Infrastructure vs. Multi-Hop D2D Networks: Availability and Performance Analysis

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***Abstract*—With the increasing number of wireless networks available, and mobile devices with access to the Internet, it is essential to obtain the best connection, whether this is a direct path through Wi-Fi or cellular or an indirect path via one or multiple peer to peer devices. As an example, multi-hop ad hoc networks are essential in areas where infrastructure networks are unavailable or sparsely available due to natural disasters such as earthquakes, or in conflict or war zone areas. In this paper, we present and analyze the accessibility of Wi-Fi and cellular networks in Rochester, NY, and compare the performance in terms of the upload and download speeds of direct Wi-Fi and cellular connections with 1-hop, 2-hop and a 3-hop ad hoc networks based on Wi-Fi Direct. Experimental results show that although Wi-Fi access points are widely available, in more than 20% of locations all of the available access points are inaccessible due to security restrictions. Moreover, the LTE cellular networks provides the highest download speed compared to Wi-Fi and multi-hop Device-to-Device (D2D) networks, while the upload speeds of Wi-Fi and cellular are comparable. Finally, our experimental results show that extending access to the Internet to devices that might not otherwise have a direct connection through multi-hop D2D connections is feasible at the expense of a 62% reduction in upload and 64% reduction in download speed, in the worst case.**

I. INTRODUCTION

According to a recent report by Cisco, smartphones' traffic represented 13% of total IP traffic in 2016, and this is expected to increase to 33% and to exceed PC traffic by 2021. Moreover, the growth rates of devices supporting Machine-to-Machine (M2M) communications, smartphones, tablets and TVs is expected to be 49%, 49%, 29%, and 21%, respectively [1].

Due to the rapid growth in the number of wireless devices with increasingly high speed demands, there is a need to profile all the available wireless networks, whether access is through Wi-Fi access points, cellular networks or by using P2P protocols such as Wi-Fi Direct [2].

Cellular and Wi-Fi networks are the two dominant infrastructure-based types of networks that provide access to the Internet. For cellular networks, the International Mobile Telecommunication (ITU) designed the third generation (3G) standard that offers a peak data rate between 200 Kbps and 84 Mbps, while the fourth generation (4G) standard, which uses either the Worldwide Interoperability for Microwave Access (WiMax) or the Long Term Evolution (LTE) standard, defines a peak rate of 100 Mbps for high mobility communication and 1 Gbps for low mobility [3]. On the other hand, Wi-Fi 802.11 legacy standard was released in 1997 with data rates up to 1 Mbps. This obsolete standard was improved with the 801.11a/b/g/n/c/d standards to achieve data rates up to 7 Gbps, and a coverage area in the hundreds of meters [4], [5]. Moreover, Wi-Fi has penetrated most buildings in the US (including 14.3 million or 65% of online households) as reported by Jupiter Research [6]. This massive Wi-Fi availability creates an opportunity for wireless devices to always be connected to the Internet. However, it is important to note that most of these Wi-Fi access points (APs) are actually deployed in homes or offices and do not allow unauthorized devices to connect to them for security reasons.

In contrast to infrastructure networks, Mobile Ad Hoc Networks (MANETs) are infrastructure-less networks in which the devices communicate between each other without the need for central control [7]. Infrastructure-less networks are necessary in situations where infrastructure-based networks are difficult to deploy, e.g., battlefields, or are inefficient to support connectivity [8]. One of the promising protocols that is capable of creating these types of networks is Wi-Fi Direct, which can play a major role in providing an Internet connection to devices that are not able or allowed to directly connect to the Internet.

Wi-Fi Direct is a protocol defined by the Wi-Fi Alliance to enhance device to device communication over traditional Wi-Fi radios without the requirement of a fixed infrastructure. The Wi-Fi Direct standard organizes devices into groups, where one device acts as the group owner and embeds soft AP functionalities such as power management mechanisms similar to an infrastructure-based Wi-Fi network [9].

The first step in creating a Wi-Fi Direct group is the device discovery process, which consists of two phases: Scan and Find. During the scan phase, the device scans the Wi-Fi social channels for a predetermined duration to collect information about the available devices. Afterwards, during the Find phase, the device in the search state sends Probe Requests and waits for a Probe Response from a device in the listen state on the same channel to start the group formation phase [8].

