Multi-Beam Power Allocation for mmWave Communications under Random Blockage

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***Abstract*—Milimeter-wave links can provide GBit/s data rates but are highly susceptible to blockage. In case a direct line-of-sight communication path becomes blocked, communication via a reflected path may allow to maintain connectivity. A common approach is to switch to such an alternative path whenever the first path becomes blocked. However, this requires detecting the blockage and then reconfiguring the transceiver to use the new path which incurs latency. For traffic with strict latency or reliability requirements, or in highly dynamic environments where path switching would be frequent, using both paths concurrently can be more beneficial. In this paper, we consider using multiple paths and dividing the transmission power over those paths, instead of path switching. We propose an algorithm to allocate power among the different mmWave communication paths to overcome link blockage under randomly distributed obstacles. The power allocation algorithm is based on analysis of the blockage probabilities of the direct and reflected paths using geometric probability, to statistically maximize the overall capacity of the path between two nodes. We evaluate the performance of the proposed algorithm via simulation for various wireless environments.**

***Index Terms*—mmWave, resource management, blockage probability, reflection, geometric probability.**

I. Introduction

For the fifth generation cellular networks, millimeter-wave (mmWave) communication is a highly promising technology to overcome the increasing wireless spectrum shortage. It provides very high data rates [1], but compared to frequency bands below 6 GHz, mmWave incurs higher propagation loss, higher penetration loss, and higher directivity [1]. For these reasons, mmWave wireless links have limited coverage and are vulnerable to blockage by obstacles. For range extension, mmWave uses highly directional phased antenna arrays or multiple input multiple output (MIMO) to achieve sufficiently high antenna gains.

For reliable mmwave networking, several approaches have been studied in previous work. In [2], multiple bands are used to increase reliability. By switching a link from one band to another, known as fast session transfer (FST), IEEE 802.11ad can maintain connectivity. However, when a lower frequency band is used in such a multi-band operation, the available bandwidth is reduced and the network performance is degraded [3]. In [4], multi-hop communication for mmWave is considered to overcome link blockage. The proposed algorithm enhances the reliability by detouring obstacles via a relay when a direct path is disconnected by the obstacles. This requires a sufficiently high node density to ensure suitable relay nodes are available.

Reflected paths can increase the capacity [3] by circumventing obstacles, as in Fig. 1. In [5], the authors derive the transition probability of a path from blocked to unblocked and propose a joint optimization algorithm for link and relay selection. Considering the blockage probabilities of links including reflected paths, the algorithm selects the link that minimizes the expected delivery time, but it does not consider joint use of multiple paths. In [6], a model is developed to evaluate the coverage probability not only considering the direct beam but also including first order reflections. It was shown that a reflection significantly improves the coverage probability under non-line-of-sight (NLOS) conditions. However, the analysis does not consider the impact on capacity.

Under random obstacles, mmWave links are randomly and unexpectedly disconnected due to the mobility of objects, such as human beings. When a path is blocked, prior algorithms [5], [6] switch from the blocked path to another one, and this switching mechanisms incurs additional latency during the transition [7]. After a node switches from one path to another, the new path may in turn be unexpectedly broken, requiring yet further switching. While the typically longer path distance of a reflected path results in lower rates compared to the direct path, the diversity provided by using both paths can enhance not only the coverage and reliability, but also the average capacity.

In this paper, we consider using multiple paths concurrently, by properly allocating transmit power to overcome link blockage. We analyze the impact of the direct and reflected paths on capacity under random blockage, using geometric probability as in [4], [8], [9]. Based on the analysis, a resource management algorithm is proposed to maximize link capacity and verified via simulations.

II. System Model and Problem to Solve

We consider a mmWave network consisting of a pair of source node and destination node, a reflector, and random obstacles, as shown in Fig. 1. The nodes are equipped with a beam-forming antenna that can generate multi-lobe beam

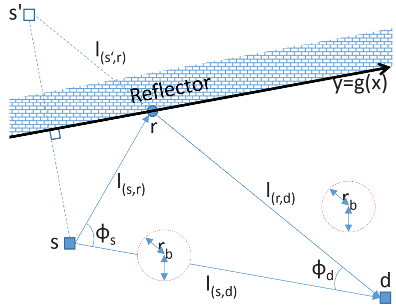


Fig. 1. System model.

