Scalable Two-hop Relaying for mmWave Networks

Junquan Deng*, Olav Tirkkonen*, Tao Chen†, Navid Nikaein‡
*Department of Communications and Networking, Aalto University,Finland
†VTT Technical Research Centre of Finland, Finland
‡Eurecom, Biot Sophia-Antipolis, France

***Abstract*—The performance of millimeter wave (mmWave) networks is limited by severe blocking effects. Mobile relaying exploiting possible two-hop line-of-sight connections is a strong candidate for coverage extension and consistent user experience in mmWave networks. Here, relaying based on opportunistic analog beamforming is investigated, and sets of fixed beams are used for cell discovery, relay discovery and data transmission. A low-complexity relay & beam discovery and selection protocol is considered. Communication performance and signaling overhead are estimated. To provide good relaying performance for cell-edge users without introducing high relaying overhead, a relay candidate set is selected by choosing a proper size, and suitable membership based on a utility function. Simulation results show that with relay candidate sets having a proper size, opportunistic two-hop mmWave relaying can achieve both high mean user performance and consistent user experience.**

I. Introduction

Mobile data traffic and the number of connected devices are predicted to grow exponentially in the 5G era. High user throughput with consistent user experience is a fundamental requirement for 5G [1]. Further network densification by using millimeter-wave (mmWave) with directional transmissions, is crucial to fulfill this requirement. However, mmWave communications suffer from pathloss and blockage problems [2], [3]. It is estimated that an inter-site distance (ISD) of $75–100\,m$ is required for full mmWave coverage [4]. Extreme densification of mmWave networks leads to high deployment cost and may not be a commercially optimal solution in future.

One way for mmWave networks to provide coverage and consistent user experience is to introduce mobile relaying technologies [5], by utilizing the mobile mmWave devices such as vehicles. Multi-hop mmWave relaying has been considered in [6] where a stochastic geometry approach was used to capture the statistical effects of density and size of obstacles. The analysis shows that multi-hop relaying can improve connectivity. Recently, the performance of relay-aided mmWave networks was investigated in [7], where it was shown that deploying relays in mmWave networks can increase the coverage probability and transmission capacity.

In this paper, we concentrate on protocol aspects of mmWave relaying, in a setting with opportunistic mobile relaying. We consider the discovery and selection problems for both relays and beams in multi-cell mmWave two-hop downlink networks. We consider switched beam analog beamforming (ABF) [8] where a fixed set of beams is adopted to provide directional transmission. Using such mmWave beams for communications poses challenges for network control functions such as cell discovery and initial access [9], [10]. Introducing two-hop relaying in mmWave networks complicates network control, as new control functions for relay discovery and selection [11], beam discovery and selection [12] have to be supported. There is a tradeoff between relaying overhead and performance in cooperative networks [11]. Overhead problems are exacerbated in mmWave cooperative networks since relay discovery is based on directional beamforming. We propose a low-complexity relay & beam discovery and selection protocol for two-hop mmWave downlink relaying. Practical mmWave propagation models are used, including pathloss and multi-path channel models, as well as one-hop line-of-sight (LOS) and two-hop LOS probabilities. The protocol is designed to exploit the two-hop LOS connectivity to boost throughput performance for user equipments (UE) in one-hop mmWave outage. It controls the relaying overhead by maintaining a set of relay candidates with a limited size. Using a utility measure which characterizes the quality of relay candidate sets, a selection algorithm is proposed to maintain the candidate set.

The rest of the paper is organized as follows. Section II describes the network scenario, mmWave channel models and the analog beamforming. Relay & beam discovery and selection protocol, and signaling overhead estimation are shown in Section III. The selection of relay candidate set is shown in IV. Simulation results are given in Section V, and conclusions are presented in Section VI.

II. System Model

A. Network Scenario

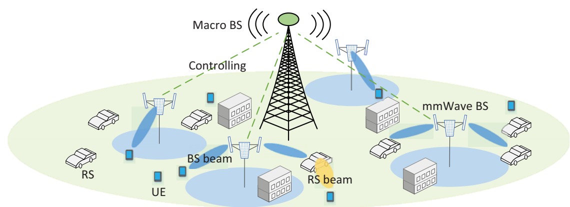


Fig. 1. Network scenario

We consider an ultra-dense network (UDN) with multiple mmWave BSs and mobile relay stations (RS), as depicted in Figure 1. The mmWave UDN is covered and controlled by a sub-6GHz macro cellular network (e.g. LTE-A). Each mmWave BS has three uniform planar arrays (UPA) with

M patch antennas. Each mobile RS has a mmWave uniform circular array (UCA) with N antennas and UEs have one mmWave antenna. RSs and UEs are assumed to be uniformly distributed in the network. For a mmWave cell, the set of all active UEs is denoted by $\mathcal{U}$, the set of all RSs by $\mathcal{R}_0$, and the set of all downlink LOS RSs by $\mathcal{R}_{\text{los}}$.

