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Outage Reduction with Joint Scheduling and Power Allocation in 5G mmWave Cellular Networks

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***Abstract*—Millimeter-wave (mmWave) communications is a promising technology which supports high datarates (multi-Gbps) by utilizing high bandwidth and the directional antenna. While the directionality reduces interference significantly and compensates the high propagation loss, it brings about two major problems. Firstly, mmWave links are easily blocked by obstacles like human bodies and buildings. Secondly, user mobility can frequently cause misalignments between transmitter and receiver beams, which is known as the deafness problem. In this paper, these problems are addressed and a joint scheduling and power allocation framework is proposed to reduce the outage probability during user movement. Extensive simulations are done to demonstrate the pros and cons of the proposed algorithms and the improvement of system performance.**

I. Introduction

Recently, millimeter-wave (mmWave) band communications have been widely recognized as a potential candidate to support emerging broadband-access and cellular system evolution with its achievable coverage comparable to traditional microwave systems. The mmWave transmission is featured with short wavelength/high frequency, high bandwidth, and sensitive to blockage against most solid materials [1]. The recent wide range of studies [2] [3] [4] [5] shows that the mmWave channels have the potential to be used in cellular network design, however, much remains to be studied to reach the phenomenal objective.

The mmWave transmission signals are more sensitive to blockage effects as compared to signals in lower frequency bands, and the increased pathloss in these bands is well-known, as indicated by the measurement data in [6]. To compensate the increased pathloss, beam forming (BF) technology is used, to provide high-directivity gain [3] [7]. With the advantage of the highly directional antenna and available large bandwidth, mmWave is able to provide high datarate throughput. However, the system throughput can still be significantly damaged due to the mobility under different geographical and environmental blockage. Specifically, human bodies and vehicular movement can contribute to severe blockage, and a small displacement is prone to cause a misalignment between transmitter and receiver beams, resulting in unstable channel conditions. Thus, reducing the outage probability is one of the critical challenges which need to be addressed in mmWave systems. Furthermore, providing mobile users with multi-Gpbs datarates while reducing the outage probability motivates our investigation of mmWave cellular systems.

In this paper, we investigate the penetration losses due to densely located buildings, vehicular movements, human bodies in urban areas for mmWave 5G cellular networks. In specific, we discuss the effects of user mobility on the mmWave wireless link, which is a major challenge in mobile communications based on narrow-beam transmission. As mentioned previously, the sensitivity of mmWave system towards all kind of blockages makes it hard to provide seamless service and system functions like user association during user mobility. This requires carefully designed mechanisms to leverage the problems of blockage and beam misalignment.

To deal with the aforementioned challenges, in this paper, we focus on minimizing the outage probability on user mobility without jeopardizing the system throughput. Our contributions can be summarized as follows.

- Firstly, we designed a framework to provide a seamless mmWave 5G design with multiple beams.
- Secondly, we propose a heuristic based joint transmission scheduling and power allocation framework in this paper, seeking to reduce the outage probability without jeopardizing the system throughput.
- Thirdly, we extensively perform simulations to evaluate the system performance in different transmission environments.

The remainder of this paper is organized as follows. In Section II, related works are presented. The network topology, the physical model, and problem formulation are provided in Section III. In Section IV, a multibeam transmission model for concurrent beamforming is presented, and our proposed algorithm is discussed. The performance is evaluated and analyzed using simulation in Section V, followed by concluding remarks in Section VI.

II. Related Works

Several works have been investigated to leverage the deafness and blockage effects in the mmWave system [7] [8] [9] [10] [11] [12]. However, previous analyses of the mentioned two problems have focused either on the indoor scenario or assuming the users' position is static.

Authors in [8] develop a blockage robust directional medium access control (MAC) protocol for mmWave wireless personal area networks (WPANs), which jointly optimizes relay selection and spatial reuse. A diffraction-based model is proposed in [9] to determine network link connectivity, and mitigate the outage problem by multi-hop communication.