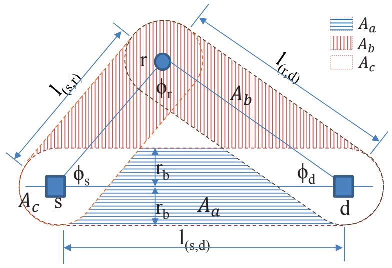


Fig. 2. Blockage areas: direct path blockage area (A_a), indirect path blockage area (A_b), and both path blockage area (A_c).

patterns [10], and know the location and shape of the reflector.[1] There are two possible paths to communicate between nodes s and d: a directed path and a reflected path. A direct path between the two nodes is denoted as an ordered pair (s, d), and modeled as a line segment of length $l_{(s,d)}$.

The geometry of the reflector is assumed to be a line $y = g(x)$. Based on the reflector, the source node can calculate the reflected image of the source s' against the reflector and the reflection point r that reflects the signal from node s to node d on the reflector surface $g(x)$. We denote by (s, r, d) the reflected path of (s, d) via r. We further assume that node s knows the distance $l_{(s,d)}$ between nodes s and d, and the angles ϕ_s and ϕ_d.

Obstacles are modeled as a disk with radius r_d, and are assumed to be independently and randomly located. The distribution of the centers of obstacles follows a homogeneous Poisson distribution with density λ in two dimensional space, which is expressed as

$$\Pr\{k \text{ obstacles in in area } A\} = (\lambda A)^k \frac{e^{-\lambda A}}{k!}. \quad (1)$$

Due to the Poisson property [12], the numbers of obstacles in disjoint (non-overlapping) areas are independent. The obstacles randomly block communication paths, so that path (s, d) between nodes s and d can be disconnected if an obstacle blocks the line segment. If either one or both of the paths (s, r) and (r, d) are blocked, then the reflected path is blocked.

Let γ be the signal-to-interference-and-noise ratio (SINR) at the receiver. Then the achievable link capacity is given by $C = B \log(\gamma + 1)$, where B is the bandwidth. The SINR is defined as $\gamma = \frac{P_{\text{rx}}}{I+N}$, where P_{rx} is the receive power at the receiver, I is the interference power from other transmitters, and N is the ambient noise.

Due to random blockage, the direct path and the reflected path can be disconnected when an obstacle is located on the path. However, different topologies result in different blockage statistics for the two paths and require different power allocations to maximize the expected link capacity. Hence, our problem is to allocate power to antenna beams in order to maximize the expected capacity at node d under a power constraint, expressed as

$$\max_{(P_1,P_2)\in[0,1]^2} E[C(P_1, P_2)] \quad (2)$$
$$\text{subject to } P_1 + P_2 \le P_{\text{Tot}}$$

where P_1, P_2, P_{Tot} are powers allocated to the direct path and the reflected path, and the total power, respectively. To solve the problem, we first analyze the blockage probabilities of the two paths under random obstacles.

III. Analysis of Expected Capacity

A. Blockage Probability

The blockage area, which is encircled by dotted lines in Fig. 2, can be divided into three areas A_a, A_b, and A_c. For notational simplicity, we also denote by A the event that no center of any obstacle is located in area A, and by $\overline{A}$ the complement of event A, if no confusion arises. When a center of an obstacle is located in area A_a (A_b), the direct (reflected) path is blocked. When a center of an obstacle is located in area A_c, the direct and reflected paths are blocked together by the same obstacle. Hence, it follows from (1) that the probability $\rho_{1\overline{2}}$ that only the direct path is available is

$$\rho_{1\overline{2}} = \Pr(A_a + A_c)\Pr(\overline{A_b}) = e^{-\lambda(A_a+A_c)}\left(1 - e^{-\lambda A_b}\right). \quad (3)$$

Similarly, the probability $\rho_{\overline{1}2}$ that only the reflected path is available and the probability ρ_{12} that the direct and reflected paths are simultaneously available can be expressed as

$$\rho_{\overline{1}2} = \left(1 - e^{-\lambda A_a}\right) e^{-\lambda(A_b+A_c)} \text{ and } \rho_{12} = e^{-\lambda(A_a+A_b+A_c)}. \quad (4)$$