B. Pathloss and LOS/NLOS/Blockage models for mmWave

Compared to current cellular frequencies, the pathloss in mmWaves is approximately $20-25\text{dB}$ higher [2]. MmWave links are vulnerable to blocking from obstacles, such as buildings, foliage and human bodies. Due to high penetration loss and lack of diffraction, the mmWave pathloss is estimated to be 20dB higher in Non-Line-of-Sight (NLOS) than in LOS [2], [3]. In addition to LOS and NLOS conditions, there is a high probability that a mmWave link is totally blocked, or in outage [2]. Assuming that the mmWave link distance is d, the LOS/NLOS/Outage model is [2]:

$$\begin{aligned} p_{\text{out}}(d) &= \max(0, 1-e^{-a_{\text{out}}d+b_{\text{out}}}) \ , \\ p_{\text{los}}(d) &= (1-p_{\text{out}}(d))e^{-a_{\text{los}}d} \ , \\ p_{\text{nlos}}(d) &= 1-p_{\text{out}}-p_{\text{los}}(d). \end{aligned} \tag{1}$$

Furthermore, the model for distance dependent mmWave pathloss is [2]:

$$L(d) = \begin{cases} \beta_{\text{los}}\,\chi_{\text{los}}\,d^{\alpha_{\text{los}}} & \text{if in LOS condition,} \\ \beta_{\text{nlos}}\,\chi_{\text{nlos}}\,d^{\alpha_{\text{nlos}}} & \text{if in NLOS condition,} \\ \infty & \text{if in Outage condition.} \end{cases} \tag{2}$$

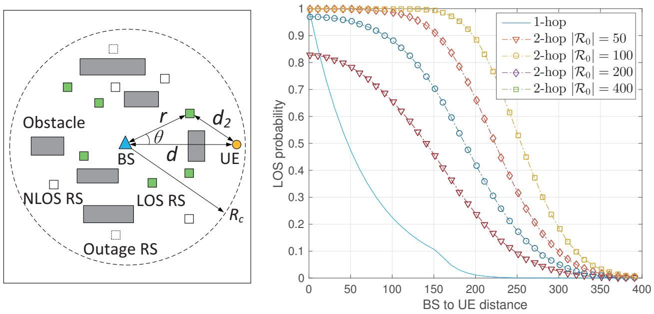
where β_{los} and β_{nlos} are pathloss constants, α_{los} and α_{nlos} are pathloss exponents. Log-normal shadowing is modeled by the coefficients $\chi_{\text{los}} \sim \ln\mathcal{N}(0, \sigma^2_{\text{los}})$ and $\chi_{\text{nlos}} \sim \ln\mathcal{N}(0, \sigma^2_{\text{nlos}})$. Information on mmWave pathloss, governed by LOS/NLOS/Outage conditions, is crucial for the network scheduler to allocate mmWave resources to UEs or RSs. We assume that BSs, RSs and UEs can perform LOS identification using e.g. the Kurtosis method [13].

C. Two hop LOS probability

The key idea in mmWave two-hop relaying is to create a two-hop LOS route between the source and destination when there is no one-hop LOS connection. Two-hop LOS probability can be analyzed based on the one-hop LOS probability model in [2]. Consider a mmWave cell depicted in Figure 2(a), modeled as a disk with radius R_c. The distance between source BS and destination UE is d. There are $|\mathcal{R}_0|$ RSs in the cell. Denote the link condition between nodes i and j by $\xi(i,j) \in \{0,1,2\}$, where $\xi(i,j) = 0$ indicates a LOS condition, and $\xi(i,j) = 1$ a NLOS condition, $\xi(i,j) = 2$ an outage condition. Assuming that RSs are independently and randomly distributed inside the cell, and LOS conditions for all paths are independent, the two-hop LOS probability between BS and UE with distance d is

$$\begin{aligned} p_{2\text{los}}(d) &= 1-\prod\nolimits_{j=1}^{|\mathcal{R}_0|}\mathbb{P}\Big(\xi(b,j)\neq 0 \text{ or } \xi(j,k)\neq 0\Big) \\ &= 1-\left(\int_0^{2\pi}\!\!\int_0^{R_c}\frac{r}{\pi R_c^2}\left(1-p_{\text{los}}(r)p_{\text{los}}(d_2)\right)dr d\theta\right)^{|\mathcal{R}_0|} \end{aligned} \tag{3}$$

where $d_2 = \sqrt{r^2+d^2-2rd\cos\theta}$. Figure 2(b) shows the two-hop LOS probability $p_{2\text{los}}(d)$ with $R_c = 250\,m$ and different $|\mathcal{R}_0|$. Two hop LOS probability is higher than one-hop, and increases as the density of RSs increases. MmWave relaying can exploit these two-hop LOS conditions by selecting LOS RSs to increase end-to-end (E2E) throughput for UEs.



