Enabling Device-to-Device Communications in Millimeter-Wave 5G Cellular Networks

Jian Qiao, Xuemin (Sherman) Shen, Jon W. Mark, Qinghua Shen, Yejun He, and Lei Lei

Jian Qiao, Xuemin (Sherman) Shen, Jon W. Mark, and Qinghua Shen are with the University of Waterloo.

Yejun He is with Shenzhen University

Lei Lei is with Beijing Jiaotong University.

ABSTRACT

Millimeter-wave communication is a promising technology for future 5G cellular networks to provide very high data rate (multi-gigabits-per-second) for mobile devices. Enabling D2D communications over directional mmWave networks is of critical importance to efficiently use the large bandwidth to increase network capacity. In this article, the propagation features of mmWave communication and the associated impacts on 5G cellular networks are discussed. We introduce an mmWave+4G system architecture with TDMA-based MAC structure as a candidate for 5G cellular networks. We propose an effective resource sharing scheme by allowing non-interfering D2D links to operate concurrently. We also discuss neighbor discovery for frequent handoffs in 5G cellular networks.

INTRODUCTION

Future fifth generation (5G) cellular networks are being developed to satisfy dramatically increasing data traffic among mobile devices with the emergence of various high-speed multimedia applications [1]. Table 1 summarizes the evolution of cellular networks from 1G to 4G from the aspects of implemented key technologies and the most supported applications. A new generation emerges about every 10 years to significantly improve the transmission rate and support more applications. 5G cellular networks are expected to have much higher network capacity and provide multi-gigabits-per-second data rate for each user to support multimedia applications with stringent quality of service (QoS) requirements. For example, uncompressed video streaming requires a mandatory data rate of 1.78/3.56 Gb/s. These newly emerging bandwidth-intensive applications create unprecedented challenges for wireless service providers to overcome a global bandwidth shortage [2].

Millimeter-wave (mmWave) communication is a very promising solution for future 5G cellular networks. An mmWave communication system has very large bandwidth (multiple gigahertz), which can be translated directly to much higher data rates and overwhelming capacity. Multi-gigabits-per-second transmission at mmWave band has been realized in both indoor (e.g., wireless personal area networks) [3] and outdoor (e.g., wireless mesh networks) systems [4]. The availability of mmWave spectrum and recent advances in RF integrated circuit (RFIC) design motivate industrial interest in leveraging mmWave communication for future 5G cellular networks. MmWave 5G cellular networks are expected to have the main characteristics of highly directional antennas at both wireless devices and base stations, lower link outage probability, extremely high data rate in the widest coverage area, and higher aggregate capacity for many simultaneous users. As a replacement of copper/fiber infrastructure, mmWave mesh networks can be used as a wireless backbone for 5G to provide rapid deployment and mesh-like connectivity.

Generally, device-to-device (D2D) communications provide the connection between two wireless devices either directly or by hopping. D2D communications can be established via the base stations in traditional cellular networks. Specifically, one wireless device needs to communicate with the base station; then the base station conveys the data to another wireless device directly or via backbone networks. Motivated by the increasingly high-rate local services, such as distributing large files among the wireless devices in the same cell, local D2D communications have recently been studied as an underlay to Long Term Evolution-Advanced (LTE-A) 4G cellular networks [5]. It can significantly enhance the network capacity by establishing a path between two wireless devices in the same cell without an infrastructure of a base station. In mmWave 5G cellular networks, local D2D communications can be formed to offload cellular communications, thus supporting more simultaneous users. Meanwhile, global D2D communications can be formed with multihop wireless transmissions via base stations between two wireless devices associated with different cells. Taking advantage of mmWave propagation characteristics and the use of directional antennas, a resource sharing scheme supporting non-interfering concurrent links is

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Generation	Features	Applications
1G	Deployed in the 1980s. Analog technology.	Voice communication.
2G	Deployed in the 1990s. Digital modulations. Primary technologies are IS-95, CDMA, and GSM.	Voice SMS and low-rate data.
3G	144 kb/s for mobile, 384 kb/s pedestrian, and 2 Mb/s for indoor. CDMA2000, WIMAX, and UMTS-HSPA.	New applications, such as video conference, location-based service.
4G	Require ability of 40 MHz channel with high spectral efficiency. LTE, LTE-A, and IEEE 802.16.m.	Higher rate data, hundreds of megabits per second.