B. The Impact of Blockage on Receiving Power

The general expression of receive power of a single path can be expressed as

$$P_{\text{rx}} = K P_{\text{tx}} l^{-\alpha} \beta = K P_{\text{Tot}} p l^{-\alpha} \beta,$$

where K is a constant, P_{tx} is the transmit power for the antenna lobe serving that path, P_{Tot} is the total available power of the transmitter, p is the ratio of the path transmit power to the total power, l is the path length, α is the attenuation exponent, and

[1]This information can be made available, for example, through a floor plan of the communication environment, or can be estimated through a mmWave location system with simultaneous localization and mapping (SLAM) [11].

β is the reflection coefficient of a reflector. In the case of a direct path, the path length is $l_{(s,d)}$ in Fig. 2 and the reflection coefficient is one. In the case of a reflected path, the path length is $l_{(s,r)} + l_{(r,d)}$ in Fig. 2 and the coefficient is a value in the range of $[0, 1]$

When two beams are simultaneously activate at the transmitter and the receiver combines the signals received from the different antenna beams[2], the receive power is

$$P_{\text{rx}} = K_1 P_{\text{Tot}} p_1 l_1^{-\alpha} + K_2 P_{\text{Tot}} p_2 l_2^{-\alpha} \beta, \tag{5}$$

where p_1 (p_2) is the power ratio allocated to the beam of the direct (reflected) path and l_1 (l_2) is the path length of the direct (reflected) path.

C. The Impact of Blockage on Capacity

According to link blockage, we have four different and disjoint cases. When both paths are blocked, SINR is zero. If only a direct path is available, SINR $\gamma_{1\bar{2}}$ becomes

$$\begin{aligned} \gamma_{1\bar{2}} &= \frac{K_1 P_{\text{Tot}} p_1 l^{-\alpha}}{I + N} \\ &= \gamma_1 p_1, \end{aligned}$$

where γ_1 is the SINR when all the power is allocated to the direct path. Similarly, when only a reflected path is available and $P_{\text{Tot}} p_2$ is allocated to the beam, then SINR $\gamma_{\bar{1}2}$ is $\gamma_{\bar{1}2} = \gamma_2 p_2$.

In the case when a direct path and a reflected path are concurrently available, SINR γ_{12} becomes

$$\begin{aligned} \gamma_{12} &= \frac{K_1 P_{\text{Tot}} p_1 l_1^{-\alpha} + K_2 P_{\text{Tot}} p_2 l_2^{-\alpha} \beta}{I + N} \\ &= \gamma_1 p_1 + \gamma_2 p_2, \end{aligned}$$

Hence, according to the law of total expectation, the expected capacity of (2) is given by

$$\begin{aligned} &E[C] \\ &= E[C|L_{1\bar{2}}]\Pr(L_{1\bar{2}}) + E[C|L_{\bar{1}2}]\Pr(L_{\bar{1}2}) + E[C|L_{12}]\Pr(L_{12}) \\ &= \rho_{1\bar{2}} \log\left(\gamma_{1\bar{2}} + 1\right) + \rho_{\bar{1}2} \log\left(\gamma_{\bar{1}2} + 1\right) + \rho_{12} \log\left(\gamma_{12} + 1\right) \\ &= \rho_{1\bar{2}} \log\left(\gamma_1 p_1 + 1\right) + \rho_{\bar{1}2} \log\left(\gamma_2 p_2 + 1\right) \\ &+ \rho_{12} \log\left(\gamma_1 p_1 + \gamma_2 p_2 + 1\right), \end{aligned} \tag{6}$$

where $L_{1\bar{2}}$ is the event that only the direct path is available, $L_{\bar{1}2}$ is the event that only the reflect path is available, and L_{12} is the event that the direct and reflected path are simultaneously available.