(a) (b)

Fig. 2. Twp-hop LOS probability in a circular cell.

D. Channel Model and Analog Beamforming for LOS Links

There are three types of links in the network: BS-to-UE, BS-to-RS and RS-to-UE links. We assume opportunistic switch-beam single stream analog beamforming (ABF) [8], with a fixed set of mmWave beams for both transmission and reception. Each BS has L_{BS} beams and each RS has L_{RS} beams. Compared to multi-stream massive-MIMO transmission, the channel estimation overhead for ABF with fixed beams is reduced since the mmWave transmitter and receiver only need to find the best beam pair to increase the signal-to-interference-plus-noise ratio (SINR).

The channel is modeled using array response vectors (ARV) $\mathbf{a}_{\text{B}}(\theta,\phi)$ for the BS, and $\mathbf{a}_{\text{R}}(\theta,\phi)$ for RS, where θ and ϕ are the azimuth and elevation angles. The received signal at $\text{UE}_k \in \mathcal{U}$ from the mmWave BS is

$$y_k = \mathbf{h}_k^{\text{H}}\mathbf{x} + v_k + n_k, \tag{4}$$

where $\mathbf{x}$ is the $M \times 1$ transmitted signal with power $\|\mathbf{x}\|^2 = P_{\text{BS}}$, v_k is the aggregate interference from other cells, and n_k is the background noise. With a possible dominant specular LOS path, and L NLOS scattering paths, the MISO downlink channel is

$$\mathbf{h}_k = \frac{a_{k,0}\mathbf{a}_{\text{B}}(\theta_k^0,\phi_k^0)}{d_k^{\alpha_{\text{los}}/2}} + \sum_{l=1}^{L}\frac{a_{k,l}\mathbf{a}_{\text{B}}(\theta_k^l,\phi_k^l)}{d_k^{\alpha_{\text{nlos}}/2}}, \tag{5}$$

where $a_{k,0}, a_{k,l}$ are channel coefficients, and $\alpha_{\text{los}}, \alpha_{\text{NLOS}}$ the pathloss exponents for the LOS and NLOS components. Path-specific azimuth and elevation angles are used. For simplicity, we consider a 2-D approximation for the mmWave channel by assuming that elevation angles for all LOS paths are zero. For LOS links, the effect of NLOS paths is marginal [3]. Thus, we can approximate the mmWave LOS channel as

$$\mathbf{h}_k \approx \frac{a_{k,0}\mathbf{a}_{\text{B}}(\theta_k^0, 0)}{d_k^{\alpha_{\text{los}}/2}}, \tag{6}$$

Similarly, in LOS, the received signal $y_{k,j}$ for UE$_k$ from a RS$_j \in \mathcal{R}_{\text{los}}$ and received signal $\mathbf{y}_j$ for RS$_j$ from a mmWave BS are

$$y_{k,j} = \mathbf{h}_{k,j}^{\mathrm{H}} \mathbf{z} + v_k + n_k, \quad \mathbf{y}_j = \mathbf{H}_j^{\mathrm{H}} \mathbf{x} + \mathbf{v}_j + \mathbf{n}_j, \tag{7}$$

where $\mathbf{z}$ is $N \times 1$ dimensional relayed signal with power $\|\mathbf{z}\|^2 = P_{\text{RS}}$, $\mathbf{v}_j$ and $\mathbf{n}_j$ are interference and noise at RS j, and the channels are

$$\mathbf{h}_{k,j} \approx \frac{a_{k,j,0} \mathbf{a}_{\text{R}}(\theta_{k,j}^0, 0)}{d_{k,j}^{\alpha_{\text{los}}/2}}, \; \mathbf{H}_j \approx \frac{a_{j,0} \mathbf{a}_{\text{B}}(\theta_j^0, 0) \mathbf{a}_{\text{R}}^{\mathrm{H}}(\psi_j^0, 0)}{d_j^{\alpha_{\text{los}}/2}}, \tag{8}$$

where ψ_j^0 is the azimuth Angle of Arrival (AoA) from BS to RS.