While effective in the indoor environment, these methods cannot be generalized to outdoor networks well. In an urban outdoor area, mobile users can have a wide variety of speed and spatial location, causing the difficulty of network connectivity estimation as well as the high cost of relay deployment.

An efficient beam-tracking technique for mmWave mobile stations can be found in [10] to identify the cause of beam error, however, the proposed solution fails to prevent it. The author in [7] further considers beam-searching, beamwidth-selection, and scheduling to facilitate multiple concurrent transmissions. However, without a proper design of transmission scheduling and power allocation, the overhead of beam-alignment is likely to affect the system throughput largely.

Furthermore, authors in [12] formulate a joint power and channel allocation problem and propose a multi-channel MAC protocol for multimedia delivery. Inspired by previous works, we believe that the mechanism of beam selection, transmission scheduling, and power allocation ought to be designed jointly in order to optimize system performance in the outage-throughput tradeoff. Consequently, we propose a framework to solve the outage problem as a whole.

To deal with the blockage and deafness problems, based on the beamforming technique and mmWave channel model proposed in [13], we develop a novel strategy of multiple-beam service in our framework, which is more robust to inaccurate beam alignment. We resort to rather simple but cost-effective methods, including multiple-beam service, transmission scheduling, and beam power allocation. First, with the intuition to serve each user with multiple beams, we carry out simulations and find that it largely avoids outage caused by the single-beam blockage. Second, we scheduled the users in small groups considering their channel conditions. In detail, users with poor links are served earlier and grouped with users with good conditions, which further prevents the users from the outage. Finally, the beam power in each transmission group is effectively allocated, that is, the transmission power for the users with better channel conditions will be shared to those with poorer links.

III. System Overview

A. Network Model

We consider a traditional hexagonal outdoor cellular network topology. For simplicity, we consider only one mmWave-enabled eNB or gigabit eNB (gNB) with several user equipments (UEs) deployed randomly with a maximum distance of 100m from the gNB, an illustration of which is shown in Fig. 1. We assume, the gNB has adaptive beamforming capabilities, which are favorable to support concurrent transmissions. Furthermore, we assumed the gNB has three cells covering 120 degrees each. In each cell, a codebook-based beamforming technique is employed and is capable to form 8 directional beams. Similarly, the 4×4 antenna array of the users is configured to form 4 directional beams. Besides, we assume the user moves with certain speed within the transmission reach of the gNB, discussed later. Our physical model, beam settings are based on [13].

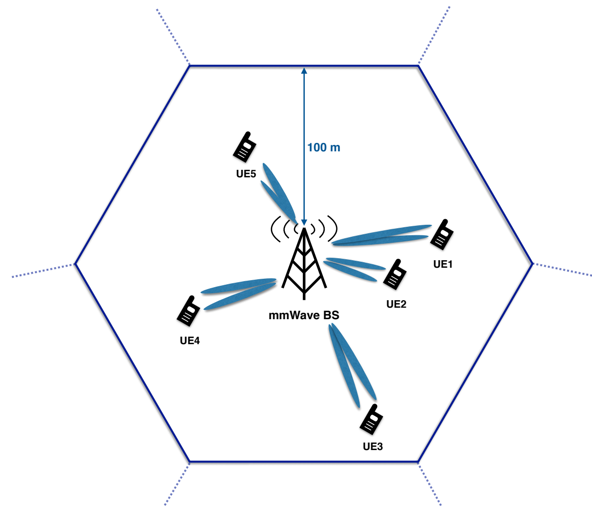


Fig. 1: Illustration of deployed mmWave cellular network

For user mobility, we adopt the random waypoint mobility model, a commonly used mobility model in the simulation of cellular networks. The initial position of all users is uniformly random within a cell. The destination, speed, and direction of each user are also determined randomly and independently. Upon arrival at a destination, a user stays for a random period and then moves toward a new destination. There are 3 intervals of user velocity: (0,5), (30,50), and (80,100) kmph, modeling walking, driving in an urban district, and driving on a freeway respectively.

