See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/324771038

Exploiting Multi-Hop Relay to Achieve Mobility-Aware Transmission Scheduling in mmWave Systems

Conference Paper · April 2018

CITATIONS
0

READS
76

1 author:

Yong Niu
Beijing Jiaotong University
179 PUBLICATIONS **4,576** CITATIONS

SEE PROFILE

All content following this page was uploaded by Yong Niu on 27 September 2018.

The user has requested enhancement of the downloaded file.

Exploiting Multi-Hop Relay to Achieve Mobility-Aware Transmission Scheduling in mmWave Systems

Yu Liu*, Yong Niu†, Yong Li*, Ming Zeng*, Zhu Han‡
*Department of Electronic Engineering, Tsinghua University, Beijing, 100084, China
†State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China
‡Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77004 USA.
Emails: niuy11@163.com; liyong07@tsinghua.edu.cn

***Abstract*—With the explosive growth of mobile traffic, millimeter wave (mmWave) systems have gained considerable attention from both academia and industry. Although relaying and concurrent transmissions have been utilized to improve the system performance, dynamics due to human mobility are still challenges for mmWave systems. In this paper, we propose a high throughput service scheduling (HTSS) scheme, which exploits multi-hop relay and concurrent transmissions to enhance throughput with the consideration of human mobility. In HTSS, we develop a relay path planning algorithm to establish multi-hop relay paths, and then utilize a global time scheduling algorithm to compute transmission scheme to achieve mobility-aware optimization. Through extensive evaluations under realistic human mobility trajectories, we demonstrate the superior performance of HTSS in terms of the system throughput compared with the state-of-the-art schemes.**

I. Introduction

Mobile traffic demand is growing explosively. According to Cisco's report, global mobile data traffic grew 63% in 2016, and reached 7.2 exabytes per month at the end of 2016 [1]. Thus, the contradiction between capacity requirement and spectrum shortage becomes increasingly prominent. To address this challenge, mmWave communications with huge bandwidth from 30 GHz to 300 GHz have received considerable attention [2]. As a promising technology for the fifth generation (5G) mobile network, mmWave communications are committed to provide multi-gigabyte broadband communication services. To overcome high propagation loss in the mmWave band, directional antennas are utilized to achieve high antenna gains. Consequently, concurrent transmissions are also developed for capacity improvement [3].

On the other hand, human mobility is universal in mmWave systems, which poses several challenges for the user service. For instance, user mobility will influence the transmission efficiency. In real communication, the channel state always varies according to different transmission distances. When users' positions change, original transmission links for fixed positions become useless. As a result, the transmission paths have to be replanned. Moreover, the replanning usually takes much time, which has a serious impact on quality of service (QoS) guarantee. Overall, the transmission efficiency will decrease significantly due to user mobility. Therefore, ensuring high throughput service of users with the consideration of mobility becomes a critical challenge for mmWave systems.

Meanwhile, both trajectory prediction and reconstruction have been widely investigated in data mining [4]–[6], which provides great opportunities for mobility-aware transmissions. Based on various available information such as GPS locations [5] and cellular data [6], numerous solutions have been proposed. Especially, these methods significantly improve the accuracy of predicted or reconstructed trajectories, making users' trajectories available. It is worth noting that, one user's weekday lives (trajectories and events) are similar. For instance, in every weekday, students always have lessons in the classroom, then eat in the canteen. Trajectories as well as events time for weekdays are quite similar. For convenience, places like the classroom and canteen, are named as service points, where users always request communication services. According to prior-known trajectories, periodic events, and service points above, the mobility-aware transmission is accessible!

In this paper, we consider exploiting multi-hop relay to overcome mobility as well as enhance the content downloading service of mobile users. Our key thought is to select the relay near the service point, and cache contents there before users' arrivals, as shown in Fig. 1 later. To overcome dynamics due to user mobility, we decouple the scheduling in two parts of space and time. In terms of space, based on mobility trajectories derived from existing techniques [5], [6], we construct multi-hop relay paths to avoid the time waste in replanning. In terms of time, we utilize concurrent time scheduling to make sure that, multi-hop relay paths could cache required service data without latency. Specifically, we develop a relay path planning algorithm and a global time scheduling algorithm to achieve both the space and time scheduling. With these algorithms, we propose the throughput-efficient scheduling scheme for mobile users in mmWave systems, termed HTSS. Our novel contributions are summarized as follows.