Each mmWave BS has a codebook of beams $\mathcal{B} = \{\mathbf{b}_{(1)}, \ldots, \mathbf{b}_{(L_{\text{BS}})}\}$ with $\|\mathbf{b}_{(m)}\| = 1$, and each RS a codebook of beams $\mathcal{W} = \{\mathbf{w}_{(1)}, \ldots, \mathbf{w}_{(L_{\text{RS}})}\}$ with $\|\mathbf{w}_{(n)}\| = 1$. The received power at UE$_k$ on BS beam $\mathbf{b}_{(m)}$ is

$$P_k = \|\mathbf{h}_k^{\mathrm{H}} \mathbf{b}_{(m)}\|^2 \|\mathbf{x}\|^2 \approx P_{\text{BS}} G_k \|\mathbf{a}_{\text{B}}^{\mathrm{H}}(\theta_k^0, 0) \mathbf{b}_{(m)}\|^2, \tag{9}$$

where $G_k = \|a_{k,0}\|^2 d_k^{-\alpha_{\text{los}}}$ is the path gain. Here we see the ABF power gain on $\mathbf{b}_{(m)}$ is $\|\mathbf{a}_{\text{B}}^{\mathrm{H}}(\theta, 0) \mathbf{b}_{(m)}\|^2$.

Similarly, the received power at UE$_k$ on beam $\mathbf{w}_{(n)}$ of RS$_j$ in terms of a RS-to-UE path gain $G_{k,j} = \|a_{k,j,0}\|^2 d_{k,j}^{-\alpha_{\text{los}}}$ and an ABF power gain is

$$P_{k,j} = \|\mathbf{h}_{k,j}^{\mathrm{H}} \mathbf{w}_{(n)}\|^2 \|\mathbf{z}\|^2 \approx P_{\text{RS}} G_{k,j} \|\mathbf{a}_{\text{R}}^{\mathrm{H}}(\theta_{k,j}^0, 0) \mathbf{w}_{(n)}\|^2 \; . \tag{10}$$

Finally, the received power at RS$_j$ on BS beam $\mathbf{b}_{(m)}$ with a RS receive beam $\mathbf{w}_{(n)}$ is

$$\begin{aligned} P_j &= \|\mathbf{w}_{(n)}^{\mathrm{H}} \mathbf{H}_j^{\mathrm{H}} \mathbf{b}_{(m)}\|^2 \|\mathbf{x}\|^2 \\ &= P_{\text{BS}} G_j \|\mathbf{a}_{\text{R}}^{\mathrm{H}}(\psi_j^0, 0) \mathbf{w}_{(n)}\|^2 \|\mathbf{a}_{\text{B}}^{\mathrm{H}}(\theta_j^0, 0) \mathbf{b}_{(m)}\|^2, \end{aligned} \tag{11}$$

with $G_j = \|a_{j,0}\|^2 d_j^{-\alpha_{\text{los}}}$ the BS-to-RS path gain.

For the three kinds of links, the spectral efficiency is assumed to be given by the Shannon mapping with an implementation loss γ_{eff} for SINR,

$$\rho = \min\left(\log_2\left(1 + \gamma_{\text{eff}} \frac{P}{I + N_0}\right), \rho_{\max}\right), \tag{12}$$

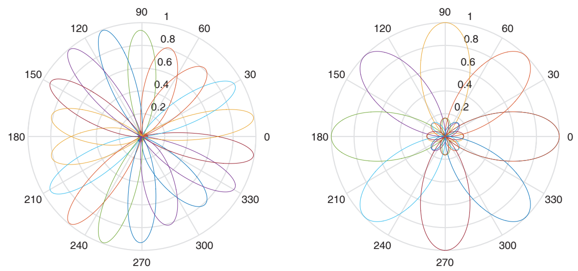
where P is the received signal power with ABF, N_0 is the noise power and I is the interference power. Interference powers on mmWave bands are typically much smaller than the noise power due to directional isolation [2], [4].

E. Design of mmWave Beams

To avoid mismatch [14] between the discoverable area and the actual supportable area of mmWave transmission, we assume that mmWave BSs and RSs use the same beam codebook for beam discovery and data transmission. For proper coverage performance, the number and half-power bandwidths (HPBW) of the beams need to be carefully designed. Differing from [7] where a simplified flat-top beam pattern is used, we consider accurate beam patterns. Beam patterns can be designed by adjusting the antenna element spacing, the number of the elements, the geometric structure of the array and the excitation phase vector (i.e. the beam codebook). We use $\mathbf{b}_{(m)} = \mathbf{a}_{\text{B}}(\theta_{(m)}, 0)$ and $\mathbf{w}_{(n)} = \mathbf{a}_{\text{R}}(\theta_{(n)}, 0)$, with $\theta_{(m)}$ and $\theta_{(n)}$ as the main-lobe pointing directions. Assuming the pointing directions are evenly spaced from 0 to 2π, to provide full angular domain coverage, the number of beams N_L and the HPBW $b_{3\text{dB}}$ should satisfy

$$N_L b_{3\text{dB}} \geq 2\pi \; . \tag{13}$$

The beam discovery overhead is proportional to N_L as more discovery signals need to be transmitted with more beams. The beamforming gain is typically smaller with wider HPBW. According to (13), there is a tradeoff between beam discovery overhead and beamforming gain. To provide high beamforming gain, we need more beams to cover the angular domain. As beam discovery and selection overhead is large in mmWave networks [9], [10], we need to limit the number of beams for both BS and RS. Figure 3 shows the beams designed for BS and RS.