B. Channel Model

In an mmWave based outdoor cellular network scenario, densely located buildings, vehicular movements, human blockage, etc are common. Thus, we assume the transmitted signals, by gNB, traveled at least through two none-line-of-sight (NLOS) paths or two scatter points, as shown in Fig. 2. For simplicity, we perform the simulation study with two such scatter points for NLOS paths. Furthermore, we assume, these scatter points are placed randomly in the network environment.

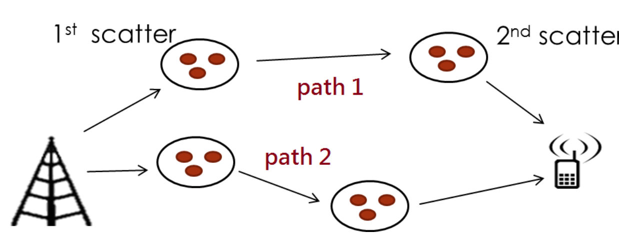


Fig. 2: An illustration of the NLOS channel model.

For mmWave communication, based on the abstraction used in the prior study [6], the received power P_r at the receiver can be calculated as:

$$P_r = P_t \cdot \psi \cdot \gamma^{-1} \cdot PL^{-1} \tag{1}$$

where P_t is a reference power or transmitted power, ψ is the combined antenna gain of transmitter and receiver, γ is the subpath attenuation, and PL^{-1} denotes the associated line-of-sight (LOS) path-loss in dB and can be derived as:

$$PL(d)\ (dB) = \alpha + 10\beta \cdot 10log_{10}(d) + \eta \tag{2}$$

where $PL(d)$ is the mean pathloss, over a reference Tx-Rx separation distance d, in dB, α is the floating intercept in dB, β is the pathloss exponent, $\eta \sim N(0, \sigma^2)$. The simulated values are provided in Table III.

The subpath attenuation γ as well as other short term fading coefficients are generated by the superposition of multiple plane waves traveling from a gNB's antenna element to an antenna element at the user through the scattering environment, which is described explicitly in [13].

The outage can be defined as, expressed in (3), by receiving signals with power less than a threshold P_{outTh} during its transmission period.

$$P_{out} = \frac{\Sigma_{t=1:T}(P_{t,received} < P_{outTh})}{T} \tag{3}$$

The system throughput, as expressed in (4), is evaluated by Shannon capacity, which is dependent of the received SINR. Specifically, the serving beams of each user will cause interference received by other users in the same transmission group.

$$Thput[bpshz] = \varphi \cdot \omega \cdot \log_2 \left(1 + \frac{P_{t,received}}{I_{ABI} + N}\right) \tag{4}$$

where φ is the bandwidth overhead, ω is the mmWave system bandwidth, and I_{ABI} is the adjacent beam interference (ABI).

C. Problem Formulation

We consider the downlink-only transmission to N number of mobile users in coverage. To provide a fair transmission opportunity for each user, the scheduling algorithm schedules and serves all the users at least once before next round of scheduling. Power allocation is activated just before serving, where the weighting is determined based on previously estimated channel conditions. We assume, the channel condition of each user can be measured by the reference signals, which are periodically transmitted by the gNB towards the mobile devices in its coverage. The accuracy of channel estimation is sensitive to the period of a reference signal and user velocity, especially for vulnerable mmWave links. Therefore, we use moving average of the sampled signals to capture a rather stable channel condition and allocate beam and transmission power to each mobile user accordingly.

In the development of our transmission strategy, we find it more effective to deal with scheduling and power allocation in combination. By joint consideration, we can ensure the group of users in each transmission period will be allocated sufficient power to satisfy their throughput demands. In detail, we determine the set of serving beams, scheduled user list, and allocated power, denoted as $\mathbf{B}$, $\mathbf{L}$, and $\mathbf{P_{alloc}}$, respectively. Firstly, multiple beams are used to serve each user, where $\mathbf{B_i}$ stands for the set of serving-beams for user i. Afterwards, the scheduling algorithm groups the users into small transmission groups and schedules each group in a given transmission period. $\mathbf{L_t}$ represents the group of users scheduled at the time slot t. Finally, the total transmission power, $\mathbf{P_{tot}}$, is allocated to the users in each group, where $\mathbf{P_{alloc,i}}$, is the power allocated to the ith user in the group.