- We formulate the problem of optimal mobility-aware transmission with multi-hop relay into a mixed integer nonlinear programming (MINLP).
- We propose a throughput-efficient transmission scheduling scheme, termed HTSS, to obtain a practical solution

978-1-5386-3180-5/18/$31.00 ©2018 IEEE

for the formulated problem. Taking the mobility into consideration, HTSS decouples the scheduling in two parts of space and time.
- Extensive evaluations under various system parameters demonstrate HTSS achieves higher system throughput compared with the state-of-the-art scheme, traditional unicast scheme. Typically, it improves the system throughput by over 100%.

The rest of the paper is organized as follows. Section II introduces the system model, and formulates the optimal problem of multi-hop transmission scheduling with user mobility considered into a MINLP problem. Section III presents our proposed HTSS scheme. Section IV evaluates the performance under various system parameters. In light of our results, this paper is concluded in Section V.

II. System Model and Problem Formulation

A. System Model

Fig. 1 exhibits a typical scenario for the system model. The story's major role, Jack, is a college student, whose weekdays are similar. In the early morning, while working out in the gym, Jack usually listens to online music. Then he walks into the teaching building for lessons, where Internet searching is always necessary. After school, Jack often learns online courses in the library, and next enjoys Internet surfing in the canteen and apartment. Referring to the illustration before, the trajectory can be obtained commonly, shown as blue lines in the figure. Furthermore, multi-hop relay paths (black links in the figure) can be established with several relays deployed around, shown as orange circles in the figure. Thus, the user would enjoy high QoS with data cached at service points.

According to the above scenario, we consider the system of cellular network with one base station (BS), static relay nodes (REs), and one mobile user (UE), where the BS is located at the cell center and REs are deployed around the cell. The system time is partitioned into non-overlapping time slots of equal length, and clocks of REs and UE are synchronized by the BS. Equipped with electronically steerable directional antennas, directional transmissions are supported between any pair of BS, REs and UE. Besides, all nodes are assumed to be half-duplex, i.e., each node has at most one connection with another node simultaneously.

The directional link from node i to j is denoted by (i, j). After the beamforming procedure, node i and j point their antennas towards each other. Then based on the path loss model, the received power at node j for (i, j), denoted by P^r_{ij} (mW), can be obtained as

$$P^r_{ij} = k_0 G_t(i,j) G_r(i,j) d_{ij}^{-\gamma} P_t, \tag{1}$$

where we denote the transmission power by P_t (mW), the transmitting antenna gain of node i by $G_t(i, j)$, the receiving antenna gain of node j by $G_r(i, j)$, the distance from transmitter i to receiver j by d_{ij} (m), the path loss exponent by γ, and k_0 is a constant coefficient and proportional to $(\frac{\lambda}{4\pi})^2$ (λ stands for the wavelength) [7].

Considering the directional transmission in a large range, concurrent transmissions are adopted for spatial reuse as

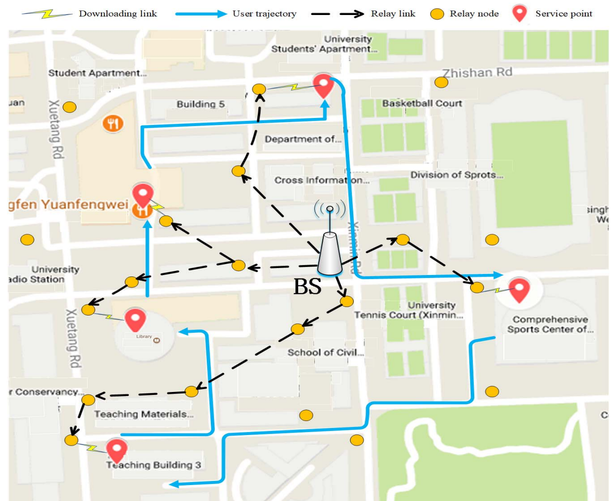

Fig. 1: The typical scenario of the system model: Jack's weekday life and the illustration of HTSS scheme.

well as capacity improvement. Since the interference among mmWave links is little enough to be omitted [8], for link (i, j), we can obtain the SNR at receiver j as

$$SNR_{ij} = \frac{k_0 G_t(i,j) G_r(i,j) d_{ij}^{-\gamma} P_t}{N_0 W}, \tag{2}$$

where we denote the bandwidth by W (Hz), and the one-sided power spectra density of white Gaussian noise by N_0 (mW/Hz) [7].

