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Performance Evaluation of 5G NR Traffic Offloading onto WiFi Direct

Siying Tan[1], Chao Shen[2], Rongtao Xu[1], Rui Shi[1], Xuemei Wang[1], Dengtao Zhang[1], and Bo Ai[1]
[1]State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China 100044
[2]Shenzhen Research Institute of Big Data, Shenzhen, China 518172
chaoshen@sribd.cn

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***Abstract*—With the fifth-generation (5G) of mobile network, users can enjoy wide coverage, multiple connections, and low-latency network access. However, the path loss and penetration loss of high frequency signal are serious in free space, especially in indoor scenario, resulting in communication blind districts. In this paper, to improve the transmission performance of the edge nodes, a multi-hop transmission scheme combining 5G and WiFi Direct is proposed. In addition, a 5G+WiFi device-to-device (D2D) system-level simulation platform is built to test the performance of the scheme. Based on the current networking algorithm, the simulation results show that the scheme can effectively improve the throughput and reduce the packet loss rate of edge nodes. In addition, the number of routing hops and new radio (NR) signal threshold will affect the transmission performance of the node.**

Keywords*—*device-to-device, WiFi direct, 5G, data offloading, multi-hop communication

I. Introduction

In recent years, with the rapid growth of wireless data services, high frequency communication has attracted extensive attention. Due to the increased frequency and bandwidth, the performance of communication system, such as data rate, delay and access quantity can be greatly improved. But these benefits are limited by the path loss and penetration, especially in complex indoor scenario. High frequency signals are prone to appear coverage blind spots, which make edge nodes communication unreliable. Traditional solutions tend to increase the number of base stations (BSs) in the scenario. But it will result in frequent switching between BSs, which complicates the control algorithm and increases latency.

Another solution is to deploy multiple relay nodes to amplify and forward the signal from the BS. In particular, forwarding signal through WiFi is a simpler and cheaper way to relay. The authors in [1] proposed a scheme of indirect connections to the internet through a multi-hop ad-hoc network based on WiFi Direct. Besides, some researchers have also studied in the area of multi-hop transmission combined with long term evolution (LTE) and WiFi Direct. The joint problem of routing, resource allocation, power control and link scheduling is analyzed in [2], hoping to offload traffic from BSs by relaying data through multi-hop D2D user equipment under cellular network. Moreover, in [3], the authors formulated the problem of data offloading in the cellular network combined with WiFi Direct as a min-max problem for optimal solution. Although the above research has achieved effective data relay and reduced coverage blind spots to some extent, it cannot be adapted to the 5G technology that is widely used today.

There are also related researches in the 5G system. Third Generation Partnership Project (3GPP) introduces NR sidelink technology in Release 16 [4]. Sidelink can realize communication between V2X devices without network. Some researchers presented design of sidelink for mobile relaying from a physical-layer (PHY) perspective [5]. Furthermore, 3GPP introduces user equipment to network relay (U2N Relay) technology in R17 [6]. When the link quality between the remote user equipment (UE) and the BS deteriorates, the remote UE can select an appropriate relay UE to ensure service continuity through the U2N relay technology. However, NR sidelink is still in the research stage and not yet commercially available.

In contrast, WiFi Direct technology is already available on most client devices. Combining 5G with WiFi Direct is a more commercially available method to relay data, which may solve the problem of communication blind spots. Therefore, this paper proposes a 5G+WiFi D2D multi-hop transmission scheme. We extend the single-hop routing to realize multi-hop networking based on WiFi direct protocol [7]. Besides, we build a system-level simulation platform and compare the performance of 5G direct transmission and 5G+WiFi D2D multi-hop transmission. Furthermore, we evaluate the performance loss caused by multiple hops and test the effect of NR signal threshold on the transmission performance of edge nodes.

The rest of this paper is organized as follows. Section II briefly introduces 5G NR, WiFi, and WiFi Direct technologies. In section III, we present specific implementation of multi-hop networking, multi-hop transmission, and data offloading. Section IV simulates two scenarios and analyze the results. Finally, we conclude the paper in Section V.