Table 1. Evolution of 1G through 4G cellular networks.

proposed to share network resources among local D2D communications and global D2D communications.

In this article, we focus on building D2D communications over mmWave 5G cellular networks. We discuss the mmWave propagation characteristics and the corresponding challenges to enable D2D communications. The future 5G cellular network architecture and MAC structure are described. A resource sharing scheme to allocate time slots to concurrent D2D links to increase network capacity is proposed. We then conclude the article with a summary and a brief discussion of future work.

MmWave D2D Communications

MmWave Propagation

MmWave communication (with wavelength on the order of millimeters), including the frequency band from 30–300 GHz, has several fundamental propagation features [6]. First, the propagation loss is much higher than that in the microwave band (e.g., 28 dB higher at 60 GHz than at 2.4 GHz) since the free space propagation loss is proportional to the square of the carrier frequency. A high-gain directional antenna is favored to compensate for the tremendous propagation loss and reduce the shadowing effect. Second, the short wavelengths of mmWave bands result in difficulties in diffracting around obstacles. Line-of-sight (LOS) transmissions can easily be blocked by the obstacles. Since non-LOS (NLOS) transmissions in mmWave channels suffer from significant attenuation and a shortage of multipaths, link outage can happen if an LOS link is blocked. Third, mmWave signals have difficulties penetrating through solid materials (e.g., at 40 GHz, 178 dB attenuation for brick wall and over 20 dB attenuation for a painted board). The limited penetration capability could confine outdoor mmWave signals to streets and other outdoor structures, although some signal power might reach inside the buildings through glass windows and wood doors. These propagation characteristics lead to challenges to achieve seamless coverage and reliability [7].

D2D Communications

Enabling D2D communications to handle local traffic can be found in [8], where D2D connections are used for relaying rather than improving the spectrum utilization efficiency. In [9], the traffic loads of the coexisting cellular and ad hoc networks are considered to be independent. Recently, D2D communications used in 4G cellular networks focus on local D2D connections as an underlay to cellular connections. The local D2D communications can reuse the cellular resources to increase spectral efficiency, which has promoted much work in recent years [5].

In mmWave 5G cellular networks, two kinds of D2D communications can be enabled: local D2D communications and global D2D communications. Local D2D communications build the path between two wireless devices associated with the same base station, either directly or by relays if the LOS link between them is blocked. They facilitate the discovery of geographically close devices and reduce the communication cost between these devices. Global D2D communications connect two wireless devices associated with different base stations by hopping via the backbone networks. They include device-to-base-station (D2B) communications and base-station-to-base-station (B2B) communications. In contrast with 4G cellular networks where communications between base stations are performed via fiber links, mmWave communication with a highly directional antenna provides wireless connections with high data rate for B2B communications in mmWave 5G cellular networks.

D2D in mmWave 5G

As described earlier, D2D communications are expected to be an essential feature of mmWave 5G cellular networks, to improve network capacity and build connections between two wireless devices. Due to the directional antenna and high propagation loss, mmWave communication has relatively low multi-user interference (MUI), which can support simultaneous communications. By allowing multiple concurrent D2D links, the network capacity can be further improved.

In mmWave 5G cellular networks, D2D communications may face two kinds of potential interference within each cell: interference among different local D2D communications (if there are multiple local D2D communications) and interference between local D2D communications and D2B/B2B communications. Most of the existing works on D2D communications focus on the design of optimized resource sharing algorithms by managing the interferences [5, 10]. In [5], the performance of frequency reuse among D2D links is analyzed with dynamic data arrival settings to obtain average queue length, mean throughput, average packet delay, and packet dropping probability. In [10], the system aims to optimize the throughput over the shared resources while fulfilling prioritized cellular service constraints. The performance of the D2D underlay system is evaluated in both a single-cell scenario and the Manhattan grid environment. It considers resource sharing between one cellular connection and one local D2D connection.

To the best of our knowledge, previous works on resource sharing for D2D communications consider the mutual interference of omnidirectional antennas. Taking advantage of high propagation loss and the use of directional antennas, more D2D links can be supported in each cell in mmWave 5G networks to further enhance network capacity and improve spectrum efficiency. A new resource sharing scheme considering directional interference is necessary in mmWave 5G cellular networks to enable multiple D2D communications.

