to UE are given as,

$$\sigma_{b,r}(j) = \frac{p_{b,r}^{mm}(j)\psi_r(x_r, y_r)|h_{b,r}(j)|^2 10^{\frac{L^{mm}(x_r, y_r)}{10}}}{N_0} \qquad (3)$$

and

$$\sigma_{r,i}(j) = \frac{p_{r,i}^{mm}(j)\psi_r(x'_i, y'_i)|h_{r,i}(j)|^2 10^{\frac{L^{mm}(x'_i, y'_i)}{10}}}{N_0} \qquad (4)$$

respectively. The data rate on the BS-UE link is,

$$\Gamma_{b,i}^{mm}(j) = w \log_2(1 + \sigma_{b,i}(j)) \qquad (5)$$

and the rate on the BS-RS-UE link is,

$$\Gamma_{b,i}^{mm,r}(j) = w \log_2(1 + \sigma_{b,r}(j) + \sigma_{r,i}(j)) \qquad (6)$$

where as, the data rate achieved by a UE i receiving from BS via RS r over a slot j in a frequency symbol w is,

$$R_{b,i}^{mm,r}(j) = \frac{1}{2} \min\{\Gamma_{b,i}^{mm}, \Gamma_{b,r,i}^{mm}\} \qquad (7)$$

The factor $\frac{1}{2}$ results from the fact that data is transmitted over two time-slots. Each time slot j will be further divided into two slots, one for each hop. For a time frame t, a UE i receiving over a slot j will be using the complete spectrum of mmWave (all K^{mm} symbols of the spectrum), therefore, the overall data rate of a UE i over slot j of duration τ^{mm} is,

$$R_i^{mm}(j) = \sum_{k=1}^{K^{mm}} \frac{\tau^{mm}}{\tau} R_{b,r,i}^{k,mm}(j) \qquad (8)$$

Here, $\frac{\tau^{mm}}{\tau}$ is multiplied to represent a fraction of time for which the transmission is taking place. As discussed already that the number of users are receiving over different slots in a time frame t, we define a variable $y_i(j)$ to indicate whether a UE i is assigned to receive over slot j, i.e.,

$$y_i^j = \begin{cases} 1 & \text{if slot } j \text{ of mmWave is allocated to UE } i \\ 0 & \text{otherwise,} \end{cases} \qquad (9)$$

Also, define $\mathbf{y}(j) = [y_1(j) \dots y_U(j)]^T \in \{0, 1\}^{U \times 1}$ as the user association vector at time slot j. The data rate of a UE i receiving through RS r using mmWave is given as,

$$R_i^{mm,r} = \sum_{j=1}^{J} y_i^j R_i^{mm}(j) \qquad (10)$$

The RS will be assigned to UE i, the relay assignment indicator is given as,

$$m_i^r = \begin{cases} 1 & \text{if UE } i \text{ is receiving from RS } r \text{ over mmWave} \\ 0 & \text{otherwise,} \end{cases} \qquad (11)$$

The rate of a UE i over mmWave spectrum is given as,

$$R_i^{mm} = \sum_{r=1}^{R} m_i^r R_i^{mm,r} \qquad (12)$$

We define a variable z_i to indicate whether a UE i is receiving over mmWave. It can be given as,

$$z_i = \begin{cases} 1 & \text{if UE } i \text{ is receiving over mmWave} \\ 0 & \text{otherwise,} \end{cases} \qquad (13)$$

and, define $\mathbf{z} = [z_1, \dots z_U]^T \in \{0, 1\}^{U \times 1}$ as the user association vector to mmWave. Thus, the data rate of all UEs using mmWave is,

$$R^{mm} = \sum_{i=1}^{U} z_i R_i^{mm} \qquad (14)$$

B. μWAVE TRANSMISSION MODEL

A spectrum of wK^{μ}Hz is considered centered at a frequency of 2.4GHz. An orthogonal frequency division multiple access (OFDMA) is considered as preferred access scheme for transmission. In OFDMA, the frequency spectrum is divided into blocks of frequency and time slot. Each RB is of w Hz and τ^{μ} duration. The time duration of the time slot of μWave is kept equal to the time duration of the time frame for which scheduling is done, i.e., $\tau^{\mu} = \tau$. OFDMA access scheme is used when users are transmitting over μWave spectrum. In OFDMA, a total of K^{μ} RBs are available in a time slot t of duration τ^{μ}.