Regardless of beam-interference, the scheduling problem can be formulated as a bin packing problem [14]. In the bin packing problem, the goal is to pack objects of different volumes into a minimum number of bins. Similarly, we wish to schedule users with different throughput demands in a minimum number of time slots, and the maximum transmission power is fixed in each time slot. Despite that the problem is NP-complete, the first-fit heuristic algorithm is proved to approximate the optimal solution of the bin packing problem with an approximation factor of 2. Hence, we refer to the first-fit heuristic and develop a greedy-based framework. We formulate the scheduling problem by considering the optimization variable $\mathbf{T}$ as the following optimization problem.

$$\text{minimize} \quad \mathbf{T} = \Sigma_{i=1:n} y_i \tag{5}$$

subject to

$$\mathbf{T} \geq 1, \tag{6}$$

$$\Sigma_{j=1:n} P_{j,demand} \cdot x_{ij} \leq \mathbf{P_{tot}} \cdot y_i,\ \forall i \in \mathbb{Z}^+ \tag{7}$$

$$\Sigma_{i=1:n} \cdot x_{ij} = 1,\ \forall j \in \mathbb{Z}^+ \tag{8}$$

$$x_{ij} \in \{0,1\},\ x_{ij} = 1 \text{ if UE } i \text{ is scheduled in slot } j$$

$$y_i \in \{0,1\},\ y_i = 1 \text{ if slot } j \text{ is used}$$

where $\mathbf{T}$ in (6) is the minimum number of time slots required to schedule all users once, P_{demand} is the requirement of transmission power for each users, and P_{tot} is the maximum transmission power that can be allocated in one time slot. Constraint (7) describes that the sum of demanded transmission power of the users in a time slot should not exceed the total transmission power that a base station can provide. Constraint (8) states that all users are scheduled once.

IV. Proposed Design

A. Multibeam Framework

During user mobility, the fast-changing NLOS paths and random blockages make it hard to acquire the most accurate channel information. Hence, we use the exponential moving average of the channel conditions to eliminate the influence of abrupt fluctuations. The exponential moving average of channel condition can be calculated using (9). Subsequently, multiple beams are allocated to each user during its transmission period, which diversifies the risk of an outage caused by the single-beam blockage.

The new exponential average when a new value Y_t arrives can be calculated using the formula:

$$S_t = \begin{cases} Y_1 & \text{if } t = 1 \\ \alpha \cdot Y_t + (1-\alpha) S_{t-1} & \text{if } t > 1 \end{cases} \tag{9}$$

where S is the channel condition, Y is the sampled channel condition estimated from reference signal, and we choose $\alpha = 0.2$ in our simulation.

$$P_t = \alpha \cdot S_t + (1 - \alpha) P_{t-1} \tag{10}$$

Tables I and II shows the simulation results of moving average and multiple-beam service with a TDMA scheduler. The outage probability is reduced by using the exponential moving average instead of simply the latest channel conditions, and it can be further decreased by employing multiple-beam service. Nevertheless, since the users scheduled simultaneously cannot share the same transmitter beam, serving users with more beams causes higher complexity in scheduling. In the remaining simulations, we serve each user with two beams that have the best average channel conditions, as it has a low implementation complexity and results in sufficiently small outage probability.

TABLE I: Average outage probability using different measurement of channel conditions.

Latest condition	Moving average condition
7.8%	6.45%

TABLE II: Average outage probability using different numbers of beams.

1 beam	2 beams	3 beams	4 beams	5 beams
6.45%	2.4%	1.6%	1.35%	1.25%

B. Joint Scheduling and Power Allocation Framework

After allocating the serving beams for each user, scheduling and power allocation are addressed jointly to further reduce the outage probability. Here we propose two scheduling algorithms: static grouping (SG) and dynamic grouping (DG), and two power allocation algorithms: static power allocation (SPA) and dynamic power allocation (DPA). The scheduling algorithms generate a schedule list, which specifies the group of users scheduled in each time slot, and the power allocation algorithms allocate the total transmission power to the users in each group. They can be employed either individually or in combination.