Network Architecture

It is expected that the current 4G cellular networks can provide seamless coverage and reliable communications because of the lower frequency band. For smooth and cost-efficient transition from 4G to 5G, 5G cellular networks use the hybrid 4G+mmWave system structure shown in Fig. 1 to achieve seamless coverage and high rate in most coverage areas. The management information and low-rate applications (e.g., voice, text, and web browser) are transmitted in 4G networks, while the mmWave bands are available for high-rate multimedia applications.

The 5G cellular networks consist of 4G base stations, mmWave base stations, and mobile devices. In 4G networks, the whole geographical area is partitioned into cells, each of which is covered by one or more 4G base stations. MmWave transmission/reception is based on high directional antennas, which can greatly reduce the mutual interference between mmWave base stations. It has been proved and demonstrated [4] that for an outdoor environment, the interference among mmWave concurrent links are negligible, and directional mmWave communication links can be considered as *pseudo-wired*. Therefore, mmWave base stations do not need to be deployed in cells. In this article, dense mesh networks are adopted for the mmWave backbone with grid topology deployment to provide high rates and aggregate capacity. As shown in Fig. 2, each wireless device has the communication modes of both 4G operation and mmWave operation, and supports fast mode transition between them. Two devices can communicate with each other in the same mode. This article focuses on enabling D2D communications at mmWave band for 5G networks. Therefore, in the following parts of the article, without special indications, the base station refers to the mmWave base station. All wireless devices and mmWave base stations are equipped with electronically steerable directional antennas for mmWave communication. All wireless devices and 4G base stations have omnidirectional antennas for 4G communications. It is assumed that with mmWave beamforming technologies [11], each transmission pair can determine the best transmission/reception beam patterns for data transmission.

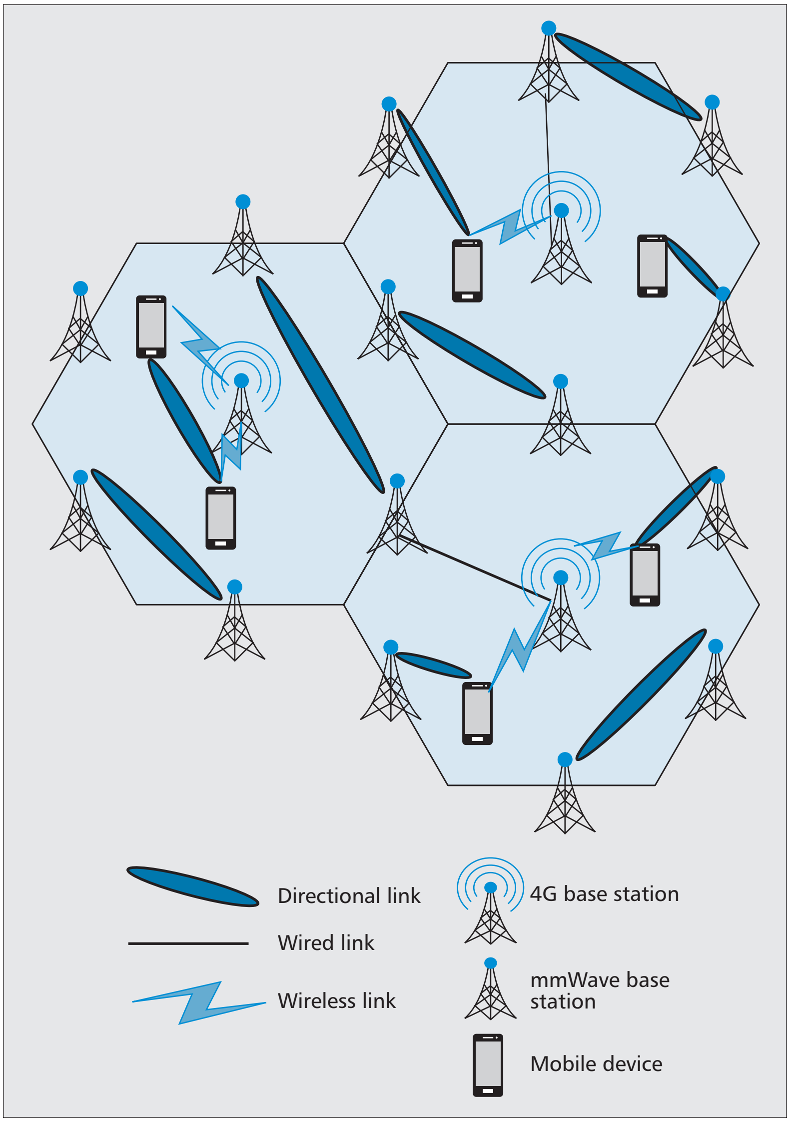

Figure 1. MmWave 5G cellular network architecture.