Based on the multipath effect to directional mmWave links [9], as well as Shannon's channel formula, link (i, j) is able to achieve a data rate of

$$R_{ij} = \eta W \log_2\left(1 + \frac{k_0 G_t(i,j) G_r(i,j) d_{ij}^{-\gamma} P_t}{N_0 W}\right), \tag{3}$$

where $\eta \in (0, 1)$ depicts the transceiver efficiency [7].

In this paper, we consider the content downloading from the BS to the mobile UE. As mentioned before, UE's mobility trajectories can be derived by trajectory data mining in GPS and other information [4]. In our solution, taking advantage of prior-known UE's mobility trajectories with BS's and REs' position information, we utilize both relaying and concurrent transmissions to achieve high system throughput.

B. Problem Formulation

We divide the session of UE's mobility trajectory into K time slots and denote the duration of each time slot by Δ. In UE's trajectory, there are several service points, as mentioned in Section I. When UE stays at each service point, it downloads contents from REs. We denote the set of UE's service points by $\mathbb{U}$, and each point is also regarded as one node in the system. We denote the set of REs by $\mathbb{V}$, and the BS in the network by B_s. For each node w in the system ($\mathbb{U} \cup \mathbb{V} \cup \{B_s\}$), we denote s_w as the transmitter node to w. Besides, for each service point $u \in \mathbb{U}$, we denote t_u as UE's arrival time at u, and τ_u as staying time at u (time here means time slots). Moreover, a bool variable b^k_{ij} is defined to indicate whether the transmission for link (i, j) is scheduled in the k-th time slot. If so, b^k_{ij} equals to 1; otherwise, b^k_{ij} equals to 0. Thus with (3), the achievable transmission rate at node w in the k-th time slot can be obtained as,

$$R_{s_w w}^k = \eta W \log_2 \left(1 + \frac{b_{s_w w}^k k_0 G_t(s_w, w) G_r(s_w, w) d_{s_w w}^{-\gamma} P_t}{N_0 W}\right). \quad (4)$$

Since data are transmitted from the BS to service point u via a specific multi-hop path, we denote H_u as the number of hops for this path, and $w_j(u)$ as the receiver node in the j-th hop. For each $w_j(u)$, we define integer variables $t_{w_j(u)}^s$ and $t_{w_j(u)}^e$. Then $w_j(u)$ starts receiving at the $t_{w_j(u)}^s$-th time slot and stops receiving at the $t_{w_j(u)}^e$-th time slot. The amount of received data for UE at u is denoted by D_u.

To achieve high performance for content downloading for UE, we should maximize the system throughput, defined as the total amount of received data divided by the total time of its mobility trajectory. Thus, the objective function can be obtained as $\sum_{u=1}^{|\mathbb{U}|} \frac{1}{K\Delta} \cdot D_u$, which can also be expressed as,

$$\sum_{u=1}^{|\mathbb{U}|} \frac{1}{K\Delta} \cdot D_u = \sum_{u=1}^{|\mathbb{U}|} \sum_{k=1}^{K} \frac{1}{K} \cdot R_{s_u u}^k. \quad (5)$$

We now consider the system constraints. First, the transmission at each service point can be scheduled only when UE stays there, which means that,

$$b_{s_u u}^k = 0, \ \forall\ u, \text{ if } k \le t_u \text{ or } k \ge t_u + \tau_u. \quad (6)$$

Second, according to the half-duplex assumption, we cannot schedule adjacent links concurrently, which is obtained as,

$$b_{s_u u}^k + b_{s_v v}^k \le 1, \text{ if link } (s_u, u) \text{ and } (s_v, v) \text{ are adjacent}, \ \forall\ u, v \in \mathbb{U} \cup \mathbb{V} \cup \{B_s\}. \quad (7)$$