In the proposed algorithms, we consider the residual power, P_{res}, of each user, which is defined by the difference between the expected received power and the minimum received power, $P_{threshold}$, required to satisfy a target throughput. In other words, a negative P_{res} indicates that the expected received power of the user is lower than $P_{threshold}$ with even power allocation, and vice versa.

Initially, the unscheduled users are sorted in ascending order of P_{res}, and the one with lowest P_{res} is scheduled first. In SG scheduler, we always schedule a fixed number of users, n, in each transmission group. For instance, if $n = 3$, SG scheduler will always group one user with poor conditions and two with good conditions together. On the contrary, with DG scheduler implemented, the group size is dynamically determined. At most n users are scheduled simultaneously in each transmission period, under the condition that their serving beams do not overlap and the total residual power is positive. Consequently, only the users with sufficiently good channel conditions are grouped together, and the users with channel conditions too poor to satisfy the minimum requirement even after power allocation are served alone. This ensures that the total transmission power in each group is sufficient for all the users. Obviously, the SG scheduler has a lower complexity and is able to provide higher throughput, whereas the DG scheduler can more effectively reduce the outage probability.

Given the determined schedule list, the transmission power in each time slot is allocated according to the channel conditions. Specifically, in SPA algorithm, a fixed proportion, λ, of the total transmission power is given to the user with relatively poor conditions, as long as it does not cause any outage on other users. In DPA algorithm, if the residual power of a user is negative, a dynamic fraction of the transmission power will be allocated to compensate the exact deficiency. Intuitively, DPA utilizes the transmission power more efficiently, while SPA is more robust to fluctuating channel conditions.

Algorithm 1 Static Grouping (SG)

Input: P_{res}: residual power of each user;
B: set of serving beams for each user;
Output: L_t: schedule list at time t;
Sort the unscheduled users in ascending order of P_{res};
while not all users are scheduled **do**
    Let v_i be the first user, find the last two users, v_j and v_k, s.t. B_i, B_j and B_k disjoint.
    $L_t \leftarrow \{v_i, v_j, v_k\}$.
    $t \leftarrow t + 1$.
end while

Algorithm 2 Dynamic Grouping (DG)

Input: P_{res}: residual power of each user;
B: set of serving beams for each user;
Output: L_t: schedule list at time t;
Sort the unscheduled users in ascending order of P_{res};
while not all users are scheduled **do**
    Let v_i be the first user, find the last user, v_j, s.t. B_i and B_j disjoint $\wedge$ $P_{res,i} + P_{res,j} > 0$.
    if $\exists\, v_j$ **then**
        if $\exists\, k \in (i, j)$ s.t. B_i, B_j, and B_k disjoint $\wedge$ $P_{res,i} + P_{res,j} + P_{res,k} > 0$ **then**
            $L_t \leftarrow \{v_i, v_j, v_k\}$.
        else
            $L_t \leftarrow \{v_i, v_j\}$.
        end if
    else
        $L_t \leftarrow \{v_i\}$.
    end if
    $t \leftarrow t + 1$.
end while

V. Performance Evaluation

A. Simulation Setup

In this section, we evaluate the proposed algorithms and compare their performances in different scenarios. In simulations, we consider only one gNB and several mobile users. We

Algorithm 3 Static Power Allocation (SPA)