The path loss model [26] is given as,

$$L^{\mu}(x, y) = 20\log(\frac{4\pi}{\lambda_c}) + 10\beta^{\mu}\log(\sqrt{x^2+y^2}) + \psi \tag{15}$$

The SNR experienced by a UE i from BS b transmitting over RB k is given as,

$$\sigma_{b,i}^{k} = \frac{p_{b,i}^{k,\mu}|h_{b,i}^{k}|^2 10^{\frac{L^{\mu}(x_i,y_i)}{10}}}{N_0 + \sum\limits_{r\neq b} p_{r,i}^{k,\mu}|h_{r,i}^{k}|^2 10^{\frac{L^{\mu}(x_i,y_i)}{10}}} \tag{16}$$

Here, $p_{b,i}^{k,\mu}$ is the transmit power from BS to UE i over RB k, $h_{b,i}^{k}$ is the channel gain experienced by user i over RB k, $L^{\mu}(x_i, y_i)$ is the pathloss gain experienced by UE i located at $(x, y) \in \Re^2$ and $\sum_{r\neq b} p_{r,i}^{k,\mu}|h_{r,i}^{k}|^2 10^{\frac{L^{\mu}(x_i,y_i)}{10}}$ is the interference experienced by UE i in the downlink. The channel gain $h_{b,i}^{k}$ is modeled as Raleigh fading. Similarly, the SNR from BS to RS and RS to UE are given as,

$$\sigma_{b,r}^{k} = \frac{p_{b,r}^{k,\mu}|h_{b,r}^{k}|^2 10^{\frac{L(x_r,y_r)}{10}}}{N_0 + \sum\limits_{r'\neq r} p_{r',i}^{k,\mu}|h_{r',i}^{k}|^2 10^{\frac{L^{\mu}(x_i,y_i)}{10}}} \tag{17}$$

and,

$$\sigma_{r,i}^{k} = \frac{p_{r,i}^{k',mm}|h_{b,i}^{k'}|^2 10^{\frac{L(x_i,y_i)}{10}}}{N_0 + \sum\limits_{r\neq b} p_{r,i}^{k,\mu}|h_{r,i}^{k}|^2 10^{\frac{L^{\mu}(x_i,y_i)}{10}}} \tag{18}$$

respectively. The achievable data rates on the BS to UE link is,

$$\Gamma_{b,i}^{k,\mu} = w\log_2(1 + \sigma_{b,r}^{k}) \tag{19}$$

and the rate on the BS-RS-UE link is,

$$\Gamma_{b,r,i}^{k,\mu} = w\log_2(1 + \sigma_{b,r}^{k} + \sigma_{r,i}^{k}) \tag{20}$$

The data rate achieved by a UE i receiving from BS b via a RS r over RB k is,

$$R_{b,r,i}^{k,\mu} = \frac{1}{2}\min\{\Gamma_{b,i}^{k,\mu}, \Gamma_{b,r,i}^{k,\mu}\} \tag{21}$$

The variable used for resource block allocation is defined as,

$$x_i^k = \begin{cases} 1 & \text{if RB } k \text{ is allocated to UE } i \\ 0 & \text{otherwise,} \end{cases} \tag{22}$$

Then, the data rate of a UE i using μWave is defined as,

$$R_i^{\mu} = \sum_{k=1}^{K^{\mu}} x_i^k R_{b,r,i}^{k,\mu} \tag{23}$$

and the data rate of all UEs using μWave spectrum is given as,

$$R^{\mu} = \sum_{i=1}^{U}(1 - z_i)R_i^{\mu} \tag{24}$$

III. PROBLEM FORMULATION

In this section, we will formulate the problem of joint spectrum allocation and relay selection for the system model discussed in Section II. As already stated, a cooperative communication network is considered and relay selection is done jointly with mmWave spectrum allocation with higher priority and μWave spectrum is used only if mmWave is unable to satisfy the rate requirement.

The users in the system are cooperative users, hence, making the transmission links favorably reachable even for mmWave transmission. A baseline comparison of BS communicating directly and via a relay to the user is shown in Figure 3. In this Figure, all the users are transmitting over μWave with a uniform distribution of LOS and NLOS scenarios. We can observe that the performance in terms of sum data rate of BS transmitting via a relay to user over μWave is significantly better than that of the direct transmission.