(a) BS beams, $L_{\text{BS}} = 18$ (b) RS beams, $L_{\text{RS}} = 8$

Fig. 3. Normalized Beam Patterns at Horizontal Plane with $\phi = 0$

III. Protocol for mmWave Relay & Beam Selection and Overhead Estimation

A. LOS and beam coherence times

In the considered mmWave networks, we use directional beamforming for network discovery [10] and data transmission. Although directional beamforming can compensate the high pathloss in mmWave bands, it increases network management overhead because directional discovery signals must be transmitted multiple times to cover the angular domain. In addition to this scanning overhead, the high carrier frequency of mmWave bands results in small channel coherence time, which requires mmWave pilot signals to be transmitted very frequently in order to perform channel estimation when mmWave links want to adopt multi-stream MIMO transmission. Considering $f_{\text{c}} = 28$ GHz and the RSs speed $v_{\text{RS}} = 30$ km/h, the channel coherence time is $T_{\text{c}} \approx 600\,\mu$s. However, for single-stream ABF in LOS, the LOS component is strong, and channel variation caused by multi-path effects is small. In addition to traditional channel coherence time, we consider a LOS coherence time T_{los} and a beam coherence time T_{b} for ABF transmissions on LOS links.

The LOS coherence time is the time interval during which the LOS condition remains unchanged. It depends on the minimum spatial range $d_{\rm los}$ of a LOS area surrounding a receiver, and is $T_{\rm los}=\frac{d_{\rm los}}{2v}$, where v characterizes the speed of the receiver and/or transmitter. The beam coherence time is the time interval during which the optimal beam for a link is unchanged. It depends on the beam width $b_{\rm 3dB}$ and link distance d as $T_{\rm b}=\frac{b_{\rm 3dB}d}{2v}$. For example, with $d_{\rm los}=2$ m, $d=10$ m, $b_{\rm 3dB}=\frac{\pi}{8}$, and $v=30$ km/h, we have $T_{\rm los}\approx 120$ ms and $T_{\rm b}\approx 236$ ms. For static RSs (e.g. parked cars), LOS and beam coherence times would be longer, and depend only on the changes in blocking in the environment.

The LOS condition, which has a strong effect on the capacity of a link, is thus significantly more stable than the small scale channel caused by multi-path effects. ABF would use the same TX/RX beams during the LOS and beam coherence times without accounting for the small-scale channel variation due to multi-path effect. In this respect, ABF is similar to long-term beamforming scheme used in [2].

B. Relay & beam discovery and selection

The goal of a relay & beam discovery protocol is to discover the LOS relays timely and find the optimal beams. The relay & beam discovery protocol must be able to track the LOS conditions well within the LOS and beam coherence times. In this regard, the signaling period for relay discovery should be in the order of 10 ms. In addition, to be detected by RSs or UEs, the discovery signals transmitted by the BSs and RSs must have a proper duration on time domain [9], which is long enough for RSs or UEs to detect the presence of the signals and decode the corresponding BS ID, relay ID, or beam ID.

Two kinds of discovery signals are used in the network. Directional Search Signals for BSs (BS-DSS) are transmitted by each BS using period $T_{\rm b}$ with time duration $t_{\rm b}$, and Directional Search Signals for RSs (RS-DSS) are transmitted by selected RS candidates using period $T_{\rm r}$ and time duration $t_{\rm r}$. RSs and UEs will monitor BS-DSSs from neighboring BSs, whereas UEs and BSs will monitor RS-DSS transmitted by RS candidates. BS-DSS is used for downlink LOS identification performed by RSs or UEs, RS-DSS is used for LOS identification on RS-to-UE link performed by UEs, and for mobility identification and AoA estimation performed by BSs. Similar to Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS) in LTE, each BS periodically transmits BS-DSS so that RSs and UEs can scan for to detect the presence of the BS and to estimate the link conditions to/from the BS. However, BS-DSSs are transmitted on narrow mmWave beams and must be transmitted multiple times to cover the angular domain. UEs and RSs have to estimate the best BS beam and inform the selected beam to the BS.