In each group, a device that supports the Wi-Fi Direct protocol is considered to be a P2P client, whereas a legacy client is a device that supports Wi-Fi but does not support the Wi-Fi Direct protocol, and sees the group owner as a traditional Wi-Fi access point. Both P2P and legacy clients can coexist in the same group [10].

Given the increasing number of communication technologies, wireless networks available, and mobile devices with access to the Internet, connecting to the Internet through a direct path through Wi-Fi or cellular or through an indirect path via one or multiple devices using D2D communication are all valuable options. However, selecting the connection that provides the highest performance becomes paramount.

In this paper, we evaluate the accessibility and the quality of wireless networks around the University of Rochester in Rochester, NY. Our evaluation focuses on the AP received signal level and on the number of total/open access points. In addition, since a higher received signal level (RSSI) does not necessarily provide the best connection, we provide analysis of the upload and download speeds of Wi-Fi networks in order to have a realistic predication of future values based on the signal level and frequency.

Moreover, we have developed an Android application to connect devices into a multi-hop D2D network using Wi-Fi Direct, and we compare the performance in terms of upload/download speeds of this indirect access to the Internet to a direct Wi-Fi or cellular connection.

The rest of the paper is organized as follows. In Section II, we present an overview of the related work in wireless networks profiling and analysis. In Section III, we briefly describe our Wi-Fi and cellular networks profiling Android application, and provide some details on how to create multi-hop D2D networks using Wi-Fi Direct. In Section IV, we present a performance evaluation of the available wireless networks in terms of RSSI, upload and download speeds. In addition, we present the upload and download speeds to the Internet when connecting through a multi-hop D2D network. Finally, conclusions are drawn in Section V.

II. Related Work

Wi-Fi coverage mapping of the Boston metropolitan area was presented in [6]. The authors evaluated the connection quality of clients connected to free Wi-Fi access points when moving at vehicular speeds. The experiment took place between July 2005 and July 2006 for a total of 290 driving hours. The authors found an average link layer connectivity of 13 seconds, an average throughput of about 30 KBytes/s, and a mean duration between successful associations to access points of 75 seconds.

The authors in [11] conducted an experiment to observe the impact of buildings on a wireless network, focusing on its performance as a function of physical distance and channel overlap. The authors also used a spectrum analyzer for a week to continuously monitor the wireless network in an office building, and found the average RSSI indoors to be 20 dB higher compared to the average RSSI recorded outdoors.

A symbolic space modeling and analysis based on Wi-Fi network data was presented in [12]. The authors' aim was to use the Wi-Fi network usage patterns to characterize the physical space. For instance, in libraries, the usage percentage of the Wi-Fi network would be high as most people use wireless devices.

An experimental evaluation of the amount of data transferred from and to the Internet on 3G and Wi-Fi access points is conducted for both driving and walking speeds in [5]. The authors show that, since the contact time of the 3G network is greater compared to Wi-Fi, Wi-Fi download throughput is less but nearly equivalent to 3G. On the other hand, Wi-Fi upload throughput surpasses 3G, since the upload data is small and on the order of kilobits per second.

A study of Wi-Fi and 3G networks accessibility from moving vehicles in Amherst, Seattle, and San Francisco was conducted in [13]. The authors have found that the average open Wi-Fi access points and 3G accessibility across the three cities is 11% and 87%, respectively, with Amherst having the highest Wi-Fi and 3G accessibility percentages of 12%, and 90%, respectively. Moreover, the results show that 3G connections have lower loss rates and higher throughput compared to Wi-Fi.

The authors in [14] presented a study of Wi-Fi connectivity in different cities in Korea using 100 mobile phones. The results show that users were in a Wi-Fi covered area for 70% of the time on average, and an average data rate from the phone to the measurement server of about 2.76 Mbps.

A three major networks characterization in terms of loss rate, round trip time, and throughput in the Boston area was presented in [15]. The authors show that 4G outperforms Wi-Fi and 3G in terms of throughput and loss rate. It was also shown that leveraging path diversity in cellular networks, using multi-path TCP, and implementing an adaptive socket buffer size, are promising solutions for more reliable data transfer.

Similarly, the authors in [16] analyzed cellular connectivity and quality of three cellular network providers in Trondheim, Norway. First, the authors have developed an Android application that collects parameters such as GPS coordinates, signal strength indicator (RSSI) and round trip delay. Based on the their results, a higher signal strength slightly improves the round-trip delay. In contrast, in the EDGE network, the round-trip delay is highly correlated with the received signal strength.