The optimization problem for a time frame t is formulated as follows,

$$\underset{z_i, x_i^k, y_i^j, m_i^r}{\text{maximize}} \sum_{i=1}^{U}\left(z_i\sum_{r=1}^{R} m_i^r R_i^{r,mm} + (1 - z_i)\sum_{r=1}^{R} m_i^r R_i^{r,\mu}\right)$$

$$\text{subject to } z_i\sum_{r=1}^{R} m_i^r R_i^{r,mm}$$

$$+ (1 - z_i)\sum_{r=1}^{R} m_i^r R_i^{r,\mu} \geq R_i^{min}, \quad \forall i \tag{25}$$

$$\sum_{i=1}^{U} y_i^j \leq 1, \quad \forall j \tag{26}$$

$$\sum_{i=1}^{U} x_i^k \leq 1, \quad \forall k \tag{27}$$

$$\sum_{i=1}^{U}\sum_{j=1}^{J} y_i^k \leq J, \tag{28}$$

$$\sum_{i=1}^{U}\sum_{k=1}^{K^{\mu}} x_i^k \leq K^{\mu}, \tag{29}$$

$$\sum_{i=1}^{U} m_i^r \leq 1, \quad \forall r \tag{30}$$

$$\sum_{r=1}^{R} m_i^r \leq 1, \quad \forall i \tag{31}$$

$$z_i, y_i^j, x_i^k, m_i^r \in \{0, 1\}, \quad \forall i, k \tag{32}$$

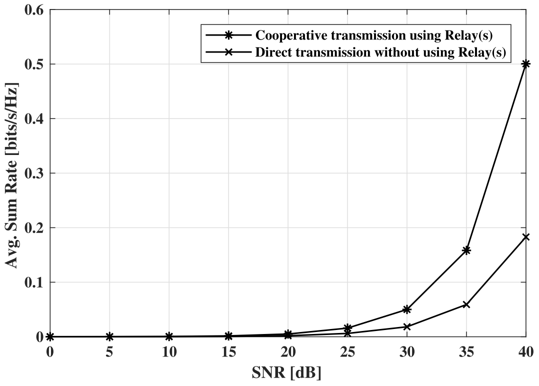

FIGURE 3. Comparison of BS transmitting directly and via relay over μWave spectrum.

The objective of the formulated problem is to maximize the rate of the user in a hybrid millimeter-microwave cooperative network. Constraint (25) is the QoS constraint and it ensures that the quality of a user with mmWave or μWave are above a certain threshold. The threshold of each user is determined based on the service requirement of the user. Constraint (26) and (27) is the interference management constraints for mmWave and μWave, respectively. Constraint (26) ensures that only one user is transmitting over a certain time slot in a time frame. As we are employing TDMA for mmWave, transmission of two users over the same time slot will result in interference. Similarly, constraint (27) ensures that a RB in case of μWave is not reused in the cell. As we consider the downlink transmission and all users are present in interference range, inter-user interference would become severe if any two users are assigned the same RB. Constraint (28) and (29) is the maximum resource constraint. Constraint (28) ensures that the number of users transmitting over different time slots cannot exceed the total number of time slots that can be formed in a time frame. Constraint (29) ensures that the number of RB's allocated cannot exceed the number of RBs available. Constraint (30) and (31) respectively, guarantee that a relay cannot be assigned to more than one user in a time slot and the user cannot use more than one relay. Lastly, constraint (32) is an integer constraint.

With the above formulated problem, relay along with mmWave or μWave is selected that has a better achievable rate. Even if the rates achieved by both mmWave and μWave are above a certain threshold, i.e., by selecting any of the available spectrum over a relay the QoS constraint is satisfied, the spectrum that provides better rate is selected. However, μWave spectrum is scarce and to minimize the use of the μWave spectrum, a sub-hybrid of the above optimization problem is proposed as follows,

$$\begin{aligned} &\underset{z_i, x_i^k, y_i^j, m_i^r}{\text{maximize}} \sum_{i=1}^{U} z_i \sum_{r=1}^{R} m_i^r R_i^{r,mm} \\ &\text{subject to Constraint}(25) - (32) \end{aligned} \tag{33}$$