II. 5G NR and WiFi

In this section, some prevalent communication technologies like 5G NR, WiFi, and WiFi Direct are introduced. These techniques are the basis of the research in this paper.

A. 5G NR

5G NR is a new radio access technology (RAT) developed by 3GPP for use in 5G mobile communication networks.

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$$W(i)=\begin{cases}\omega_1 E(i)+\omega_2 S_c(i)+\omega_3 S_w(i)+\omega_4\frac{1}{h(i)}+\omega_5\frac{1}{n(i)}, & \text{if } h(i)=1\\ 0, & \text{if } n(i)\geq N \text{ or } h(i)\geq M\geq 1 \text{ or } t(i)\geq T_{th}\\ \omega_1 E(i)+\omega_2\left(R(i)+\frac{1}{t(i)}\right)+\omega_3 S_w(i)+\omega_4\frac{1}{h(i)}+\omega_5\frac{1}{n(i)}, & \text{others}\end{cases} \quad (1)$$

3GPP's 38 series specification [8] defines the technical details for NR. The bands of 5G NR are generally divided into two frequency ranges: frequency range 1 (FR1), which includes bands below 6 GHz, and frequency range 2 (FR2), which includes bands in the mmWave range (20-60 GHz). As compared to the previous generation of mobile communication technology, 5G has many advantages, including high reliability, low latency, wide connectivity, and ubiquitous network, which greatly facilitate economic and social development as well as industrial digitization.

B. WiFi

IEEE 802.11 wireless local area network (commonly referred to as WiFi network), with its technical advantages of flexible deployment, low cost, high-speed transmission, good interoperability and compatibility, makes the wireless local area networks (WLAN) network based on the WiFi standard the most popular today [9].

IEEE 802.11 protocol mainly uses the carrier sense multiple access with collision avoid (CSMA/CA) mode to access the channel. If the channel is idle, the node can start transmitting data after a distributed inter-frame spacing (DIFS). Otherwise, the node executes the distributed coordinated backoff algorithm until the channel is idle again.

The WiFi system in this article is based on the IEEE 802.11ac protocol. The system adopts orthogonal frequency division multiplexing (OFDM) technology. The modulation method is improved to 256 quadrature amplitude modulation (QAM). The frequency band of 802.11ac is 5.17 $\sim$ 5.835 GHz, and the bandwidth is extended to 160 MHz. 802.11ac protocol also adopts technologies such as multi-user multiple-input multiple-output (MU-MIMO) and beamforming [10].

C. WiFi Direct

WiFi Direct [7], officially known as WiFi Peer-to-Peer (P2P), is a new technology standardized by the WiFi Alliance to enable D2D communication between nearby devices without the need for a wireless access point (AP). Based on IEEE 802.11 architecture, WiFi Direct enables efficient D2D connectivity in unlicensed frequency bands. In this case, the device negotiates to play the roles of AP and client. WiFi Direct inherits the QoS (Quality of Service), security and energy saving mechanisms of WiFi [11]. Compared to LTE, it consumes less energy and is a simpler protocol. Since it operates on shorter links, it also achieves a better level of spatial reuse than 5G.

III. 5G+WiFi D2D Scheme

Currently, most mobile devices are multi-radio capable, allowing flexible use of 5G and WiFi interfaces. Therefore, we propose a networking transmission method that combines 5G and WiFi, hoping to improve the performance of edge nodes. The 5G+WiFi D2D scheme in this paper mainly includes three parts: multi-hop networking, multi-hop transmission, and data offloading.

A. Multi-hop Networking

The WiFi Direct protocol [7] specifies the end-to-end connection process which only supports one-hop routing. However, multi-hop routing is needed in our study. Therefore, we extend the single-hop routing to realize multi-hop networking. The network topology is shown in Fig. 1. We define two device states: relay group owner (relay GO) and gateway group owner (gateway GO). There is only one device in each group (i.e. group owner). The relay GO can only connect with other GOs through WiFi, while the gateway GO can not only communicate with the relay GO through WiFi, but also directly connect with the BS through NR.