Using BS-DSS and RS-DSS, the procedure of relay & beam discovery and selection protocol is:

1) Each BS transmits BS-DSSs using $T_{\rm b}$, $t_{\rm b}$ and a beam sequence $\mathcal{B}$. All RSs and UEs monitor BS-DSSs, and estimate the best BS beam and the corresponding mmWave BS. Each RS performs directional scanning using a beam sequence $\mathcal{W}$ and estimates the best RS beam for reception. RSs in LOS indicate to the BS by feedback that they are in LOS. All UEs transmit feedback indicating LOS/NLOS/outage condition to the BS. If the mmWave connection is poor or absent, sub-6GHz channel can be used for feedback.
2) Each BS maintains a RS candidate set $\mathcal{R}_{\rm c}\subseteq\mathcal{R}_{\rm los}$ considering the utilities and dissimilarities of the LOS RSs. Initially, all RSs in LOS are in this set. The BS updates the set by adding new RSs and deleting bad RSs which provide low utility. The BS broadcasts candidate set information and time-slot synchronization information to the RSs in the set. Orthogonal time slots will be allocated to the RS candidates for their transmission of RS-DSSs.
3) According to the time-slot synchronization information, each RS in the candidate set transmits RS-DSSs using $T_{\rm r}$, $t_{\rm r}$ and a beam sequence $\mathcal{W}$. The BS monitors RS-DSSs from the candidate RSs and estimates the pathloss L_j and channel covariance v_j for each ${\rm RS}_j\in\mathcal{R}_{\rm c}$. UEs in downlink NLOS/Outage conditions monitor these RS-DSSs to perform RS-to-UE link LOS identification, estimation of best RS beam. UEs report LOS and RS beam information to the BS via the feedback channel.
4) BSs performs relay selection and resource scheduling for the three kinds of links according to the estimated link capacities and a fairness metric. Scheduling decisions are transmitted to the selected RSs to perform beamforming reception for the first hop from BS to RS, and beamforming transmission for the second hop from RS to UE.

C. Overhead estimation for relay & beam selection

We define the signalling overhead as the portion of time-domain resources that are used for relay & beam discovery and selection. The $L_{\rm BS}$ BS beams and the $L_{\rm RS}$ RS beams must be transmitted during periods with durations $T_{\rm b}$ and $T_{\rm r}$ respectively. For one mmWave cell, there are $N_{\rm los}=|\mathcal{R}_{\rm los}|$ RSs in LOS and $N_{\rm c}=|\mathcal{R}_{\rm c}|$ RSs in the candidate set, with $N_{\rm c}\leq N_{\rm los}$. The signalling overhead for BS-DSSs is $L_{\rm BS}t_{\rm b}/T_{\rm b}$, and for RS-DSSs is $L_{\rm RS}N_{\rm c}t_{\rm r}/T_{\rm r}$. The total signalling overhead is thus

$$\eta=\frac{L_{\rm BS}t_{\rm b}}{T_{\rm b}}+\frac{L_{\rm RS}N_{\rm c}t_{\rm r}}{T_{\rm r}}. \tag{14}$$

We use $t_{\rm b}=t_{\rm r}=10\mu$s [9] which are much smaller than the channel coherence time, and $T_{\rm b}=T_{\rm r}=10$ms which are much smaller than $\min(T_{\rm los},T_{\rm b})$ to ensure that the protocol can track the LOS condition and the best LOS beam. The overhead is linear in N_c and is quite significant when $N_c>10$.

When there are many RSs in the network, there is a tradeoff between increasing two-hop LOS probabilities for outage/NLOS UEs and reducing signaling overhead for relay selection.

IV. Selection of RS Candidate Set

To exploit the benefit of two-hop LOS transmission for outage/NLOS UEs and to reduce the discovery overhead, we need find a set of RS candidates $\mathcal{R}_{\rm c}$ which is optimal for the population of outage/NLOS UEs. For this, we use a relay utility function and a dissimilarity metric. The number of active relays $|\mathcal{R}_c|$ is limited to be smaller than a parameter $N_{\max}$ set by a central controller at the macro BS. The relay utility function evaluates the quality of a downlink LOS RS, and the dissimilarity metric evaluates the redundancy of the RS candidate set $\mathcal{R}_c$. The set size $N_{\max}$ is also parameter to be optimized.

A. Relay Utility and Dissimilarity Metric

Each downlink LOS RS has an estimated utility which characterizes its probability to be a favorable relay for the population of outage/NLOS UEs. An optimal measure characterizing the quality of a RS candidate set is vital for selection of RS candidates, and is a non-trivial task. Basically, a proper RS candidate set should be able to cover the outage areas (i.e. RS candidate set has high spatial dispersion) and give priority to cell-edge outage UEs.