The objective of this formulation is to maximize the sum of the achievable data rate of users on mmWave network with the optimal relay selection. Constraint (25) is the fall-back QoS constraint. R_i^{min} in Constraint (25) represents the minimum rate requirement of UE i. This constraint ensures that the data rate requirement of the UE is satisfied for mmWave based transmission using optimal relay selection and if mmWave is unable to satisfy the UEs requirement, a fall-back strategy is adopted and μWave spectrum is employed to satisfy the UEs requirement. In case that μWave is also unable to satisfy the requirement of the user then the solution of the problem is infeasible. Thus, the objective function together with constraint (25) ensures the QoS of all users with priority to mmWave. In case of blockages (NLOS condition), fall-back strategy is adopted and the μWave spectrum is used.

The formulated problem is NP-hard mainly because of the integer constraints. By relaxing the integer constraints, the objective function can be transformed into a concave function. However, the constraint (25) is still non-convex when μWave is employed because of the intra-cell interference in relays. The interference term in the denominator of the SNR expression in (16), (17) and (18) makes the expression non-convex. The interference is from the relays on the user in the downlink of μWave. Interference can be reduced at the cost of increased complexity using sophisticated interference mitigation techniques or use of space-time block codes (STBC) [28]. If mmWave is able to satisfy the user rate requirement, μWave is not employed then the constraint is concave.

Thus, due to the integer constraints along with the interference in μWave, the spectrum allocation and relay selection results in a combinatorial and non-convex optimization problem, and cannot be solved optimally in polynomial time.

IV. ITERATIVE BIPARTITE RELAY-SPECTRUM SELECTION

In this section, we will propose a solution of the formulated problem of the joint selection of relay and spectrum (mmWave or μWave), further RB's in case of μWave, and time slots in mmWave are allocated as well. As discussed, the formulated problem is an integer combinatorial problem and cannot be solved optimally in polynomial time. We decompose the problem in two parts. The two decomposed problems are:

1) **P1: Relay and Spectrum Selection**
2) **P2: RB/time slot allocation**

RB's are allocated to users that have selected μWave spectrum and time slots are allocated to users with mmWave. In case all users have selected mmWave, the time duration for which it is allocated is reduced and similarly, if all users are allocated μWave spectrum, the numbers of RB's allocated to each user are reduced. The two decomposed problems are dependent on each other and keeping this in view, we adopted an iterative approach to solve the two problems sequentially.

Matching theory can be adopted for relay and spectrum selection based on the achievable rate on the links and channel gain based algorithms can be used for RB and time slot allocation. Next, in this section, we will discuss in detail the solution of the decomposed problems **P1** and **P2**, and then will discuss the Iterative Bipartite Relay Spectrum Allocation Algorithm.

A. WEIGHTED BIPARTITE GRAPH CONSTRUCTION AND MATCHING

A traditional bipartite graph can be formed in this scenario. We constructed a weighted bipartite graph $G = ((U \times V), E, W)$. Here, U is the set of users and V is a set of relays. A total number of R relays are present in the scenario, each relay is represented by two vertices of the set U, for mmWave and μWave cases, respectively. Thus, the total number of vertices in set $|V| = |R| + |R|$. E represents a set of edges between the two sets of vertices and W represents the weight of each edge. The objective is to find the best matching between the user and the relay with mmWave or μWave such that it satisfies the constraints of the optimization problem (25)-(32).

Next, the weight of each edge is determined based on the rate it can achieve if the link is established. The weight of an edge between vertex u to vertex v is,

$$w_{u,v} = R_{u,v} \tag{34}$$

where, $R_{u,v}$ can be determined using the (12) and (23) if the vertex v represents mmWave and μWave, respectively. The link with the best possible rate is selected using Hungarian algorithm [29]. In this way, a user selects a relay and spectrum which specify the maximum achievable rate for that user, and can be given as,

1) For each vertex of set U, a relay with a spectrum is selected as follows:

$$r_u = \underset{v \in V}{argmax}\ \{w_{u,v}\} \tag{35}$$

Here $r_u \in V$ is selected for $u \in U$

2) Set U and V are updated as $U = U - |u|$ and $V = V - |r_u|$

Step 1 ensures that the best possible rate is achieved for any user and, step 2 ensures Constraint (31) and (32) are satisfied. For each user, a relay and spectrum is selected. All users using mmWave are put in a set U^{mm} and users using μWave are put in U^{μ}. Block diagram for weighted bipartite graph construction and matching is represented in Figure 4.