IV. Optimal Power Allocation Algorithm

Since $p_1 + p_2 = 1$, we can express (6) as a function of p_1 such that

$$\begin{aligned} f(p_1) &= \rho_{1\bar{2}} \log\left(\gamma_1 p_1 + 1\right) + \rho_{\bar{1}2} \log\left(\gamma_2 (1 - p_1) + 1\right) \\ &+ \rho_{12} \log\left(\gamma_1 p_1 + \gamma_2 (1 - p_1) + 1\right), \\ &= \rho_{1\bar{2}} \log\left(\gamma_1 p_1 + 1\right) + \rho_{\bar{1}2} \log\left(-\gamma_2 p_1 + \gamma_2 + 1\right) \\ &+ \rho_{12} \log\left((\gamma_1 - \gamma_2) p_1 + \gamma_2 + 1\right). \end{aligned} \tag{7}$$

[2] This requires channel estimation and a multi-lobe beam pattern with corresponding phase shifts in the different lobes, which can be generated even with a single RF chain and a phased array [10].

Since the log function is strictly concave and a non-negative weighted sum of concave functions is also concave, $f(\cdot)$ is also strictly concave with respect to p_1 [13]. Hence, our problem is a convex optimization problem to find an optimal power p_1^* of a direct path, which is defined as

$$\begin{aligned} p_1^* = &\underset{p_1}{\operatorname{argmax}}\, f(p_1) \\ &\text{subject to } 0 \le p_1 \le 1. \end{aligned} \tag{8}$$

The optimization problem is a standard convex optimization problem with an inequality constraint. We first find a solution $\hat{p_1}$ to satisfy the first order necessary condition, which is expressed as

$$f^{'}(\hat{p_1}) = 0, \tag{9}$$

where $f^{'}(\cdot)$ is the derivative of $f(\cdot)$. If a solution of (9) is in $(0, 1)$, the solution becomes the solution of (8). If it is less than or equal to zero, the solution is zero, which means that all power is allocated to the reflected path. If it is greater than or equal to one, the solution is one, which means that all power is allocated to the direct path.

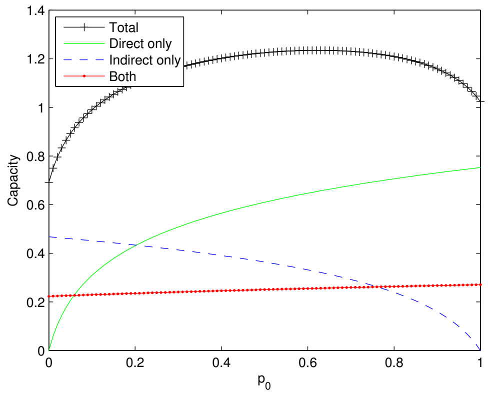
V. Numerical Study

In this section, we numerically study our proposed resource allocation algorithm. For simplicity, we model the reflector surface as a horizontal line. The same observations hold for a rotated reflector.

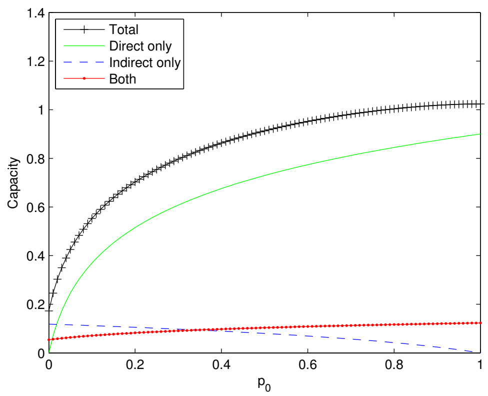
First, we study the impact of multiple paths on the link capacity (normalized by the bandwidth). For the numerical study, a sender and a receiver are located at the origin (0, 0) and (20, 0) on the x-axis, respectively, i.e., the communication distance is 20 m. Obstacles with a radius r_b of 0.3 m are randomly distributed following a Poisson distribution with density $\lambda = 0.1$. Unless stated otherwise, the reflection coefficient is set to 0.9 (-1 dB loss) which corresponds to the coefficient measured for metal [14].

Figure 3 shows the contribution of the direct and reflected paths on the link capacity according to the ratio of power allocation when the horizontal reflector location is varying. When only the direct path is available and when two paths are simultaneously available, the capacity statistically increases, as the power (p_1) allocated to the direct path increases, while the capacity decreases when only the reflected path is available. Since $(\gamma_1 - \gamma_2)$ in (7) is small, the capacity contributed by two simultaneously available paths is approximately a linear function of p_1. The longer path results in a larger blocking probability and higher path loss, so the capacity of the direct path with full power is higher than the capacity of the reflected path with full power in both cases. However, the optimal power allocation to the direct and reflected paths bring higher capacity as well as larger coverage area [4] than using either the direct or the reflected path exclusively.