Note that the outage/NLOS probability increases with the link distance. Most of the outage/NLOS UEs are at the cell edge. A natural relay utility is the distance between a downlink LOS RS and its serving BS. A downlink LOS RS with a larger downlink pathloss has a higher probability to be a favorable relay than one with a smaller downlink LOS pathloss. Based on the measured pathloss, a simple relay utility function can be defined as

$$u(j) \triangleq [L_j/\beta_{\text{los}}]^{1/\alpha_{\text{los}}}, \ \text{RS}_j \in \mathcal{R}_{\text{los}}. \tag{15}$$

The applied dissimilarity metric between two RSs is based on the difference between their AoAs and pathlosses, as seen at the BS. Two RSs in the same beam with similar path loss are similar. For $\text{RS}_i, \text{RS}_j \in \mathcal{R}_{\text{los}}$ with BS beams b_i, b_j and downlink pathlosses L_i, L_j, we define a dissimilarity metric

$$s(i,j) \equiv \mathbb{1}\Big(b_i \neq b_j\Big) + \mathbb{1}\Big(|u(i) - u(j)| > d_{\min}\Big) \tag{16}$$

where $\mathbb{1}(A) = 1$ if A is true, and else $\mathbb{1}(A) = 0$. For an N-element RS candidate set $\mathcal{R}_c \subseteq \mathcal{R}_{\text{los}}$, we can compute a $N \times 1$ utility vector $[u(j)]$ and an $N \times N$ dissimilarity metric matrix $[s(i,j)]$. To measure the quality of candidate set $\mathcal{R}_c$, we consider the heuristic utility function

$$U(\mathcal{R}_c) = \sum_{i,j} \left(\frac{s(i,j)}{2} + 1\right) \frac{u(i) + u(j)}{2}. \tag{17}$$

This is the sum of relay utilities with dissimilarity coefficients. Each RS candidate in $\mathcal{R}_c$ contributes to the overall set utility. Other relay utility functions, dissimilarity metrics and candidate set utility functions may be used.

B. RS Candidate Set Selection Algorithm

Using the RS candidate set utility function $U(\mathcal{R}_c)$, a candidate selection algorithm can be run at mmWave BS controllers to reduce the discovery overhead by selecting a proper set $\mathcal{R}_c$ with at most $N_{\max}$ elements. Algorithm 1 computes the utility contribution of each RS in the set, and greedily removes the least useful to reduce size of the set step-by-step. This method is compared to a random selection of $N_{\max}$ RSs out of N_{los} RSs in simulation.

Algorithm 1 RS candidate set selection algorithm

```
1: R_c ← R_los, R_c = {RS_{c_1}, ..., RS_{c_N}} with N = N_los
2: while N > N_max do
3:     Δ ← [0, ..., 0]_{1×N}
4:     for k ← 1 to N do
5:         Δ[k] = U(R_c) − U(R_c \ RS_{c_k})
6:     end for
7:     [Δ_min, k*] ← min(Δ), R_c ← R_c \ RS_{c_{k*}}, N ← N − 1
8: end while
```

V. Simulation Results

To assess the performance of the considered two-hop mmWave relaying protocols, system simulations have been performed. Details of the mmWave channel models and some parameters used in the simulation are shown in Table I. The maximum size of the RS candidate set is set to be $N_{\max} =$ 0, 10, 20, 30 or 40. In the simulated scenario, only one third of UEs have direct LOS connection to BSs. If no coverage extension technique is adopted, the remaining two-thirds of the UEs would suffer from low throughput. Compared to one-hop LOS, the number of two-hop LOS UEs increases dramatically when relaying is available. When $N_{\max} = 10$, 86% of the UEs can find a two-hop LOS connection to BSs, and almost all UEs have a two-hop LOS connection when $N_{\max} \geq 20$.

Figure 4 shows the performance of two-hop relaying when the RS and beam selection protocol and RS candidate set selection algorithm are applied with different settings of $N_{\max}$. Without mmWave relaying ($N_{\max} = 0$), 35% of the UEs enjoy E2E throughput larger than 200 Mbps, while the 52% of the UEs that are in Outage/NLOS have E2E throughput smaller than 20 Mbps. A mmWave network with ISD = 250 m cannot provide full coverage and consistent user experience. Compared to case without relaying, two-hop relaying with $N_{\max} = 10$ increases the percentage of UEs with E2E throughput larger than 200 Mbps to 70%, and decreases the percentage of UEs with E2E throughput smaller than 20 Mbps to 12%. Increasing $N_{\max}$ further improves cell-edge performance, with $N_{\max} = 30$, only 2% of the UEs have