B. TIME SLOT ALLOCATION IN MMWAVE

As TDMA is used as an access technology for mmWave, therefore each user allocated with mmWave spectrum needs to be allocated with a time slot on which its transmission will take place. We used the channel gain based criteria to allocate each user to a time slot. A total of $|U^{mm}|$ UEs are allocated to a time slot. For each time slot j, a UE $i \in U^{mm}$ is selected such that it has the highest gain on it and can be mathematically expressed as:

$$i^* = \underset{i \in U^{mm}}{argmax} \Bigg(\psi_b(x_r, y_r)|h_{b,i}(j)|^2 10^{\frac{L^{mm}(x_r,y_r)}{10}} + \psi_r(x'_i, y'_i)|h_{b,i}(j)|^2 10^{\frac{L^{mm}(x'_i,y'_i)}{10}} \Bigg) \tag{36}$$

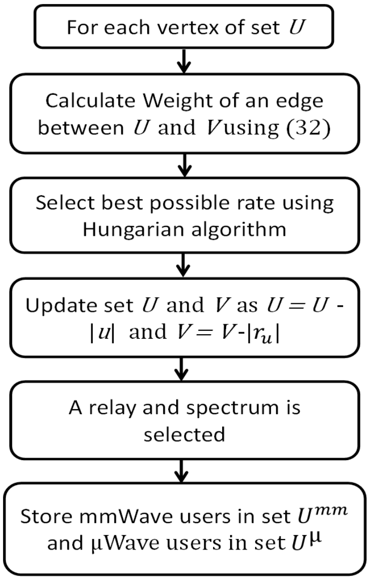

FIGURE 4. Block Diagram for weighted bipartite graph construction and matching.

C. RB ALLOCATION FOR μWAVE

The UE $i \in U^{\mu}$ to which the RB k is assigned is calculated according to the following criteria:

$$i^* = \underset{i \in U^{\mu}}{argmax} \left(|h^{k'}_{b,i}|^2 10^{\frac{L(x_i,y_i)}{10}} + |h^{k}_{b,i}|^2 10^{\frac{L^{\mu}(x_i,y_i)}{10}} \right) \tag{37}$$

D. ITERATIVE BIPARTITE RELAY-SPECTRUM ALLOCATION ALGORITHM

An iterative approach is considered for solving the hybrid problem as given below,

```
Algorithm 1 Iterative Bipartite Relay-Spectrum Allocation Algorithm
Result: Relay Selection and Spectrum Allocation
Initialization: RB from set $K$ are allocated to all users ($U^{\mu} \leftarrow U$) and similarly timeslots of mmWave are allocated to all UEs ($U^{mm} \leftarrow U$);
while
    $\sum_{i \in U} |R_i^{m+1} - R_i^{m}| < \epsilon$
do
    Repeat 1 and 2,
        1) Bipartite Graph Construction and Matching
        2) RB allocation for mmWave and timeslot for $\mu$wave
```

For step 1, a weighted bipartite graph is constructed and matched as discussed in Section IV-A. Set U^{μ} and U^{mm} are updated based on the matching. Based on the updated sets U^{mm} and U^{μ}, RB's and timeslots are allocated as discussed in Section IV-B and IV-C, respectively in step 2.

E. COMPLEXITY OF THE ITERATIVE BIPARTITE RELAY-SPECTRUM ALLOCATION ALGORITHM

The presented algorithm is based on bipartite graph matching. Bipartite graph matching is a well-studied problem in combinatorial optimization. The bipartite graph matching in this case is of the order of complexity $O(|U| \times |R|^2)$. The order of complexity of RB allocation in μWave and time slot in *mm*Wave is $O(|U^{\mu}| \times K^{\mu})$ and $O(|U^{mm}| \times J)$, respectively. Thus, the total worst case order of complexity of the algorithm is $O(|U| \times |R|^2 + |U^{\mu}| \times K^{\mu} + |U^{mm}| \times J)$. In the next Section, we will present results and discuss our findings.