Third, the j-th hop in the path u should be scheduled before the $(j+1)$-th hop, and only when UE stays at u, can the last hop transmit cached data, which can be acquired as,

$$t_{w_j(u)}^s \le t_{w_j(u)}^e \le t_{w_{(j+1)}(u)}^s \le t_{w_{(j+1)}(u)}^e, \ \forall\ u,\ j = 1, 2, \cdots, H_u - 1. \quad (8)$$

$$t_u \le t_{w_{H_u}(u)}^s \le t_{w_{H_u}(u)}^e \le t_u + \tau_u, \ \forall\ u. \quad (9)$$

Fourth, UE's received data at u cannot exceed the data forwarded by each hop of the path, which means that,

$$\sum_{k=t_{w_j(u)}^s}^{t_{w_j(u)}^e} R_{s_{w_j(u)} w_j(u)}^k \Delta \ge \sum_{k=t_{w_{H_u}(u)}^s}^{t_{w_{H_u}(u)}^e} R_{s_u u}^k \Delta, \quad (10)$$
$$\forall u,\ j = 1, 2, \cdots, H_u.$$

Therefore, the mobility-aware optimal scheduling problem (P1) can be formulated as follows,

$$\text{(P1)} \quad \max \sum_{u=1}^{|\mathbb{U}|} \frac{1}{K\Delta} \cdot D_u, \quad (11)$$
$$\text{s. t.} \quad \text{Constraints (6)–(10).}$$

In problem P1, it can be observed that the objective function (5) and constraint (10) have nonlinear terms. Accordingly, it is a MINLP, where $b_{s_u u}^k$ is the binary variable, $t_{w_j(u)}^s$ and $t_{w_j(u)}^e$ are integer variables, and $R_{s_u u}^k$ is the real variable. The transmission data for each service point cannot be determined until transmission paths and scheduling time are determined. This problem is more complex compared with the NP-complete 0-1 Knapsack problem [7], [10]. Thus, we propose the high throughput service scheduling scheme to solve it with good performance as well as low complexity in the next section.

III. The HTSS Scheme

In this section, we propose the throughput efficient scheduling scheme for the formulated problem above. As mentioned before, to overcome dynamics due to user mobility, we achieve the transmission scheduling of each service point in space and time. First, we construct a relay path planning algorithm to establish the multi-hop relay path from the BS to each service point. Then, we propose a global time scheduling algorithm to accommodate the time or cache demand at each service point.

For the best channel condition, the nearest RE to service point u is selected as s_u, responsible for caching and serving UE. Based on this, we establish a multi-hop relay path from the BS to s_u with predetermined hops, borrowing the ideas of Dijkstra Algorithm. In particular, the relay path planning algorithm is modelled as a function p_*=**PathPlanning** ($\mathbb{V}$, H_*, s_u), in which p_* is the selected multi-hop path from B_s to s_u, and H_* is the predetermined hop number.

To be specific, the algorithm first generates the relay path from B_s to its closest relay node (visited node), and iteratively extends the path from last visited node to the closest unvisited relay node, until reaches s_u. If the found path's hop number does not equal to H_*, the algorithm removes the path and iteratively searches for the relay path with H_* hops, until the path is found or there is no path left; otherwise, the relay path p_* is obtained and returned.

Consequently, the worst case computational complexity for relay path planning algorithm is $\mathcal{O}(|\mathbb{V}|^2)$.

Now we consider the concurrent time scheduling in Algorithm 1. Since UE reaches service points by order, the scheduling is from the earliest service point to the last one. For each service point, we construct the relay path with predetermined hops by function **PathPlanning**. Then multiple judgements are utilized to make sure that, the relay path could finish data cache before UE's arrival. In each time slot, concurrent transmissions of links are enabled with half-duplex assumption satisfied. If judgements are not approved, to accommodate the scheduling, the algorithm decreases the hop number or data amount by multiplying a shrinking parameter less than 1.