TABLE I
SYSTEM-LEVEL SIMULATION PARAMETERS

Parameter	Setting
mmWave network deployment	4×4 square cells with ISD=250 m
Average number of UEs/RSs	10 UEs per cell, 100 RSs per cell
mmWave frequency/bandwidth	28 GHz/1GHz
mmWave pathloss model	$\alpha_{\text{los}}=61, \beta_{\text{los}}=2, \sigma_{\text{los}}=6$dB $\alpha_{\text{nlos}}=72, \beta_{\text{nlos}}=3, \sigma_{\text{nlos}}=9$dB
LOS/NLOS/Outage model	$a_{\text{out}}=1/30, b_{\text{out}}=5.2, a_{\text{los}}=1/67$
LOS correlation distance	10 m
Number of mmWave antennas	BS: 8×8 elements planar array RS: 16 elements circular array
Maximum mmWave TX power	BS: 30 dBm , RS: 24 dBm
Number of mmWave beams	BS: 18, RS: 8
Resource scheduling for UEs	Proportional Fairness
Resource partition for relaying with capacities $\rho_{\text{1st}}, \rho_{\text{2nd}}$	$\rho_{\text{2nd}}/(\rho_{\text{1st}}+\rho_{\text{2nd}})$ for 1st hop, $\rho_{\text{1st}}/(\rho_{\text{1st}}+\rho_{\text{2nd}})$ for 2nd hop.

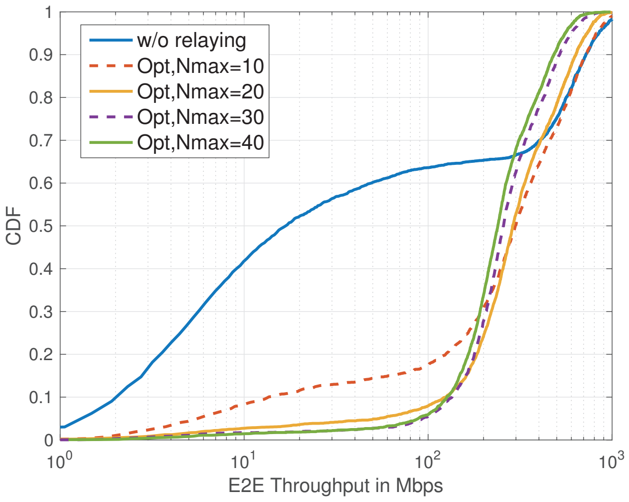


Fig. 4. CDF of E2E throughput. Different relay set sizes $N_{\max}$.

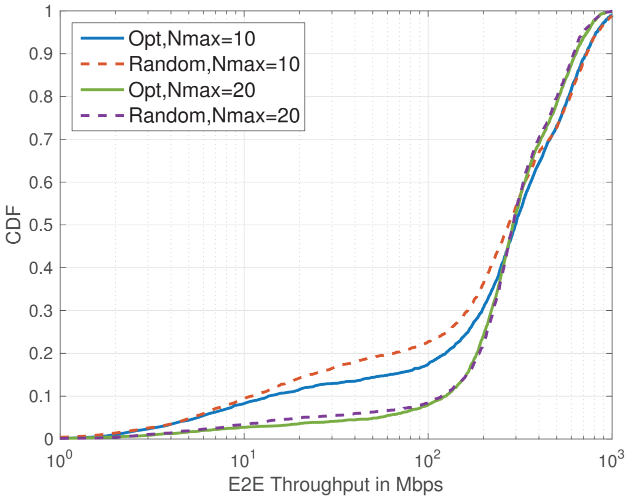


Fig. 5. CDF of E2E throughput. Random vs. optimized relay subset selection.

throughput smaller than 20 Mbps.

As the number of RS candidates increases, the overhead for mmWave relaying also increases, and the resources used for data transmissions decreases. The mean throughput starts to drop when $N_{\max} \geq 30$. The results show that $N_{\max} = 20$ provides the best overall network performance considering both mean and the cell-edge throughput. Comparisons between the candidate set selection Algorithm 1 and random candidate selection are shown in Figure 5 for $N_{\max} = 10, 20$. For small $N_{\max}$, Algorithm 1 can provide significantly better performance than random selection. As $N_{\max}$ increases, the performance of the two methods become similar. As the number of available LOS RS candidates is limited, there is no space for candidate set optimization when almost all candidate relays are selected.

VI. Conclusion

We have considered using relaying technology in mmWave networks for coverage extension and consistent user experience. Opportunistic analog beamforming with fixed beam sets is considered for both directional network discovery and data transmission. Beamforming increases the cell discovery and relay discovery overheads for mmWave networks. A low-complexity relay & beam discovery and selection protocol is proposed and its overhead is estimated. To provide good relaying performance for users in mmWave outage without introducing high relaying overhead, we consider selection of a relay candidate set by choosing a proper size and by optimizing the relay set selection based on a utility function. Simulation results show that choosing a proper size for the relay candidate set is important to achieve both high mean user performance and consistent user experience.

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