Medium Access Control

Several works on directional mmWave MAC for networks with low user mobility (e.g., WLAN or WPAN) have appeared in the literature [12, 13]. Cross-layer modeling and design approaches are presented in [12] to account for the problems of directionality and blockage. In the proposed MAC protocol, an intermediate node is randomly selected as the relay if the LOS link between the source and the destination is not available. In [13], an exclusive region (ER)-based resource management scheme is proposed to exploit the spatial reuse, and the optimal ER sizes are derived. The main challenge in mmWave MAC design is how to use the spectrum efficiently to achieve higher capacity considering mmWave propagation features while providing reliable high-rate connections.

MmWave 5G cellular networks support multimedia applications with stringent QoS requirements. To provide guaranteed performance, time-division multiple access (TDMA) is adopted for mmWave channel access in 5G networks with the superframe shown in Fig. 3. Each base station handles the local D2D transmissions, B2B transmissions, and D2B transmissions. Time is partitioned into superframes, each of which are composed of *M* time slots called channel time allocation (CTA). In each CTA, multiple local D2D communications can operate simultaneously to exploit spatial reuse and improve spectrum utilization efficiency. Due to the half-duplex constraint, there should be at most one D2B/B2B link in each CTA since the base station cannot transmit and receive simultaneously. The 4G base stations collect the transmission requests and signaling information for mmWave communication by reliable 4G networks.

For each local communication (including local D2D and D2B), the transmitter polls the receiver to check connectivity. Each receiver has to respond within a fixed interval, that is, a poll inter frame space (PIFS), with a poll response message if the connection is not blocked. The absence of a poll response at the receiver indicates the link blockage and triggers multihop transmission to bypass the obstacles by intelligently selecting a relay within the wireless devices under the control of the base station. Relay selection has great impact on its flow throughput and interference to other links operating at the same time. There are many existing schemes to determine relay selection [3]. Since the main focus of this article is to enable D2D communications, we simplify the relay selection by randomly picking up a node that is close to the direct path of the source and destination with LOS transmissions available to both. The link budget is used to ensure the link reliability over the coverage range. After the transmitter receives the polling response message, it starts to send packets to the receiver. Then the receiver acknowledges the successful packet reception with an ACK message. For transmissions among mmWave base stations, it is assumed that the path can be determined by routing protocol without the involvement of a blocked link in the path.

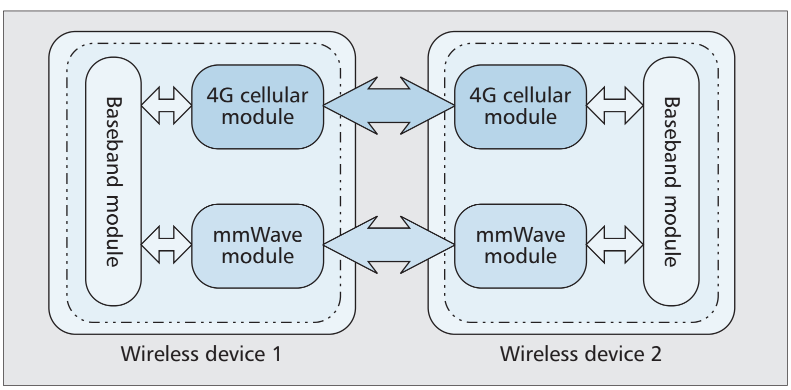

Figure 2. Wireless operation mode of each node.