To be clear, we introduce notations in Algorithm 1 first. For each service point $u \in \mathbb{U}$, t_u, τ_u, and D_u are denoted as UE's arrival time, stay time, and received data at u. Respectively, the number of remaining available time slots before UE's arrival is denoted by $r\tau_u$. For simplicity, these variables at service points are expressed in vector form, i.e., $\vec{t}$, $\vec{\tau}$, $\vec{D}$, and $r\vec{\tau}$. Besides, to track the state of each RE and BS in K time slots, we define a binary table $\mathbf{S}_{(|\mathbb{V}|+1)\times K}$. For instance, $\mathbf{S}(1, k) = 1$ means RE 1 is scheduled (busy) in the k-th time slot, and 0 means unscheduled (free). The last row of $\mathbf{S}$ is for BS. As for the path, the maximum hop number for relay paths is denoted by H_m. The hop number for the relay path from BS to s_u is denoted by H_u, and the path is denoted by p_u. The h-th hop on p_u is denoted by p_u^h. For p_u^h, we denote st_u^h as the start time slot for transmission, T_u^h as the number of transmission time slots. Moreover, b_u^h is denoted as busy time slots for p_u^h (transmitter or receiver of p_u^h is busy).

The pseudo-code for the global time scheduling algorithm is presented in Algorithm 1. It iteratively schedules service points one by one according to the arrival time order. For each service point u, lines 8-9 find the nearest RE s_u, and derive the maximum transmission data D_u. Line 10 initializes H_u to the maximum hop number for paths. Based on function **PathPlanning**, a relay path p_u with H_u hops is generated, and rates for hops on p_u are also obtained, as in lines 12-14. Then in line 15, without considering busy states, the algorithm calculates p_u's remaining time $r\tau_u$ before UE's arrival. If time is not enough, line 29 decreases H_u for a new path. Otherwise, in line 17, the temporary state table $\mathbf{S}'$ and count variable h are initialized for multiple judgements and links scheduling in lines 18-28. We hope p_u^h to be available during $st_u^h \backsim (st_u^h + T_u^h)$ time slots, yet the hop may be busy at some time slots by checking $\mathbf{S}'$, as shown in lines 19-21. If the algorithm can skip all busy time slots, and schedule p_u^h in free remaining time instead, the schedule goes to the next hop with $r\tau_u$, $\mathbf{S}'$ and h updated, as in lines 22-24. With all hops on p_u^h scheduled, the algorithm updates $\mathbf{S}$, and schedules for the next service point, as in lines 27-28. Nevertheless, line 29 decreases H_u for inadequate $r\tau_u$. Furthermore, when H_u is decreased to 1, the algorithm decreases transmission data by multiplying β, as in line 30. With less transmission data, the algorithm tries new scheduling for u. However, if D_u is decreased to 0, which indicates the scheduling for u is failed, the algorithm will schedule for the next service point, as in lines 31-33. For UE, received data D_u at u are returned in line 34.

For Algorithm 1, the while loop in line 7 has at most $|\mathbb{U}|$ iterations, and the while loop in line 11 has no more than H_m iterations. In the while loop, the complexity of function **PathPlanning** is $\mathcal{O}(|\mathbb{V}|^2)$. However, the while loop and judgements in lines 18-26 have about KH_m iterations, generally more than the function. Thus, the worst case computational complexity for Algorithm 1, i.e., the HTSS, is $\mathcal{O}(K|\mathbb{U}|H_m^2)$, which can be implemented in practice.