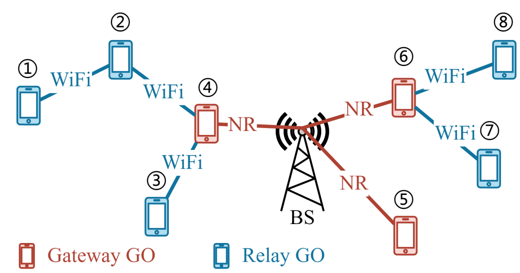

Fig. 1: Network Topology.

The networking process is shown in Fig. 2. In our study, whether a device can be a gateway GO depends on the device's cellular signal strength. When the cellular signal strength $S_c(i)$ of device i is higher than the threshold P_c, we determine the device as a gateway GO.

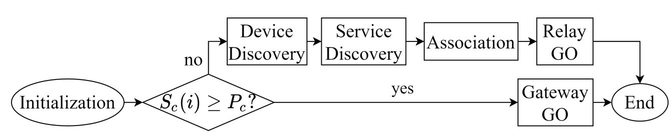

Fig. 2: Multi-hop Networking Process.

When the cellular signal strength $S_c(i)$ of device i is lower than the threshold P_c, the device i will look for a host device to connect to. There are three steps for device to select the last hop device: device discovery, service discovery and association. In the device discovery stage, device i will periodically scan different channels for other devices. When device i discovering other devices, it will enters the service discovery stage. In this stage, device i will collect the capability information of surrounding devices (such as power, cellular signal strength, hop count, etc.). Based on the collected information, the device will calculate the weighted scores of surrounding devices. The calculation method of the weighted

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score is shown in (1). Table I shows the meanings of each symbol in (1).

TABLE I: Notation

Symbol	Definition
i	The index of the device
$n(i)$	The number of connected devices
$h(i)$	The hop count of device i
$E(i)$	The battery level
$S_c(i)$	The power of cellular signal
$S_w(i)$	The power of WiFi signal
$R(i)$	The transmission rate of device i
$t(i)$	The delay of device i
N	Maximum number of connected devices
M	Upper limit of hops from the device to the BS
ω_k	The weights of capability information, $k \in [1:5]$

After calculating the weighted scores of surrounding devices, device i will connect to the device with the highest score and become a relay GO. Each device in the scenario will go through the above networking process. After a period of time, the network topology gradually becomes stable, that is, the multi-hop networking in this scenario is completed. When the communication condition of the device is extremely poor, the device will fail to join the network. It will not be discussed here due to limited space.

B. Multi-hop Transmission

Based on our proposed networking method, relay forwarding is indispensable when data packets are transmitted from the source node to the destination node. The forwarding mechanism we proposed is a deterministic multi-hop routing which is simple and easy to maintain. It is different from the classical dynamic ad hoc network protocol [12].

At the beginning, the source node generates an application layer packet containing the media access control (MAC) address of the destination node. According to the routing table, the source node can find out the MAC address of the next hop and queue the packet for unicast transmission. The next hop node will receive the data packet from the source node and judge:

a) If the MAC address of the final destination is the same as the local, the node will receive the packet and update the simulation statistics.

b) If the MAC address of the final destination is different from the local, the node will act as a relay. Then the node will determine whether the final destination MAC address is in its routing table:

i) If the MAC address of the final destination is included in the routing table of the local, the MAC address of the next hop can be determined. The packet is then put into the sending queue of the current node for relay transmission.

ii) If the MAC address of the final destination is not included in the routing table of the local, the data packet will be discarded. We regard this transmission as a failure and then update the simulation statistics.

C. Data Offloading

Under the scheme proposed in this paper, the devices in the scenario first complete multi-hop networking. Then the data is offloaded to neighboring devices through D2D communication according to the multi-hop transmission process.

The offloading of data is mainly reflected in two aspects. On the one hand, the sending queue of a node not only receives data packets from the application layer of this node, but also receives data packets from other nodes that need to be forwarded. On the other hand, packets entering the queue are ordered based on the first-in-first-out (FIFO) mechanism. If the sending queue buffer is full, discard the packets waiting to enter the queue and update the simulation statistics. Packets that are discarded will be retransmitted later.