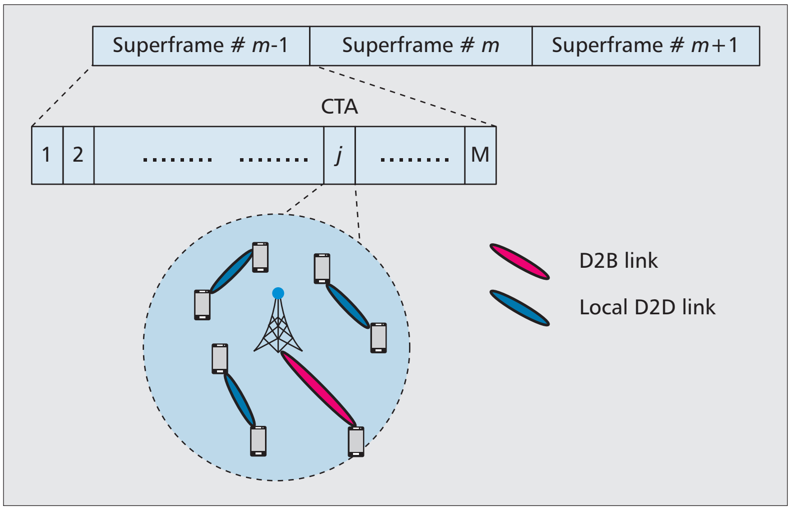

Figure 3. MmWave communication superframe in 5G cellular networks.

Resource Sharing

From the above discussions, resource sharing is the essential problem in enabling concurrent D2D communications in mmWave 5G cellular networks. This section presents the resource sharing modes, formulates the general resource sharing problem in directional mmWave 5G networks, and proposes an efficient algorithm to obtain the resource sharing solution.

Resource Sharing Modes

The local D2D and D2B/B2B links share the resources in mmWave 5G cellular networks. The resource sharing decisions are made by the base station. Generally, there are two resource sharing modes in the network:

- Non-orthogonal sharing (NOS) mode: Local D2D links and D2B/B2B links reuse the same resource, causing interference with each other. The base station coordinates the usage of resources (e.g., transmission power and time slot) for both kinds of links.
- Orthogonal sharing (OS) mode: Local D2D links use part of the resources while the other resources are allocated to D2B/B2B links. Thus, there is no interference between them, which simplifies the resource sharing.

Although orthogonal sharing mode can make resource sharing simple, non-orthogonal sharing can result in better resource utilization efficiency with proper sharing schemes. In this article, the non-orthogonal sharing mode is adopted for multiple concurrent links under the control of the base station. The use of directional antenna and high propagation loss can result in relatively lower mutual interference or even no interference by properly selecting the concurrent links formed by geographically distributed wireless devices.

Some of the existing work on resource sharing of D2D communications consider the scenario of one local D2D and one D2B link to simplify the interference [10]. Concurrent transmissions are also enabled in WLAN/WPAN networks to exploit spatial reuse [14, 15]. These papers consider D2D connections as local communications within the network operated by a network controller. The resource sharing scheme can be either distributively determined by the wireless devices themselves or centrally operated by the base station. As the mmWave 5G cellular networks are centralized in nature, the resource sharing scheme in this article is determined by the base station considering mutual interference among D2B and local D2D connections.

Optimization of Resource Sharing

Due to the long transmission distance and highly directional antennas, the interferences of the concurrent transmissions among mmWave base stations are negligible. The network capacity is mainly constrained by the interferences generated by local network. Each time slot can be allocated to multiple communication links which are spatially separated or overlapped without much interference. Both D2D and D2B/B2B links use the same time slots, and they might interfere with each other. Different sets of active local D2D links may affect the transmission rate of D2B/B2B links and vice versa. How to share the resources among D2D and D2B/B2B links to achieve optimal system throughput is an important and challenging issue.

The resource sharing determines a set of active links for each time slot in the superframe. Total data transmitted in the whole superframe is used as the objective function to achieve the best resource sharing while satisfying the transmission requests of each link. A variable $X_{i,j} = 0$ or 1 indicates if link i is active in the jth time slot. Total data transmitted in the whole superframe can be expressed as the function of $|X_{i,j}|_{L\times M}$ with each rate estimated by Shannon capacity formula. M denotes the number of time slots in each superframe, and L is the number of collected transmission requests.

The above optimization problem is a nonlinear integer programming problem. One possible approach is to relax the integer variables into continuous ones, and use optimization tools to solve the approximated problem. However, the approximated problem is still difficult to solve, since its objective function is not necessarily concave. The complexity of the above problem increases exponentially with the number of concurrent links and number of time slots. In this article, a heuristic resource sharing scheme is proposed to assign a set of active links for each time slot effectively.