Fig. 3a shows the capacity when the power allocation (p_1) to the direct path varies from 0 to 1. When all the power is allocated to the direct path (i.e., $p_1 = 1$) the capacity is 1.024. When it is allocated to the reflected path (i.e., $p_1 = 0$)



(a) Horizontal reflector located at $y = 6$



(b) Horizontal reflector located at $y = 15$

Fig. 3. Capacities of links versus power ratio allocated to the direct path (p_1) with source and destination located at the origin and (20, 0), respectively.

the capacity is 0.6911. However, the expected overall capacity is maximized when 62% and 38% of the total transmission power are allocated to the direct path and the reflected path, respectively. At the optimal power allocation, the capacity is increased by 21.1% compared to that of only the direct path and by 78.7% compared to that of only the reflected path. Compared to Fig. 3a, in Fig. 3b the direct path has a more dominant contribution to the overall capacity since the blocking probability of the reflected path is larger. In case the reflector is located far away from the source-destination pair, the direct path dominantes and the capacity becomes maximum at $p_1 = 1$, which means that the all the power should be allocated to the direct path.

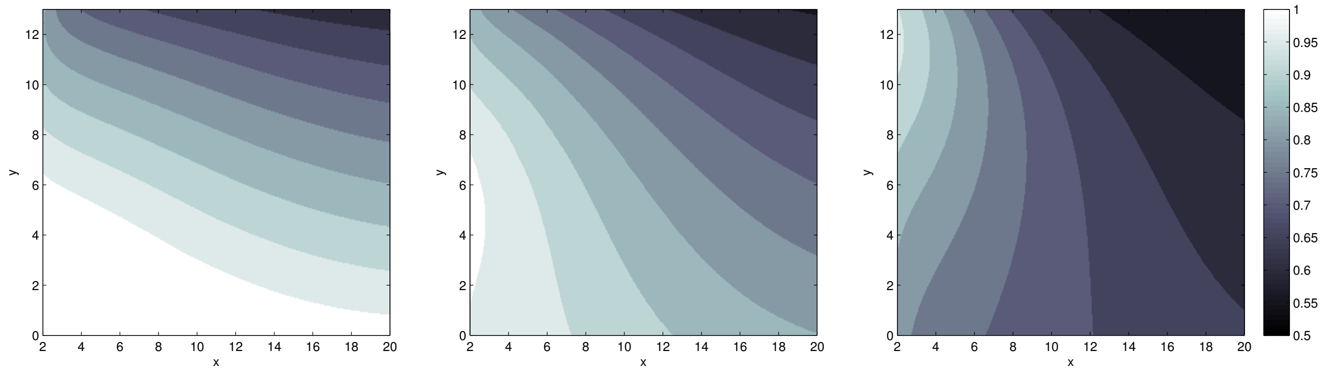
Figure 4 shows the optimal power allocation (p_1) to the direct path with respect to the destination location (x, y) for a given source and reflector location to study the impact of the geometry of the direct path on the capacity. The horizontal reflector is located at $y = 15$ and the source is located at the origin, $(0, 6)$, and $(0, 12)$ in Figs. 4a, 4b, and 4c, respectively. As the source gets closer to the reflector, the length of the reflected path becomes shorter and the blocking probability smaller. The contribution of the reflected path to the overall capacity increases and the optimal power allocation to the direct path decreases from one. For a given destination at $(10, 0)$, the optimal direct path power allocation is one when the source is located at the origin. However, the optimal power allocation is reduced to 0.9 and 0.7 when the source is located at $(0, 6)$ and $(0, 12)$, as shown in Figs. 4b and 4c, respectively.