IV. Simulation

In order to test the performance of the 5G+WiFi D2D system, we built a system-level simulation platform, which supports link-level and system-level simulation of NR and WiFi D2D. Additionally, the platform supports the simulation of NR and WiFi D2D wireless environments (including scenario, channel, NR and WiFi physical layer), terminal model (including traffic model, terminal distribution model, mobility model, energy consumption model and interference model), transmission protocol (including real-time networking assisted by cellular network, multi-hop routing, forwarding and data offloading). Moreover, the platform has implemented CSMA/CA and link rate adaptation technology.

Two scenarios are considered: the chain scenario and the indoor home scenario. We use throughput, delay, and packet loss rate as our main performance metrics. The throughput mentioned in the following paragraphs is calculated under the full buffer traffic. The delay and the packet loss rate are calculated under the file transfer protocol (FTP) traffic. Some important simulation parameters are shown in Table II.

TABLE II: System Parameters

Parameter	Value
NR Up/down link carrier frequency	3.45 GHz / 3.55 GHz
WiFi carrier frequency	5.775 GHz
NR/WiFi channel bandwidth	40 MHz / 80 MHz
Number of NR Tx / Rx antennas	4 / 4
Number of WiFi antennas	1
Traffic model	Full Buffer / FTP

A. Chain Scenario

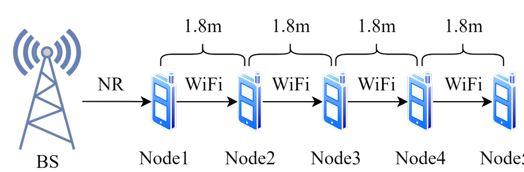

Fig. 3: Chain Scenario.

In order to evaluate the performance loss caused by multiple hops, we set up a chain scenario with a fixed networking topology for testing. As shown in Fig. 3, five nodes are arranged in a straight line at equal intervals (1.8 m). Each time we only configure traffic for one node and record transmission information. Due to the limited space, here we only give the results of the downlink transmission, as shown in Fig. 4.

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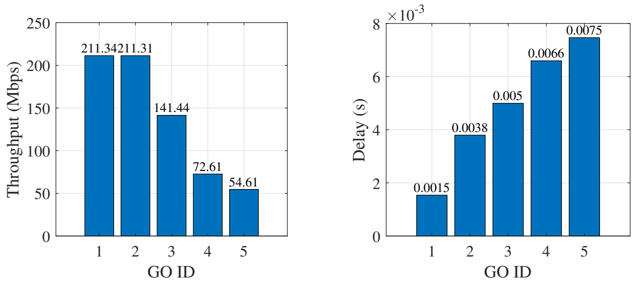
As Fig. 4(a) suggests, as the number of hops increases, the throughput of the node decreases, and the delay of the node increase. It is noteworthy that the throughput of node 3, 4, and 5 in downlink is reduced to about 1/2, 1/3, and 1/4 of node 2, respectively. This is a result of CSMA/CA mechanism, which is the core of IEEE 802.11ac protocol. The transmission between node 2, 3, 4, and 5 is all on the same WiFi channel, which will trigger CSMA/CA mechanism, so that nodes with different hops will back off during the transmission. This is equivalent to dividing the channel resources equally by each hop, making the throughput drop regularly. Meanwhile, transmission time also becomes longer, as shown in Fig. 4(b).



(a) Throughput (b) Delay

Fig. 4: Downlink throughput and delay of nodes with different hops in chain scenario.

The above analysis shows that although more routing hops can make nodes farther from the BS join the network, the performance loss of nodes is very serious. Therefore, future research will consider dynamic adjustment of networking conditions to avoid excessive routing hops in the network topology.

B. Indoor Home Scenario

In order to test whether our proposed scheme can improve the transmission performance, we set up an indoor home scenario to compare the performance of 5G direct transmission and 5G+WiFi D2D multi-hop transmission.