Algorithm 1: Global Time Scheduling Algorithm

1 **Input:** The set of service points $\mathbb{U}$, the set of REs $\mathbb{V}$;
2 Arrival time vector $\vec{t}$ for $\mathbb{U}$;
3 Stay time vector $\vec{\tau}$ for $\mathbb{U}$;
4 The maximum hop number H_m;
5 The shrinking parameter β;
6 **Initialization:** $r\vec{\tau} = \vec{0}$, $\vec{D} = \vec{0}$, $\mathbf{S} = \mathbf{0}$;
7 **while** $|\mathbb{U}| > 0$ **do**
8 Find the nearest RE s_u with the minimum t_u;
9 $D_u = R_{s_u u} \cdot \tau_u$;
10 $H_u = H_m$;
11 **while** $H_u > 1$ **do**
12 p_u=**PathPlanning** ($\mathbb{V}$, H_u, s_u);
13 **if** $p_u \neq \emptyset$ **then**
14 Obtain the rate of p_u^i, R_u^i;
15 $r\tau_u = t_u - \sum_{i=1}^{H_u} \frac{D_u}{R_u^i}$;
16 **if** $r\tau_u \geq 0$ **then**
17 $\mathbf{S}' = \mathbf{S}, h = 1$;
18 **while** $h \leq H_u$ **do**
19 Obtain start time slot for p_u^h, st_u^h;
20 Obtain transmission time slots for p_u^h, $T_u^h = \frac{D_u}{R_u^h}$;
21 Check p_u^h's state with $\mathbf{S}'$, and obtain the number of busy time slots in $st_u^h \backsim (st_u^h + T_u^h)$ time slots, b_u^h;
22 **if** $b_u^h \leq r\tau_u$ **then**
23 Skip busy time slots, and schedule p_u^h in free $r\tau_u$;
24 Update $r\tau_u$, $\mathbf{S}'$, $h = h + 1$;
25 **else**
26 Go to line 30;
27 Update $\mathbf{S} = \mathbf{S}'$;
28 Go to line 34 for the next service point;
29 $H_u = H_u - 1$;
30 $D_u = \lfloor D_u \cdot \beta \rfloor$;
31 **if** $D_u > 0$ **then**
32 Go to line 10 with less transmission data;
33 $\mathbb{U} = \mathbb{U} - u$;
34 **Return** received data D_u at each service point u.

IV. Performance Evaluation

In this section, we evaluate the performance of our proposed HTSS scheme in realistic environments driven by human mobility trajectories, by investigating the impact of various system parameters on the system throughput.

A. Evaluation Setup

In the evaluation, we use human mobility trajectories, collected in the campus of Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea. The trajectories are generated from 32 students who live in a campus dormitory, recorded by Garmin GPS 60CSx handheld receivers. In addition, these GPS devices achieve a position accuracy of better than 3 m 95% of the time [11]. 88 UE's trajectories are evaluated in a square area of $300m \times 300m$, and several service points are detected in each trajectory by time and position records. For generality and convenience, we have the assumption that, the BS locates in the center of the area, and several static REs are deployed in the area with Poisson distribution. To be close to the real environment, the reference antenna model in IEEE 802.15.3c is adopted in the evaluation [12]. We denote $G(\theta)$ as the antenna gain (dB), which can be expressed as,

$$G(\theta) = \begin{cases} G_0 - 3.01 \cdot \left(\frac{2\theta}{\theta_{-3\text{dB}}}\right)^2, & 0^\circ \leq \theta \leq \theta_{ml}/2; \\ G_{sl}, & \theta_{ml}/2 \leq \theta \leq 180^\circ, \end{cases} \tag{12}$$

where $\theta \in [0^\circ, 180^\circ]$ is the angle to main lobe center, $\theta_{-3\text{dB}}$ is the angle of the half-power beamwidth, and θ_{ml} denotes the angle of the main lobe. The relationship between θ_{ml} and $\theta_{-3\text{dB}}$ can be derived as $\theta_{ml} = 2.6 \cdot \theta_{-3\text{dB}}$. On the other hand, G_0 denotes the maximum antenna gain, expressed as $G_0 = 10\log\left(\frac{1.6162}{\sin(\theta_{-3\text{dB}}/2)}\right)^2$. G_{sl} denotes the side lobe gain, expressed as $G_{sl} = -0.4111 \cdot \ln(\theta_{-3\text{dB}}) - 10.579$. We present simulation parameters in Table I. For every result, we perform 30 independent experiments for each trajectory, and obtain the results by the mean of trajectories.

TABLE I: Simulation Parameters

Parameter	Symbol	Value
Bandwidth	W	2160 MHz
Background noise	N_0	-134dBm/MHz
Path loss exponent	γ	2
Transmission power	P_t	30 dBm
Time slot duration	Δ	1 s
Half-power beamwidth	$\theta_{-3\text{dB}}$	30°
Efficiency of the transceiver design	η	0.5
Shrinking parameter	β	0.9
Maximum number of hops	H_m	7
Relay node group size	$\lvert\mathbb{V}\rvert$	20

In this evaluation, we compare the HTSS scheme with traditional unicast scheme, in which the BS directly transmits to UE at service points. In addition, the system throughput defined in (5) is the main performance metric. To analyze the impact of algorithm parameters, we investigate the relationship between the system throughput and RE group size, maximum number of hops H_m, as well as shrinking parameter β. We also look at the relationship between the system throughput and transmission power P_t, as well as half-power beamwidth θ_{-3dB} to analyze the impact of system hardware parameters.

