Millimeter-Wave Device-to-Device Multi-Hop Routing for Multimedia Applications

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Abstract—Millimeter-wave (mm-wave) communication is a promising technology for the next generation cellular networks. Motivated by the huge available bandwidth at these bands, it can be used to support the fastest-growing demands for the mobile data traffic such as multimedia applications. However, there are some challenges on the network connectivity at the mm-wave frequency bands. The high path loss, the limited diffraction capability due to the short wavelength, and having difficulties in penetrating through solid materials necessitate the line-of-sight and multi-hop communication in mm-wave networks. In this paper, we develop a multi-hop routing protocol which maximizes the sum quality of the uncompressed high-definition video applications for the device-to-device connections. The quality is measured as a function of the rate in this paper. We take into account the unique characteristics of the mm-wave propagation in our model. Simulation results show that the proposed algorithm achieves the optimal solution for high cooperation probability. It is also verified by the simulation that our algorithm outperforms the max-min flow routing protocol solution.

I. INTRODUCTION

Demands for cellular data traffic have been growing exponentially in recent years. The future fifth generation (5G) cellular network is expected to provide high data rates for the end users and support multimedia applications with stringent quality of service (QoS) requirements. Towards this end, there is an increasing attention to the millimeter-wave (mm-wave) bands, where the available bandwidth is much wider than the traditional microwave frequencies (i.e., more than 200 times growth) [1]. However, there are significant technical challenges in the development of cellular networks in mm-wave bands that should be surmounted.

A distinguishing feature of mm-wave communications is that they are more sensitive to blockage than the signals in the lower frequency bands. For example, in [2], the authors mentioned 178 dB attenuation for brick wall. Moreover, the mm-wave signals have a limited ability to diffract around obstacles. Furthermore, Friis law indicates that the omnidirectional path loss increases at higher frequencies. To overcome these difficulties, multi-hop transmissions are receiving attention in mm-wave communication [3]-[6]. In addition, it is necessary to perform beamforming in order to overcome high path loss by array gain. It also helps reducing the interference level leveraging the spatial division multiplexing. Thus, the mm-wave communication can be used efficiently for low-range communications, such as indoor wireless networks, small cell transmissions, and device-to-device (D2D) connections. In [3], a multi-hop MAC protocol for a centralized wireless personal area networks (WPAN) at 60 GHz is proposed. It is shown that due to low-diffraction and high path loss at the mm-wave bands, it is imperative to introduce few relay nodes to maintain network connectivity. In [4], the authors designed a hop selection metric in mm-wave WPAN to improve network flow throughput. Then, a multi-hop concurrent transmission scheme is presented to avoid harmful interference. These ideas are extended into cellular and D2D communications. An effective resource sharing policy for non-interfering D2D links at the mm-wave bands is presented in [5]. It introduces global D2D connections that can be established by multi-hop transmissions via backbone network, between the two mobile phones associated with different cells. It includes device-to-base-station (D2B) communications and base station to base station (B2B) connections. The paper also discusses neighbor discovery for frequent handoffs in 5G mm-wave networks. To avoid undesirable non-line-of-sight (NLOS) high attenuation in D2D communications, multi-hop routing via mobile phones has been presented in [6]. However, it has not considered fading and interference. Note that employing multi-hop D2D by mobile phones is highly debatable because of battery limitations and secrecy issues. Thus, in this study, in addition to introducing cooperation probability ($P_{co}$) for mobile devices, we place preplanned relays to ensure the seamless line-of-sight (LOS) coverage when mobile phones are not willing to relay data. As shown in Fig. 1, by placing preplanned relays at some locations with LOS link accesses to mobile devices, the LOS range of the network can be expanded and we can bypass obstacles via relays. Such preplanned relays are prevalent in cellular networks [7].