In indoor home scenario, there are 2×2 rooms. The size of each room is 5 m $\times$ 5 m $\times$ 3 m. In each room, three users are randomly distributed. The BS is located outdoors with coordinates $[100, 100, 25]$m, as shown in Fig. 5. Path loss and penetration loss are considered in the simulation.

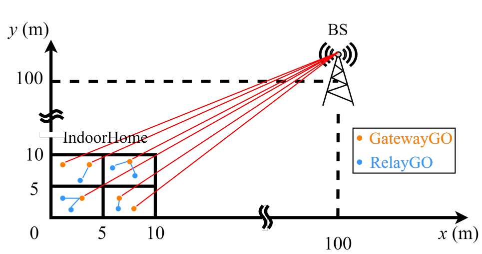
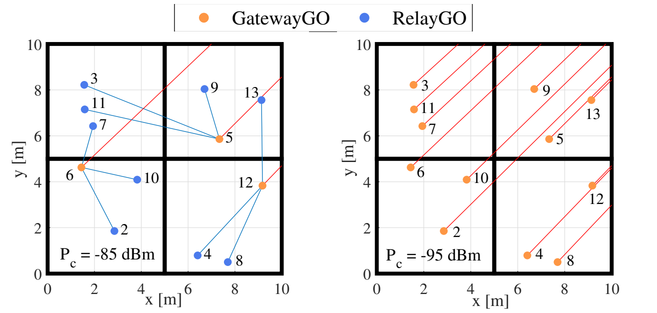


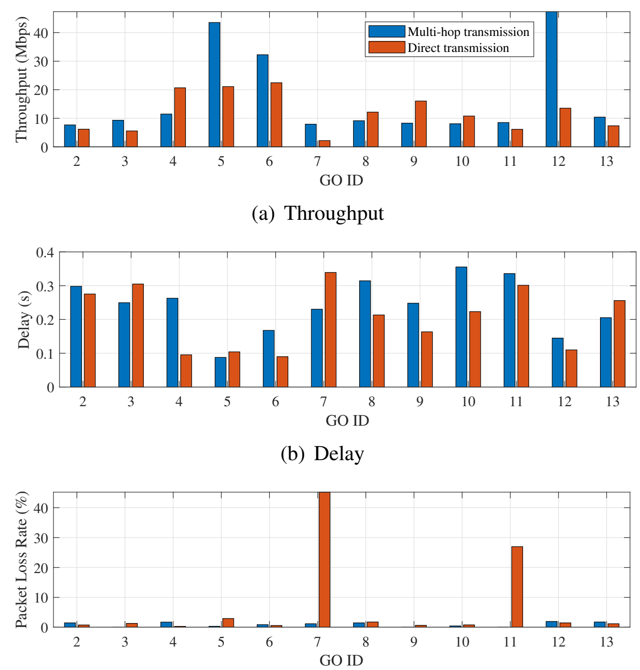
Fig. 5: Indoor Home Scenario.

Fig. 6 shows the networking topology in two cases: (1) direct transmission ($P_c = -95$ dBm) (2) multi-hop transmission ($P_c = -85$ dBm). After several simulations, we find that when $P_c \leq -95$ dBm, all nodes can become gateway GO, which means that all nodes are directly connected to the BS through NR. When $P_c > -85$ dBm, no node can become the gateway GO, which means multi-hop networking fails. Therefore, it is essential to determine an appropriate NR signal strength threshold range before multi-hop networking. Designing an adaptive algorithm to obtain a suitable NR signal threshold is one of our future work.



(a) multi-hop transmission (b) direct transmission

Fig. 6: Network topology under different NR signal strength thresholds in indoor home scenario



(a) Throughput

(b) Delay

(c) Packet loss rate

Fig. 7: Throughput, delay and packet loss rate of each node in two cases .

The throughput, delay and packet loss rate of each node in two cases are shown in Fig. 7. As shown in Fig. 7(a), we can notice that the throughput of gateway GOs has improved significantly in multi-hop transmission. This is because 5G transmission resources are all allocated to three gateway GOs. The throughput of gateway GOs also includes the data forwarded.