B. Result Analysis

1) Algorithm Parameter Analysis: To evaluate the role played by RE group sizes, we adjust the number of relays in the system and plot the system throughput in Fig. 2. Other simulation parameters are shown in Table I. We can clearly observe that, HTSS improves the system throughput by about 118.2% compared with the unicast scheme when the RE group size is 20. Since relays in physical proximity are advantageous for relaying communications, more REs means shorter distance and higher system throughput. With the group size varying from 10 to 35, HTSS improves the system throughput by 87.5%. However, since the relay is not enabled in the unicast scheme, its throughput does not change with the RE group size. For one thing, it seems costly that such relays are deployed for only one user. Nevertheless, the data cached at relays can also serve other mobile users at service points. According to this, HTSS is a potential and promising solution for the scenario with multiple mobile users.

We study the gain of the maximum number of hops, and plot the system throughput comparison of two schemes with different RE group sizes under different H_m in Fig. 3(a). As the maximum number of hops increases, the system throughput of HTSS increases. With more hops, more paths with larger transmission data can be scheduled for service points. Hence, higher system throughput can be achieved. We can observe that when H_m is small like 1 or 2, the gaps between different RE group sizes are not large since the choice for relaying

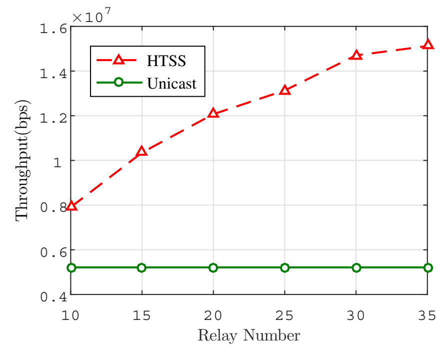

Fig. 2: The system throughput comparison of two schemes under different RE group sizes.

paths is few. When H_m increases, the gaps become quite large, which demonstrates advantages of multi-hop relaying communications. We also observe that when H_m is 6 or 7, the system throughput of HTSS with 10, 20 REs stops growing with H_m. However, the system throughput of HTSS with 30 REs is still increasing. Therefore, the plot indicates a positive correlation between the average number of hops and RE group sizes. However, larger H_m also stands for more computational time. Thus, we should select suitable value of H_m according to the RE group size and time restrictions. As for the unicast scheme, its throughput does not change with H_m.

Considering the impact of shrinking parameter on transmission data, Fig. 3(b) exhibits the system throughput of two schemes with different RE group sizes under different β. Since β is introduced to reduce transmission data D_u to $\beta \cdot D_u$ during scheduling, transmission data for service points may decrease a lot if β is too small. For example, we can observe that when RE group size is 20, HTSS with $\beta = 0.9$ enhances the system throughput by about 57.7% compared with $\beta = 0$. Furthermore, HTSS with 30 REs under $\beta = 0.3$ can achieve a little higher system throughput than HTSS with 20 REs under $\beta = 0.9$. Accordingly, β should be selected according to the RE group size and system throughput requirements. Although small β decreases the system throughput significantly, when $\beta = 0$, HTSS with 20 REs still improves the system throughput by 51.9% compared with the unicast scheme. The unicast scheme does not change with β for no shrinking operations.

2) System Parameter Analysis: In order to evaluate the impact of transmission power, we show the system throughput of schemes with different RE group sizes under different P_t in Fig. 3(c), where Y-axis is the logarithmic coordinate for better view. With the transmission power increases, the system throughput of different schemes increases due to higher transmission rates. Though lower transmission power means lower energy consumption for the network, it also leads to lower system throughput. Therefore, the transmission power should be selected according to the practical energy consumption and system throughput requirements. We also observe that HTSS still has greater system throughput than the unicast scheme, and larger RE group size brings larger gains.

To illustrate the impact of half-power beamwidth, we plot the system throughput of two schemes with different RE group sizes under different θ_{-3dB} in Fig. 4. We examine five cases,

View publication stats