In this paper, we study the mm-wave D2D multi-hop routing for multimedia applications. Exploiting the huge available bandwidth at the mm-wave bands, we only consider the uncompressed high definition (HD) video flow that is one of the most popular form of the mobile data traffic. In the literature, multi-hop routing protocols have various metrics including delay, security, fairness, and so forth. Particularly, maximization of sum rates, and maximization of minimum rate were widely used as the target functions. In contrast, in this study, we aim to maximize the sum video quality, which
is a concave function of the rates. The problem is formulated as mixed integer nonlinear programming (MINLP) that is very difficult to solve, even for small number of users. To overcome this difficulty, we propose a suboptimal algorithm, regarding the special characteristics of mm-wave propagations, namely directional transmission and different channel parameters for LOS and NLOS links. Finally, we verify the suboptimality of the proposed scheme, and compare the performance of the algorithm with max-min flow (MMF) routing protocol and a random policy.

The rest of the paper is organized as follows. In Section II, we describe the network reference model and assumptions. In Section III, the problem is formulated as an optimization problem. Then, we propose our suboptimal algorithm in Section IV. Simulation results and remarks are presented in Section V and the conclusion is drawn in Section VI.

II. SYSTEM MODEL

Consider a single cell scenario containing a set of UEs $U = \{U_1, \ldots, U_N\}$ and a set of preplanned relays $R = \{R_1, \ldots, R_M\}$, both are distributed uniformly within the area. All UEs and relays are equipped with steerable directional antennas and mm-wave transceivers. The relays are able to transmit or receive $k_r$ data streams simultaneously. Due to the cost and space limitations, each UE can transmit or receive only a single data stream. The data information flow between a source and destination is called a commodity. Assume there is a set of commodities $C = \{1, \ldots, c\}$ and each commodity is associated with a pair of source and destination $(s_c, d_c)$. Suppose each link can support at most one commodity. We denote routing matrix by $L$, where $L(i,j) = 1$, if node $i$ transmits data to node $j$, otherwise $L(i,j) = 0$.

The path loss in dB can be expressed as [8]

$$PL(d)[dB] = \alpha + \beta 10 \log_{10}(d) + \xi, \quad \xi \sim N(0, \sigma^2),$$

(1)

where $\alpha$ and $\beta$ are path loss parameters and $\sigma^2$ represents the variance of log-normal shadowing random variable, $\{\xi\}$. We utilize different parameters for LOS and NLOS conditions. Hence, we can state the pathloss gain of the channel as [9]

$$PL(d) = \mathbb{B}(p(d))PL_{LOS}(d) + (1 - \mathbb{B}(p(d)))PL_{NLOS}(d),$$

(2)

where $\mathbb{B}(x)$ is a Bernoulli random variable with parameter $x$ and $p(d)$ is the LOS probability function of a path of length $d$, which is explained in detail in continue.

Independent Nakagami fading is assumed for each link with parameters $N_L$ and $N_N$ for LOS and NLOS links, respectively [9]. Measurements have shown that at the mm-wave frequency bands, NLOS conditions adversely affect the small-scale fading [2]. Therefore, we consider a larger Nakagami parameter for LOS links corresponding to a smaller variance than NLOS links. The model can be further enhanced by introducing noise power in dB as

$$P_N[dB] = 10 \log_{10}(K_B T_r B) + NF,$$

(3)

where $K_B T_r$ is the noise power spectral density. According to [10], it is equal to -174dBm/Hz, $B$ is the channel bandwidth and $NF$ is the receiver noise figure.

The following assumptions are used in order to model the system.

1) LOS Probability Function: The longer paths are more likely to be obstructed by the objects. Thus, we use a non-increasing distance-dependant LOS probability function. We consider the negative exponential LOS probability function $p(d) = e^{-\gamma d}$, proposed in [11]. Parameter $1/\gamma$ determines the average LOS range of the network. Other LOS probability functions have been presented in [8].

Although in an actual case, the LOS probability of the neighbor links are not independent, in order to simplify our model, we further assume there is no correlation among geographically close links.

2) Directional Beamforming: Directional beamforming is a key feature of the mm-wave systems that can be exploited to obtain high array gains and spatial multiplexing to overcome extreme path loss at mm-wave frequency bands. To make the model more tractable, we approximate the actual array patterns by a sectored model [12]. We denote $M_{G,\theta,\phi}$ as the approximated antenna pattern. We assume different array gains and beamwidth for relays and UEs. Let $\theta_i$, $G_i$ and $g_j$ be respectively the beamwidth, main lobe and side lobe gain of node $i$. Let $D_{i,k}$ be the total directivity gain between nodes $i$ and $k$ $(i,k \in U \cup R)$. According to [9], $D_{i,k} = a_{mk}$ is a random variable with probability $b_m$, $m \in \{1,2,3,4\}$, where $a_{mk}$ and $b_m$ are constants presented in Table II. $c_i = \theta_i/2\pi$ and $c_k = \theta_k/2\pi$.