Resource Sharing Scheme Design

The complexity of achieving the best resource sharing comes from the possible mutual interference of directional antennas. To simplify the problem and obtain an efficient resource sharing scheme, only non-interfering links are allocated to each time slot to share the resources. The concurrent transmission condition is that two links can operate simultaneously without interference if and only if any transmitter is outside the beamwidth of the other receiver or does not direct its beam to the other receiver if it is within the beamwidth of the other receiver. We apply an ideal "flat-top" model for directional antennas, that is, unit gain within the beamwidth and zero gain outside the beamwidth.

The details of the proposed resource sharing scheme are as follows. By a polling process, if an LOS link is blocked, a relay is selected to build a multihop path. At the beginning of each superframe, all the transmission requests are collected by 4G networks. Transmission requests would be forwarded to mmWave base stations if they require high data rate. The mmWave base station makes the resource sharing decisions for each superframe (i.e., a specific set of active links for each time slot) and sends the decisions to all the involved wireless devices via reliable 4G networks. It is assumed that all the wireless devices and base stations are synchronized.

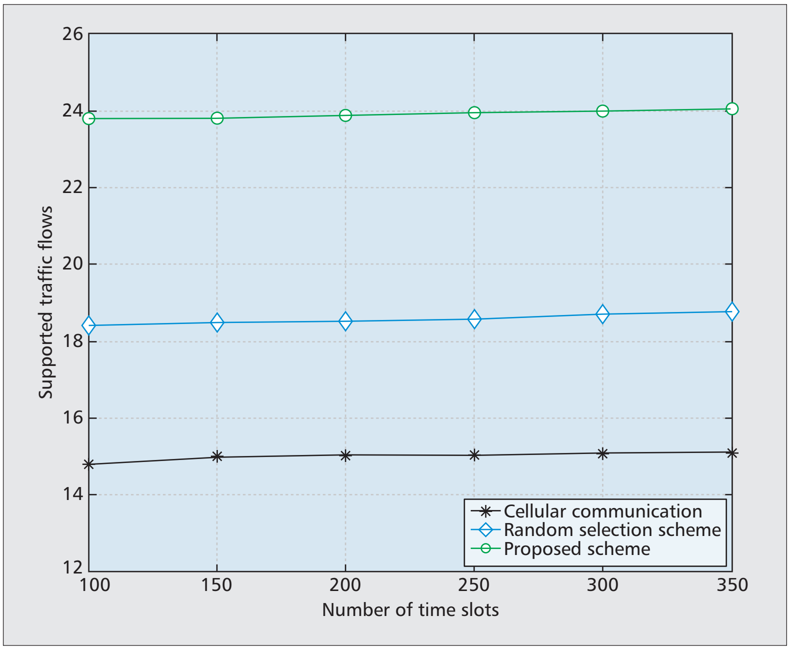

Figure 4. Number of supported traffic flows.

Since the concurrent links rely on LOS transmission, and we allow non-interfering links to operate concurrently, the wireless channel can be modeled by the free space Friis transmission equation. The instantaneous transmission rate can be estimated by the Shannon capacity formula. Each transmission request indicates a minimum average throughput to support multimedia applications. Thus, the number of time slots in each superframe for each transmission request can be predetermined. We randomly sort the transmission links in a specific sequence. A transmission request r_i from the ith link needs $n(i)$ slots. The base station sequentially checks if the ith link can operate concurrently with all the existing links in the same time slot according to the concurrent transmission condition. Note that two links having the same node cannot operate simultaneously due to the half-duplex constraint of wireless communications. If a link does not interfere with all existing links, this link is set to be active in the current time slot. After traversing all the links, the active link set for the current time slot is obtained. This active link set is used for the following time slots until at least one link's throughput requirement is satisfied. If a link's required number of time slots has been satisfied, it should be set inactive, and it is not necessary to check the concurrent transmission condition of this link in the following time slots. The above procedure is repeated until all the time slots have been traversed. If a link's request is not satisfied in the current superframe, it will be re-sent in the next superframe to share the resources with other links.