V. NUMERICAL RESULTS AND DISCUSSION

In this section, we study the performance of the spectrum allocation, relay selection and associated repercussions in a cooperative scenario. We compare the performance of the proposed algorithm with the exhaustive enumeration approach, considering the following two approaches:

- When all users are transmitting over mmWave; and
- When all users are transmitting over μWave.

These are centralized approach and are based on the algorithm presented in [30]. We considered a macrocell with BS placed in the center of a region with a radius of 1km. For μWave, we use a bandwidth of 5MHz with a data rate of 10Mbps and for mmWave, we use a bandwidth of 40MHz with a data rate of 80Mbps as depicted in Table 2. We use 30dBm as total transmit power and for fairness in comparison with the direct transmission, we divide the total power between the user and the associated relay in the cooperative setup. As cooperative communication is considered, the users considered are far away from the BS and are distributed uniformly outside a radius of $L/2$, and all the relays are deployed uniformly within this radius. Figure 5 shows the deployment of the users and the relays for the performance evaluation. We considered a total of 25 UEs and 5 RSs to serve the users.

TABLE 2. Measurement parameters.

Parameter	μWave	mmWave
Carrier Frequency [GHz]	2.4	40
Total Transmit Power [dBm]	30	30
Bandwidth [MHz]	5	40
Data Rate [Mbps]	10	80

Figure 6 shows the data rate achieved using our proposed hybrid transmission scheme when compared to conventional mmWave and μWave transmission schemes. HMMC outperforms the classical counterparts by extracting the advantage of their prominent features e.g., higher data rate offered by using mmWave transmission and greater coverage area of the case of μWave transmission, which otherwise would not have been possible.

It is quite pertinent to mention that the improvement in performance is a reflection of total transmit power. Figure 7 illustrates the total transmit power comparison. In terms of transmitting power, distance of BS from UE is an important factor. With the increase of distance, the transmit power increases to reach a desired data rate and ensure QoS. It can be noted that mmWave based transmission operates at peak power levels for any given distance, followed by our proposed scheme and μWave based transmissions, respectively. Also, when the distance is 500m, our proposed hybrid scheme transmits with almost half (greater than 2dBM) of the power level as compared to mmWave transmission in achieving a desirable data rate. Hence, HMMC can achieve high data rates for a set transmit power level when compared to conventional schemes.

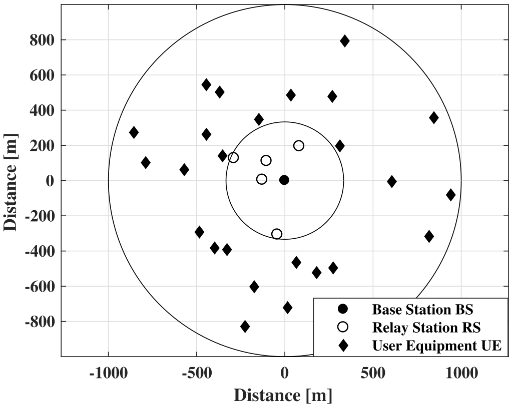

FIGURE 5. Deployment of BS, RS's and UE's.

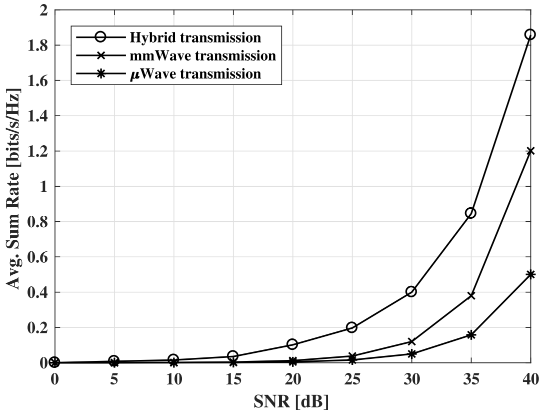

FIGURE 6. Comparison of HMMC with conventional schemes in terms of Sum rate vs SNR.

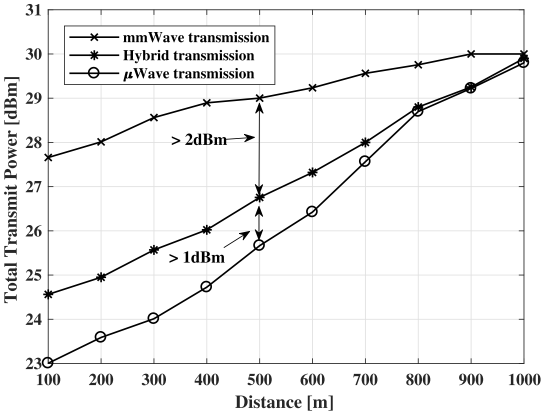

FIGURE 7. Comparison of HMMC with conventional schemes in terms of Transmit power vs distance.