Shannon’s equation is considered for the data rate, as

$$C(i,j) = B \log_2(1 + SINR_{i,j}).$$

The received SINR at node $j$ is calculated as

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**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>$61.4$</td>
</tr>
<tr>
<td>NLOS</td>
<td>$12$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$2$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$2.92$</td>
</tr>
<tr>
<td>$\xi_{NLOS}$</td>
<td>$8.7$</td>
</tr>
<tr>
<td>$\xi_{LOS}$</td>
<td>$5.8$</td>
</tr>
<tr>
<td>$\gamma_{relay}$</td>
<td>$24.5$ dBi</td>
</tr>
<tr>
<td>$\gamma_{UE}$</td>
<td>$15$ dBi</td>
</tr>
<tr>
<td>$\theta_{relay}$</td>
<td>$10$</td>
</tr>
<tr>
<td>$\theta_{UE}$</td>
<td>$30$</td>
</tr>
</tbody>
</table>

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where $h_{i,j}$ is the Nakagami fading channel gain, $d_{i,j}$ is the distance between nodes $i$ and $j$, and $P_n$ represents the normalized noise power by the transmit power ($P_T$). This type of SINR modeling for mm-wave systems has been presented in [9] and [11].

### III. Problem Formulation

In this section, we formulate the problem of multi-hop routing for mm-wave D2D communications as an optimization problem. The set of links emanating from and terminating at node $k$ is denoted as $E(k)$ and $T(k)$, respectively. All the source nodes have data to transmit as

$$\sum_{l \in E(s_c)} l = 1, \quad \forall c \in C,$$

where $f_i^c$ stands for the flow on the $l^t$ link, corresponding to commodity $c$. Moreover, each flow is restricted by the link capacity. That is, we have

$$\sum_{l \in E(i)} f_i^c \leq C_l, \quad l \in E(i), T(j), \quad \forall c \in C. \quad (14)$$

In (14), $C_l$ represents the capacity of the link $l$, which is originated from node $i$ and terminated at node $j$, and $L(i,j) = 1$, if node $i$ transmits data to node $j$.

We assume only video-related applications. Thus, if the amount of the flow at a source node exceeds the amount of the required flow to achieve full quality, there will be no improvement on the video quality. Let $f_{req}^c$ denote the required flow of the commodity $c$ to reach full quality.

$$\sum_{l \in E(s_c)} f_i^c \leq f_{req}^c, \quad \forall c \in C. \quad (15)$$

The objective of this paper is to maximize the overall quality of multimedia applications in our model and provide a set of links satisfying the constraints (6)-(15). Mathematically, the objective can be defined as

$$\max_{f^c} \sum_{c \in C} Q_c(f^c), \quad (16)$$

where $Q_c$ is the quality function of the commodity $c$, which will be discussed in details in the following section.

### IV. MM-Wave D2D Multi-Hop Routing for Multimedia Applications

#### A. Multimedia Quality Model

One of the promising aspects of communication systems employing mm-wave is that they provide immense amount of bandwidth for the bandwidth-intensive applications. This property makes them well-suited for multimedia applications. Hence, we consider only video-related applications in this paper. The quality function for the HD video signals is a monotonically increasing function of the flow until the amount of flow reaches the required data rate, then it will be saturated [13]. The linear form of the quality function is the simplest model. It corresponds to the sum rate maximization problem, regarding the fact that the saturating part of the quality function prevents allocating more flow than required. The author in [14] has stated that, due to the inelasticity of the video streaming traffic, they are modeled by a family of non-concave quality functions, called $s$-curve [15]

$$U(f^c) = \frac{1 - e^{-C_1(f^c)^C_2}}{1 - e^{-C_1}}, \quad (17)$$

where $C_1$ and $C_2$ are constants depending on the video properties and encoder, and $r_c$ is the coding rate of the video source $c$. In this article, we use logarithmic utility functions, which is pertinent to uncompressed HD video transmission [13]. We define the quality function as

$$Q_c(f^c) = \frac{\log(f^c + 1)}{\log(f_{req}^c + 1)}.$$
Using (18) as the quality function, the problem will be an MINLP. In the literature, branch and bound is widely used to obtain optimal solution of MINLP [16]. Due to high computational complexity, we present a heuristic algorithm to obtain a suboptimal solution.