Paris Wi-Fi and 3G connectivity were studied in [4] to evaluate the potential of Wi-Fi offloading using 82 Km of the bus routes of the city. The authors have obtained 92% 3G cellular coverage, and 99% Wi-Fi coverage using Wireless Internet Service Providers (WISPs) access points.

In this paper, we present an Android application that we have developed to profile the accessibility and quality of Wi-Fi and cellular networks around the University of Rochester in Rochester, NY. Furthermore, our Android app creates a multi-hop D2D network using Wi-Fi Direct, and allows the D2D network to connect to the Internet through a gateway node that supports either Wi-Fi or cellular. Using the app, we then collect experimental results of the upload and download speeds to the Internet of one, two, and three hops ad hoc networks, and compare them to the performance of a direct Internet connection through Wi-Fi and cellular. To the best of our knowledge, this paper provides the first look at the performance of providing Internet connectivity through multi-hop Wi-Fi Direct networks.

III. System Architecture

In this section, we provide a brief description of our data collection application. Furthermore, we provide a description of the functionalities required to create a D2D network using Wi-Fi Direct, and to evaluate the performance of providing access to the Internet through the D2D network.

In what follows, we describe two Android applications that collects data about the available wireless networks, and creates a multi-hop Wi-Fi Direct network to extend connectivity to devices that do not have direct connection to the Internet. Our Android applications can be downloaded from [17].

A. Wireless Infrastructure Networks

We have developed an Android application that collects information about the accessibility, quality and attributes of Wi-Fi access points. The application utilizes the built in scanning functionality of Android OS to obtain information about the Wi-Fi connection, including:

- Scan time;
- GPS coordinates of the device;
- AP SSID, BSSID, and signal strength;
- Wi-Fi frequency range and channel bandwidth and
- Security, authentication, and encryption capabilities.

Based on this data, for each geographical location we have then extracted the following extra information:

- Number of open and total access points and
- Maximum, average, and minimum AP signal strength.

In addition, after connecting to a Wi-Fi network, we obtain the upload and download speeds by transferring an 8 MByte file to and from an Internet server to allow the TCP window to reach its maximum size.

For cellular networks, we record the following information:

- Scan time;
- GPS coordinates of the device;
- Number of cellular base stations and
- Reference Signal Received Power (RSRP).

The Reference Signal Received Power represents the average received power of the cellular tower reference signal and is used for cell selection, re-selection, and handover.

B. Multi-Hop D2D Networks

In order to compare the performance of a direct Wi-Fi or cellular connection to multi-hop D2D networks in terms of upload and download speeds, we have developed an Android application that uses Wi-Fi Direct to create a D2D network. We note that, as discussed in [18], creating multi-hop Wi-Fi Direct networks using Android devices is not straightforward.

1) 1-Hop D2D Network: For a one-hop D2D network, the network consists of a client device (acting as a Wi-Fi Direct group member, GM) and a gateway device (acting as a Wi-Fi Direct group owner, GO), as shown in Figure 1(a). The application works as follows: the client and the gateway initiate the peer discovery process every 3 minutes. When the client discovers the gateway, it sends a connection invitation to it to form a Wi-Fi Direct group. Afterwards, the client

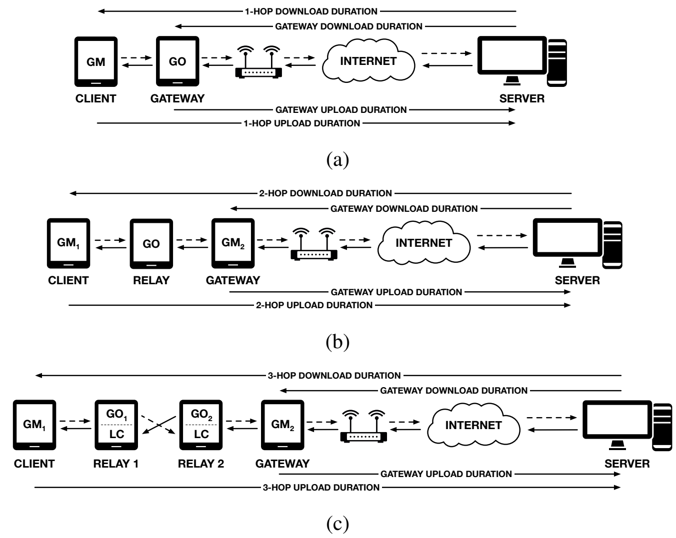

Figure 1: 1-hop, 2-hop and 3-hop D2D network system architectures.

device starts sending 8 MByte of data to the gateway, which is responsible for uploading the data to the Internet server. Subsequently, the gateway starts downloading 8 MByte of data from the Internet server and thereafter transfers it to the client through the P2P interface. For clarity, the dotted lines in Figure 1 show the upload route, while the solid lines represent the download route.