Input: L_t: schedule list at time t;
P_{res}: residual power of each user;
P_{tot}: total transmission power;
λ: power allocation weighting;
Output: P_{alloc}: allocated power for each user;
for each L_t **do**
  if $|L_t| = 1$ **then**
    $P_{alloc,1} \leftarrow P_{tot}$.
  else if $|L_t| = 2$ **then**
    $P_{alloc,1} \leftarrow \lambda \cdot P_{tot}$.
    $P_{alloc,2} \leftarrow (1-\lambda) \cdot P_{tot}$.
    if $P_{res,2} + P_{alloc,2} < 0$ **then**
      $P_{alloc,1} \leftarrow P_{tot}/2$.
      $P_{alloc,2} \leftarrow P_{tot}/2$.
    end if
  else
    $P_{alloc,1} \leftarrow \lambda \cdot P_{tot}$.
    $P_{alloc,2} \leftarrow (1-\lambda)/2 \cdot P_{tot}$.
    $P_{alloc,3} \leftarrow (1-\lambda)/2 \cdot P_{tot}$.
    if $P_{res,2} + P_{alloc,2} < 0 \vee P_{res,3} + P_{alloc,3} < 0$ **then**
      $P_{alloc,1} \leftarrow P_{tot}/3$.
      $P_{alloc,2} \leftarrow P_{tot}/3$.
      $P_{alloc,3} \leftarrow P_{tot}/3$.
    end if
  end if
end for

Algorithm 4 Dynamic Power Allocation (DPA)

Input: L_t: schedule list at time t;
P_{res}: residual power of each user;
P_{tot}: total transmission power;
Output: P_{alloc}: allocated power for each user;
for each L_t **do**
  if $|L_t| = 1$ **then**
    $P_{alloc,1} \leftarrow P_{tot}$.
  else if $|L_t| = 2$ **then**
    if $P_{res,1} < 0 \wedge P_{res,2} + P_{res,1} > 0$ **then**
      $P_{alloc,1} \leftarrow -P_{res,1}$.
      $P_{alloc,2} \leftarrow P_{tot} + P_{res,1}$.
    else
      $P_{alloc,1} \leftarrow P_{tot}/2$.
      $P_{alloc,2} \leftarrow P_{tot}/2$.
    end if
  else
    if $P_{res,1} < 0 \wedge P_{res,1} + P_{res,2} + P_{res,3} > 0$ **then**
      $P_{alloc,1} \leftarrow -P_{res,1}$.
      $P_{alloc,2} \leftarrow (P_{tot} + P_{res,1})/2$.
      $P_{alloc,3} \leftarrow (P_{tot} + P_{res,1})/2$.
    else
      $P_{alloc,1} \leftarrow P_{tot}/3$.
      $P_{alloc,2} \leftarrow P_{tot}/3$.
      $P_{alloc,3} \leftarrow P_{tot}/3$.
    end if
  end if
end for

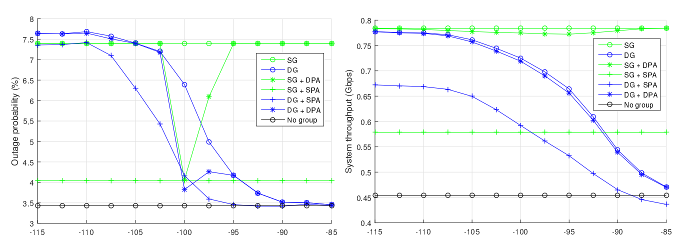
set the maximum group size for scheduling to $n = 3$ for simplicity. However, increasing the group size is straightforward. The system bandwidth is allocated evenly to all users within each transmission period. The basic system parameters used for simulation are listed in Table III, and are based on [15] [16]. In order to show the effects on the system performance, we perform the simulation with the alternative combination of our proposed scheme such as SG with DPA, SG with SPA, and so on.

TABLE III: Simulation Parameters

Parameter	Value
Carrier frequency	28 GHz
System bandwidth	100 MHz
Transmit power (P_{tot})	37 dBm
Pathloss parameter (PL), $PL = \alpha + 10\beta \log_{10}(d)$ [dB], d in meters	$\alpha = 72.0$ $\beta = 2.92$
Shadow fading (σ)	8.7 dB
Background noise (AWGN)	-174 dBm/Hz
Outage threshold (P_{outage})	-101 dBm
SPA weighting (λ)	0.8
Number of users (N)	100 per cell