B. Proposed Solution

We assume that each link can pass at most one commodity. Moreover, involving few devices in a multi-hop D2D connection can improve the energy-efficiency and secrecy issues. Security can be enhanced by reducing exposure of the data information flow to fewer number of intermediate nodes. In addition, for each commodity, both source and destination are associated with a single base station. Thus, they are geographically close enough to communicate either directly or via a relay node to overcome the strict NLOS conditions.

We propose an alternative algorithm to solve the optimization problem (16), in a heuristic way. We denote $\hat{C}$ as the set of commodities with unassigned rate, and $\hat{R}(i,j)$ as the achievable data rate between the nodes $i$ and $j$ by single hop transmission (i.e., $\hat{R}(i,j)$ is equal to the capacity of the link unless the link is blocked).

While there are commodities with no assigned rate, we first identify the intermediate nodes that maximize the commodity data rates by two-hop transmission. Since the quality function is a non-decreasing function of rates, maximizing the data rates will maximize the quality function as well. Then, the quality value for each commodity is computed and we pick the commodity with the maximum quality to assign rate to that. If the achieved quality is higher than the quality with direct D2D transmission, the rate obtained by two-hop is assigned to the commodity flow. Otherwise, the source transmits directly to the destination. Note that UEs are able to support one commodity simultaneously. Therefore, if the helper node is a phone device, we remove the corresponding values of the node from $\hat{R}$. The above process continues until all commodities have rates allocated. In each iteration, the algorithm checks the achievable quality by the two-hop transmissions via each intermediate node for all the remaining commodities. One commodity flow is determined in each iteration. Hence, we need $|C|$ iterations and the total computational complexity of the algorithm is $O(|C|^2V)$, which is polynomial in $|C|$ and $V$, where $V$ is the number of intermediate nodes.

Algorithm 1 Routing and Rate Allocation

Input: $\hat{R}$

Output: $F = \{f_1, \ldots, f_c\}$

1: while $|\hat{C}| \neq 0$ do
2:    for $i = 1, \ldots, |\hat{C}|$ do
3:        find the node that maximizes quality of commodity $\hat{c}$
4:        $q_{\hat{c},j^*} = Q(\hat{R}(\hat{c},j^*))$
5:    end for
6:    find the maximum quality $Q_{\hat{c}^*,m^*} = \max(q_{\hat{c},j^*})$
7:    calculate direct D2D quality for commodity $\hat{c}^*$
8:    $f_{\hat{c}^*,dir} = \hat{R}(\hat{c}^*,d_{\hat{c}^*})$
9:    $Q_{\hat{c}^*,dir} = Q((\hat{R}(\hat{c}^*,dir))$
10: if $Q_{\hat{c}^*,m^*} \leq Q_{\hat{c}^*,dir}$ then
11:    $f_{\hat{c}^*} = \hat{R}^{\hat{c}^*,dir}$
12: else
13:    $f_{\hat{c}^*} = \hat{R}^{\hat{c}^*,m^*}$
14: end if
15: if node $m^*$ is fully occupied then
16:    remove corresponding values to node $m^*$ from $\hat{R}$
17: end while
Fig. 3. Comparison of the achieved quality between optimal solution and proposed scheme, differentiated cooperation probability.

Fig. 5. Total achieved quality of the proposed scheme, MMF and random policy.

Fig. 4. Comparison of the throughput of the optimal quality (TOQ) solution and the proposed algorithm, differentiated cooperation probability.

Fig. 6. Network flow throughput of the proposed scheme, MMF and random policy.

scheme with a random policy and MMF routing protocol, which is widely used to obtain a fair solution in this literature. In the random policy, each source either transmits directly to the desired destination or randomly selects an intermediate available node, who has LOS link accesses to both source and destination nodes, to run a two-hop transmission.