In addition, we consider nodes with throughput less than 10 Mbps in direct transmission as edge nodes, i.e. node 2, 3, 7, 11, 13. The throughput of most edge nodes has improved in multi-hop transmission. In multi-hop transmission, the average throughput of edge nodes is 60.05% higher than that of direct transmission.

According to Fig. 7(b), the delay of multi-hop transmission

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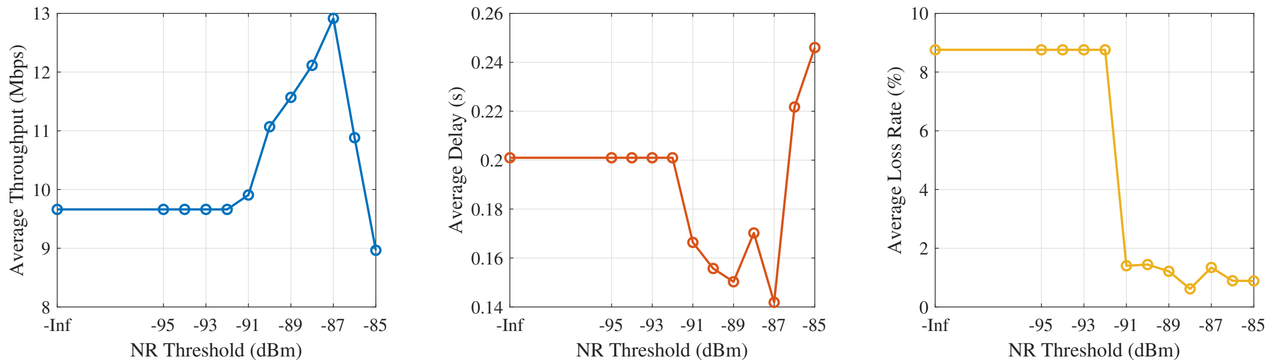

(a) Throughput (b) Delay (c) Packet loss rate

Fig. 8: Throughput, delay and packet loss rate of edge nodes under different NR signal strength thresholds.

is similar to that of direct transmission. The average delay of edge nodes under multi-hop transmission is only 0.034s longer than that of direct connection transmission.

Multi-hop transmission can also reduce the packet loss rate of edge nodes. The packet loss rate of most nodes is at a low level in Fig. 7(c). But the packet loss rates of node 7 and 11 change significantly. The reason is that the channel quality between nodes 7, 11 and the BS is so poor that the index of modulation and coding scheme (MCS) has been reduced to the lowest level during the link adaptation. But the block error rate is still high. After the node completes the multi-hop networking, the channel quality of node 7 and 11 is improved, the packet loss rate is correspondingly reduced.

We also test the effect of NR signal threshold P_c on the transmission performance of edge nodes. In Fig. 8(a), as the threshold of NR signal increases, the average throughput of edge nodes increases first and then decreases. This is primarily due to the fact that under good transmission conditions, a small number of gateways GO can improve the overall throughput. However, a lot of edges nodes will trigger the CSMA/CA mechanism in the process of preempting resources, resulting in a decrease in overall throughput. The reason for the variation of the delay in Fig. 8(b) is similar. For the packet loss rate in Fig. 8(c), under the CSMA/CA mechanism and retransmission mechanism, edge nodes sacrifice the performance of delay and throughput to ensure the reliability of transmission. Therefore, choosing an appropriate NR signal strength threshold and networking algorithm is the key to improving system performance in the future.

V. Conclusion

In this paper, we propose a multi-hop transmission scheme combining 5G and WiFi Direct and build a 5G+WiFi D2D system-level simulation platform. Based on the platform, we compare the performance of 5G direct transmission and 5G+WiFi D2D multi-hop transmission. The performance loss caused by multiple hops has been evaluated. Furthermore, we test the effect of NR signal threshold on the transmission performance of edge nodes. The simulation results show that our scheme can improve the throughput and reduce the packet loss rate of edge nodes. However, as the number of routing hops increases, the node performance gradually decreases. Besides, NR signal threshold will also effect the performance of the edge nodes. Therefore, in the future, we will design a threshold selection strategy to optimize network performance.

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