B. Simulation Results

Fig. 3 shows the outage probability (Fig. 3a) and system throughput (Fig. 3b) under different levels of power allocation threshold with user velocity 3 kmph. For DG algorithm, the threshold on the X-axis represents the minimum requirement of the received power of the users in each group. For DPA algorithm, the threshold value stands for the target received power for power allocation. Observing from Fig. 3a, DG algorithm reduces the outage probability significantly as the power allocation threshold increases, since there are more poor-conditioned users scheduled alone. Specifically, the outage probability can be reduced by approximately 4% at any threshold higher than -90dBm. Furthermore, while DPA results in low outage probability at a power allocation threshold close to the outage threshold (-101dBm), SPA averagely performs better in reducing outage. On the other hand, SG algorithm can merely avoid the outage by at most 3.4% combining with SPA. In the curve of SG + DPA, the outage probability is reduced via power allocation as the threshold gets close to the outage threshold, but it goes high again as the threshold becomes too high to make up for the lack of transmission power. The fluctuation in the curves of SG+DPA and DG+DPA shows their sensitivity to power allocation threshold. For DPA algorithm, it can work well with grouping algorithms and lead to low outage only when the threshold is precisely around the outage threshold.

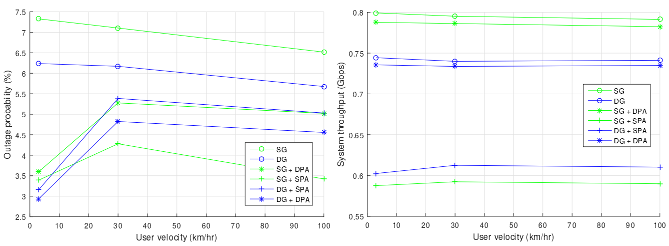


(a) Outage Probability (b) System Throughput

Fig. 3: System performance with varying $P_{threshold}$.

While it seems plausible that serving fewer users in each transmission period can most effectively prevent the outage, it compromises the system throughput. As shown in Fig. 3b, SG generally produces higher throughput than DG since it always serves multiple users simultaneously, and DPA produces higher throughput than SPA since it allocates less power to the users with poor conditions.

On the other hand, in Fig. 4, we compare the performance of the algorithms in various scenarios of user velocity. The speed of 3, 30, and 100kmph represents the movement of pedestrians, driving in urban districts, and driving on freeways, respectively. As user velocity increases, the fast-varying channel conditions and out-dated reference signal used for power allocation are likely to cause higher outage probability. The impact of user velocity is severe especially for DPA, where the accuracy of the reference signal is more critical. On the other hand, the system throughput is barely affected by user velocity.



(a) Outage Probability (b) System Throughput

Fig. 4: System performance with varying user velocities.

Different combinations of the scheduling and power allocation algorithms suit different scenarios. When the scheduling algorithms are employed individually, the transmission power is allocated evenly to the users in each group, which results in high outage probability. Working together with power allocation algorithms, however, reduces the system throughput since more power is allocated to the users with poor conditions. Consequently, a good combination of algorithms with appropriate threshold should be chosen to deal with the outage-throughput tradeoff.

VI. Conclusion

Our focus in this paper is to prevent severe outage probability in mmWave outdoor cellular networks caused by user mobility. To address this challenge, we have proposed a framework, by integrating methods of moving-averaged beam condition, multiple-beam service, user grouping, and power allocation. We have formulated the outage problem with the objective of minimizing the total number timeslots while scheduling users with different throughput requirements. We have implemented our proposed algorithm in combination. Extensive simulations show that DG + SPA gives the best performance in reducing the outage probability and is more robust to various user velocities, whereas DG + DPA provides higher system throughput. With a wisely chosen threshold between -90dBm and -100dBm, they both successfully prevent outage while maintaining high throughput. Therefore, we suggest DG + SPA for an urban mobile environment or vehicular communications, and DG + DPA for applications with higher throughput demands. With the proposed framework, mmWave communication can be more reliable in an urban outdoor environment while preserving its advantage of high throughput.

Acknowledgment

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