Fig. 3 illustrates the suboptimality of the proposed algorithm with various $P_{co}$ for mobile phones. It is shown that our algorithm achieves the optimal solution of (16) in low link failure probabilities. In Table III, the suboptimality of our algorithm for different $P_{co}$ are compared. It also can be seen in Fig. 3 that as $P_{co}$ decreases, the overall quality decays faster with link failure probability. This is because the fact that in the strict NLOS channel conditions, the mobile phones have LOS links only to their geographically close nodes. Therefore, if a source node is situated near a fixed relay, it can transmit data to that. Otherwise the formation of a LOS path connecting the source to the destination is contingent upon the participation of the intermediate mobile phones. Thus, in addition to fixed relays, cooperation of the intermediate phone devices can improve mm-wave network connectivity drastically.

As it is delineated in Fig. 4, our algorithm shows relatively close performance to the optimal solution of (16) in terms of network flow throughput. We compare the throughput of the network in the presence and absence of interference, $P_{co} = 1$. Short wavelength at mm-wave bands enables deployment of larger number of antennas in mobile devices. Then, beam-forming techniques can be used efficiently to direct transmit power, leading to lower level of interference than traditional microwave bands, where wireless devices transmit in an omnidirectional manner. In this study, we considered interference because according to the realistic antenna beamwidth for the
28 GHz band [2], they are not as narrow as previous studies in 38 GHz [6]. Although interference does not affect the total achieved quality significantly, it has a considerable impact on the network flow throughput. The reason is that the quality function is a concave (logarithmic) function of the flows, and the throughput is sum of the flows, therefore according to Jensen inequality, the quality function varies less than flow variations.

Simulation results in Fig. 5 and Fig. 6 demonstrate the superiority of our algorithm to MMF and random policy. Fig. 5 shows the overall achieved quality for the MMF solution and proposed algorithm. As $P_{co}$ decrease, our algorithm shows better performance than MMF. In MMF, the objective is to maximize the minimum flow, in order to attain a fair solution. Hence, in the strict NLOS conditions with high link failure probability, if there exists a source node who cannot find a LOS path to the destination, MMF aims to maximize that flow. If the source node is isolated from the network, it cannot transmit data to the destination and MMF algorithm simply fails. This is the reason of rapid decay of MMF solution with $P_{co} = 0$ in Fig. 5. On the other hand, our algorithm first identifies the commodity with the highest potential flow, and then maximizes quality for that commodity and it continues until all flows have been determined. Therefore, the algorithm tries to maximize all flows regardless of the amount of other flows. Fig. 6 illustrates that the proposed scheme outperforms MMF and random policy in terms of network flow throughput. In the case with $P_{co} = 1$, where MMF and the proposed algorithm obtain relatively the same quality, the difference between them is low in sum rates. However, when $P_{co} = 0$, as the link failure probability grows, the gap become larger and our algorithm reaches higher throughput than the MMF solution. In other words, MMF solution is more sensitive to the cooperation of intermediate nodes than our algorithm. This is because the fact that in the strict NLOS channel conditions where a source node has LOS link accesses only to its close nodes, cooperation of the neighbor nodes is imperative to form a LOS path. If these neighbor nodes do not serve as relays, the source node cannot transmit data to the destination, consequently MMF fails to work.

VI. CONCLUSION AND FUTURE WORKS

In this paper, we investigated the potential of mm-wave multi-hop D2D communications for multimedia applications with logarithmic utility function. First, the problem was formulated as an MINLP problem. Then, benefiting from the proximity of the source and destination in mm-wave D2D connections, we proposed a heuristic algorithm. Simulation results showed the suboptimality of the algorithm and superiority of our scheme to the MMF routing protocol, which is widely used for the application with stringent QoS requirements. Furthermore, the cooperation of intermediate phone devices can improve the achieved video quality drastically.

There are several directions for future works. The algorithm can be extended to consider the power allocation for energy-efficient routing protocols. Another direction is to determine the optimal location of preplanned relays while the video quality is maximized. In addition, the multicell scenario can be further investigated in future.

REFERENCES