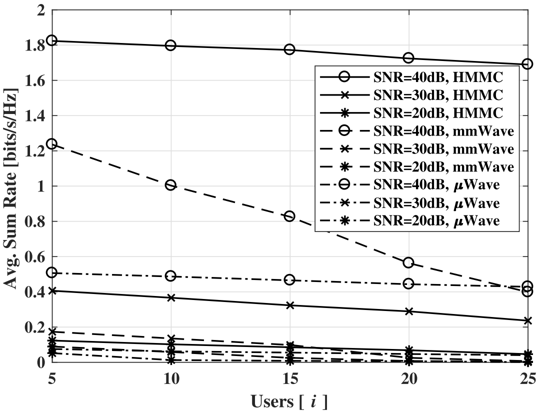

FIGURE 8. Comparison of HMMC with conventional schemes in terms of Sum rate vs No. of Users.

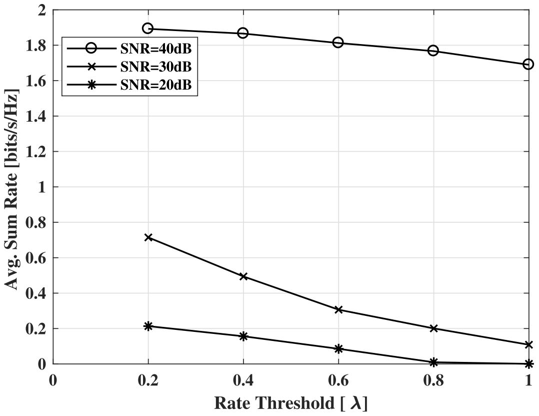

FIGURE 9. Performance of HMMC in terms of Sum rate vs Rate Threshold.

Next, we consider the implication of the increasing number of users to the data rate achieved. We compared our hybrid scheme with the conventional ones over different SNR levels i.e., low SNR (20dB) regime, medium SNR (30dB) and high SNR (40dB) regime in Figure 8. In general, with the increase in the number of users the average data rate declines, but the extent of variation is different in each case. For the HMMC case at medium SNR, the data rate falls almost in half with increasing the number of UEs from 5 to 25. With mmWave prone to anomalies such as blockage, the data rate drops to less than half with increasing number of users even at high SNR regime. μWave transmission achieves the lowest data rate achieved overall. Thus, the number of users affects the data rate with the highest impact on μWave and the lowest on HMMC.

In order to estimate a desirable data rate for a minimal number of users, we consider a case of defining a rate threshold level λ. The rate threshold factor acts as a switch between mmWave and μWave transmission for our proposed hybrid scheme. This enables us to determine the influence of SNR on our data rate. In Figure 9, for the high SNR regime, the increasing value of threshold slightly lowers the data rate achieved. With the case of medium and low SNR regime, the increasing threshold greatly reduces the data rates achieved for more than half. So, in general, by increasing the threshold, we expect more switching between mmWave and μWave and as a result, decrease the data rate. As, rate threshold is a QoS measure and would actually be dependent on the type of service or application under consideration, hence, needs to be chosen appropriately.

VI. CONCLUSION AND FUTURE WORK

This work studied the joint selection of frequency spectrum in a downlink of a dual mode BS and also considered relay selection towards a cooperative network. Allocation of mmWave is given priority and in case mmWave is unable to satisfy the requirement of the user, a fall back strategy is adopted, i.e., μWave spectrum is employed. We show that the performance of our proposed scheme HMMC is significantly better than that of mmWave and μWave in terms of data rate achieved, total transmit power and the number of users served. The paper provides insights into the use of a hybrid architecture. The algorithm proposed is not optimized to reduce the complexity of the scheme. In future, more sophisticated algorithms will be adopted to allocate the resources in a distributed manner. Future work will also focus on interference mitigation by employing channel estimation techniques along with a complete test bed deployment to corroborate our theoretical findings.

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