Figures 4 and 5 show the performance of the proposed resource sharing scheme. There are 40 transmission requests received in the base station. All the wireless devices are randomly distributed in a 20 m × 20 m square area. The transmission

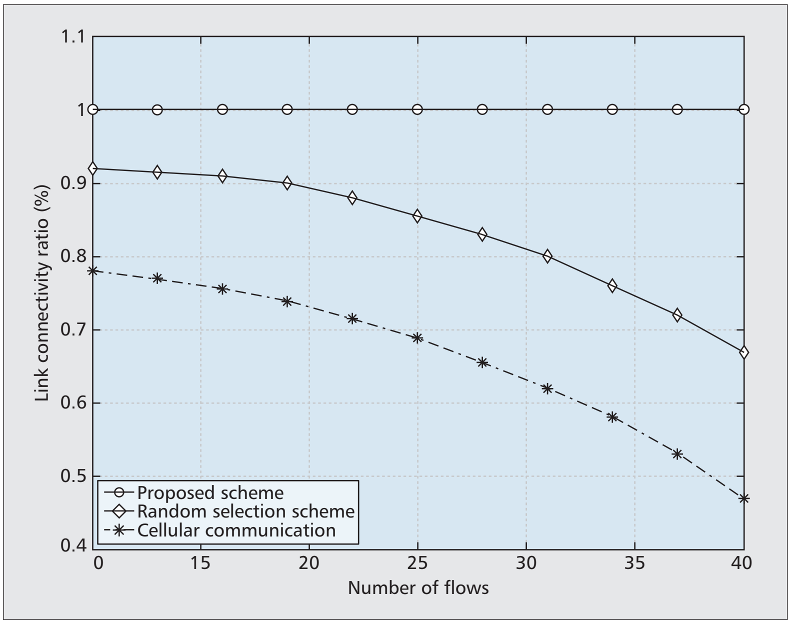

Figure 5. Network connectivity ratio.

power is 0.1 mW, and the background noise level is 134 dBm/MHz. The antenna beamwidth is 45° for both mobile devices and mmWave base stations. The performance of the proposed resource sharing scheme is compared to two other schemes, traditional cellular and random selection. The traditional cellular scheme does not have local D2D communications, while the random selection scheme just randomly selects several links to share the resource. In Fig. 4, the proposed resource sharing scheme significantly outperforms the other two schemes in terms of the number of supported flows by effectively exploiting the spatial reuse opportunities. The proposed resource sharing scheme is very useful, especially for a dense network in the urban area. Network capacity for mmWave 5G networks is an essential issue in the deployment of mmWave base stations. This article considers concurrent transmissions to improve local network capacity.

The proposed resource sharing scheme uses multihop transmission with relays to deal with link blockage. The blockage model defined in the IEEE 802.11ad channel model document is adopted. In mmWave 5G cellular networks, both the obstacles and the mobility of mobile devices can cause link outage if LOS transmission is blocked. Network connectivity is shown in Fig. 5 with various numbers of transmission requests in the network. A relaying mechanism can reduce the link outage probability by replacing a blocked link with an alternative path with two links. The relaying mechanism to keep network connectivity is effective for users with low mobility.

Conclusion and Future Research

In this article, we have discussed the suitability of mmWave band for 5G cellular networks. We have also proposed a resource sharing scheme for concurrent D2D communications in mmWave 5G cellular networks that can significantly improve network capacity while keeping network connectivity well. The article should be useful for future research on enabling D2D communications in mmWave 5G cellular networks.

To achieve high transmission rate and aggregate capacity, mmWave base stations may be densely deployed, especially for urban areas. Thus, mobile users may have to hand off frequently between mmWave base stations. Fast neighbor discovery is required in the handoff procedure for mobile users to find nearby base stations and switch to the base station with better link quality. Although directional antennas offer many advantages on improving spatial reuse and network capacity, there are challenges (e.g., deafness problem) in neighbor discovery. In our future work, we will study neighbor discovery for frequent handoffs with directional antennas in mmWave 5G cellular networks.

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Biographies

Jian Qiao (qiaojian1@gmail.com) received his B.E. degree from Beijing University of Posts and Telecommunications, China, in 2006 and his M.Sc. degree in electrical and com-

puter engineering from the University of Waterloo, Canada, in 2010. He is currently working toward his Ph.D. degree at the Department of Electrical and Computer Engineering, University of Waterloo. His research interests include next generation cellular networks, millimeter-wave communication, medium access control, and resource management.