Network environmental parameters, such as the obstacle density or different reflector materials, also affect the power allocation to paths. To study the impact of these parameters, we evaluate the optimal power allocated to the direct path with changing density (λ), radius (r_b) of obstacles, and reflection coefficient (β) in the same environment as in Fig. 4b. Figure 5 shows the impact of the parameters on the optimal power ratio of the direct path. The increment of the obstacle density results in decreasing probability that a path is available in (3) and (4). Since the blockage area (A_b) of the reflected path is greater than that (A_b) of the direct path, and the probability that a path is available is a negative exponential function of the density and the blockage area, the reflected path is more affected by the density than the direct path. Hence, the capacity becomes maximal at a higher power for the direct path than the reflected path, as shown in Fig. 5a. Larger obstacles result in larger blockage areas in Fig. 2. Similar to the larger density, the larger radius reduces the contribution of the reflected path to the capacity, as shown in Fig. 5b, which means that the power allocation to the direct path becomes higher than that of Fig. 4b.

The reflection coefficient depends on the properties of the material [14], which in turn changes the contribution of the reflected path to the overall capacity. If the absorption of power is larger, then the reflection coefficient becomes smaller and the received power of the reflected signal in (5) decreases. Hence, a smaller reflection coefficient results in a higher power allocation to the direct path to maximize the wireless link capacity, as shown in Fig. 5c.

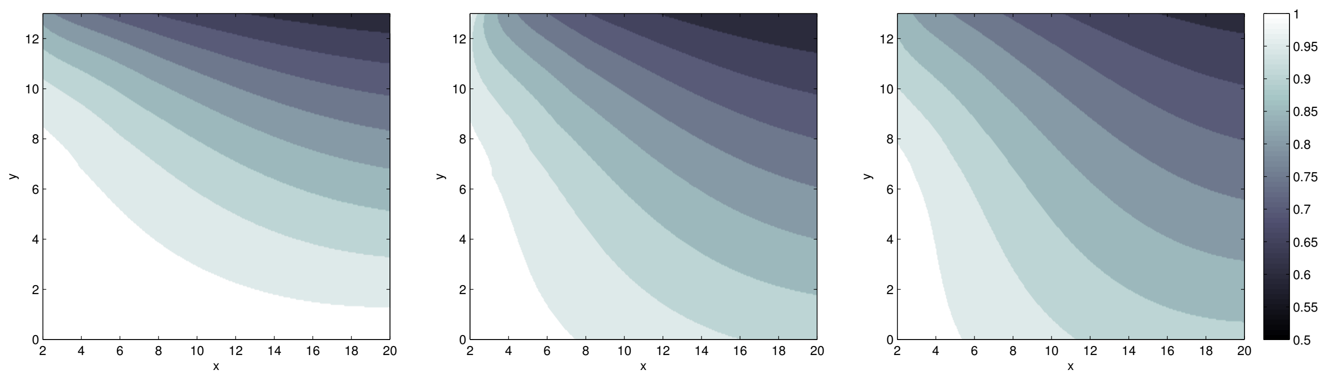
VI. Conclusions

We proposed a resource allocation algorithm for mmWave communications when a reflector exists. Due to high propagation loss and directivity, mmWave links are vulnerable to blockage. A reflected path can increase the coverage by avoiding blockages. Unlike previous works, we propose to use multi-lobe beam patterns with a phased antenna array, and to simultaneous allocate power to a direct and reflected paths, instead of switching between the paths. We first analyzed the blockage probabilities of the direct and indirect paths using geometric analysis. Based on the analysis, we showed that there exists an optimal power allocation for the two paths in order to statistically maximize the overall capacity between two nodes, and proposed a power allocation algorithm for the direct and reflected path to increase the overall capacity in a random blockage environment. We showed via simulations that the reflected path can increase not only the coverage but also the capacity, depending on the characteristics of the wireless environment.



(a) Source located at $(0, 0)$ (b) Source located at $(0, 6)$ (c) Source located at $(0, 12)$

Fig. 4. The optimal power allocation ratio (p_1) of the direct path according to the destination location (x, y) when the horizontal reflector is located at $y = 15$.



(a) $\lambda = 0.3$ (b) $r_b = 0.6$ (c) $\beta = 0.5$

Fig. 5. The impact of various parameters on the optimal resource allocation. For the comparison, the parameters were set as those of Fig. 4b, and we changed the density λ from 0.1 to 0.3, the radius r_b of obstacles from 0.3 to 0.6, and the reflection coefficient β from 0.9 to 0.5.

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