XUEMIN (SHERMAN) SHEN [M'97, SM'02, F'09] received his B.Sc. (1982) degree from Dalian Maritime University, China, and his M.Sc. (1987) and Ph.D. (1990) degrees from Rutgers University, New Jersey, all in electrical engineering. He is a professor and University Research Chair, Department of Electrical and Computer Engineering, University of Waterloo. He was the Associate Chair for Graduate Studies from 2004 to 2008. His research focuses on resource management in interconnected wireless/wired networks, wireless network security, social networks, smart grid, and vehicular ad hoc and sensor networks. He served as the Technical Program Committee Chair/Co-Chair of IEEE INFOCOM '14 and IEEE VTC '10 Fall, Symposia Chair of IEEE ICC '10, Tutorial Chair of IEEE VTC '11 Spring and IEEE ICC '08, Technical Program Committee Chair of IEEE GLOBECOM '07, General Co-Chair of Chinacom '07 and QShine '06, Chair of the IEEE Communications Society Technical Committees on Wireless Communications, and P2P Communications and Networking. He also serves or has served as Editor-in-Chief of *IEEE Network*, *Peer-to-Peer Networking and Application*, and *IET Communications*; a Founding Area Editor of *IEEE Transactions on Wireless Communications*; an Associate Editor of *IEEE Transactions on Vehicular Technology*, *Computer Networks*, *ACM/Wireless Networks*, among others; and a Guest Editor of *IEEE JSAC*, *IEEE Wireless Communications*, *IEEE Communications Magazine*, *ACM Mobile Networks and Applications*, and more. He received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004, 2007, and 2010 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. He is a registered Professional Engineer of Ontario, Canada, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, and a Distinguished Lecturer of the IEEE Vehicular Technology and Communications Societies.

Jon W. Mark [M'62, SM'80, F'88, LF'03] received his Ph.D. degree in electrical engineering from McMaster University in 1970. In September 1970 he joined the Department of Electrical and Computer Engineering, University of Waterloo, where he is currently a Distinguished Professor Emeritus. He served as the Department Chairman during the period July 1984–June 1990. In 1996 he established the Center for Wireless Communications (CWC) at the University of Waterloo and is currently serving as its founding Director. He was on sabbatical leave at the following places: IBM Thomas J. Watson Research Center, Yorktown Heights, New York, as a visiting research scientist (1976–1977); AT&T Bell Laboratories, Murray Hill, New Jersey, as a resident cConsultant (1982–1983): Laboratoire MASI, Université Pierre et Marie Curie, Paris, France, as an invited professor (1990–1991); and the Department of Electrical Engineering, National University of Singapore, as a visiting professor (1994–1995). He has previously worked in the areas of adaptive equalization, image and video coding, spread spectrum communications, computer communication networks, ATM switch design, and traffic management. His current research interests are in broadband wireless communications, resource and mobility management, and cross-domain interworking. He is a Fellow of the Canadian Academy of Engineering. He is the recipient of the 2000 Canadian Award for Telecommunications Research and the 2000 Award of Merit of the Education Foundation of the Federation of Chinese Canadian Professionals. He was an Editor of *IEEE Transactions on Communications* (1983–1990), a member of the Inter-Society Steering Committee of IEEE/ACM Transactions on Networking (1992–2003), a member of the IEEE Communications Society Awards Committee (1995–1998), an Editor of *Wireless Networks* (1993–2004), and an Associate Editor of *Telecommunication Systems* (1994–2004).

QINGHUA SHEN received his B.Sc. and Master's degrees in electrical engineering from Harbin Institute of Technology, China, in 2008 and 2010, respectively. He is currently working toward a Ph.D. degree in the Department of Electrical and Computer Engineering, University of Waterloo. His research interests include resource allocation for e-healthcare systems, cloud computing, and smart grid.

YEJUN HE received a Ph.D. degree in information and communication engineering from Huazhong University of Science and Technology in 2005. He is a professor at Shenzhen University. He has been a visiting professor at the University of Waterloo and Georgia Institute of Technology. His research interests include channel coding and modulation, MIMO-OFDM wireless communication, space-time processing, and smart antennas.

LEI LEI received a B.S. degree in 2001 and a Ph.D. degree in 2006, respectively, from Beijing University of Posts and Telecommunications, both in telecommunications engineering. From July 2006 to March 2008, she was a postdoctoral fellow at Computer Science Department, Tsinghua University, Beijing, China. She worked for the Wireless Communications Department, China Mobile Research Institute from April 2008 to August 2011. She has been an associate professor with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, since September 2011. Her current research interests include performance evaluation, quality of service, and radio resource management in wireless communication networks.