2) 2-Hop D2D Network: In a two-hop D2D network, the network consists of a client device (Wi-Fi Direct GM_1), a relay device (Wi-Fi Direct GO) and a gateway device (Wi-Fi Direct GM_2), as shown in Figure 1(b). After the Wi-Fi direct group is formed, the client device sends the data through the relay device to the gateway, which is responsible for uploading the data to the Internet server. Similarly, the gateway device downloads data from the Internet server and sends it to the client through the relay.

It is important to note that for one-hop and two-hop D2D networks, all the communication can be routed through the devices' P2P interfaces.

3) 3-Hop D2D Network: A three-hop D2D network is built of 4 devices organized in two groups, in which each group consists of one GM and one GO, and two devices belonging to different groups need to be connected to each other to relay information across groups. However, creating a 3-hop D2D network using Wi-Fi Direct is not straightforward compared to 1-hop and 2-hop networks, since the stock Android OS implementation of the Wi-Fi Direct protocol assigns the same IP address to the GOs in different groups, therefore not allowing a connection between two GOs due to routing conflicts [18]. To overcome this obstacle, we have created legacy client (LC) interfaces in both relay nodes, alongside their primary GO_1 and GO_2 interfaces, and connect this additional interface to the P2P interfaces of the other device (i.e., GO_1 and GO_2), as shown in Figure 1(c).

Moreover, to send data from the client device to the gateway, and due to limitations imposed by the Android operating system, the client cannot reach the gateway directly, therefore, we have specified the LC interface of Relay 2 as the destination address. When Relay 2 receives the data from the client device through Relay 1, it will act as a relay and transfer the data from its legacy client interface to its *GO* interface and finally to the gateway, which is responsible for uploading the data to the Internet server.

Similarly, to send data from the gateway to the client device, we need to specify the LC interface of Relay 1 as the destination address. After the gateway device downloads the data from the Internet server, it will send it to the client device through Relay 1, and when Relay 1 receives the data, it will act as a relay and transfers the data from its LC interface to its *GO* interface and finally to the client device.

Finally, we record the total time from when the client device starts sending data, until all the data is received by the Internet server through the gateway device to calculate the upload speed for the multi-hop D2D network. Similarly, we record the time since the gateway device starts downloading data from the Internet server, until all of the data is received by the client device, to calculate the download speed.

IV. Performance Evaluation

In this section, we present the Wi-Fi and cellular network coverage around the University of Rochester in the Rochester, NY. Using the application described in Section III, we have gathered data about Wi-Fi access points using 3 off-the-shelf Android devices running Android 6.0 OS.

We provide an analysis of the upload and download speeds of 1-hop, 2-hop, and 3-hop D2D networks, and compare these speeds with the speeds obtained through a direct Wi-Fi and cellular connections.

A. Wi-Fi & Cellular Coverage

Figure 2 shows a heat map of the received signal strength of a cellular network using the data collected over the period of 7 days. The data collection campaign was carried out by students carrying Android tablets.

In Figure 2, the red and blue colors indicate high and low cellular reference signal received power values, respectively. Here, we have averaged the recorded signal level for the same location. The maximum recorded cellular signal strength was -69 dBm recorded outdoors, which suggests the existence of a nearby cellular base station. On the other hand, the minimum recorded signal was -128 dBm. To put these values into perspective, the reporting range of RSRP is defined from -140 dBm to -44 dBm with 1 dB resolution [19].

Similarly, Figure 3 shows a heat map of the average Wi-Fi received signal strength. The maximum average recorded Wi-Fi signal strength was -45 dBm obtained when connected to a home access point in which the Android device was meters away from the access point. On the other hand, a Wi-Fi signal of only -94 dBm was recorded when riding a car in the freeway, which is expected as no access points are installed in this area.

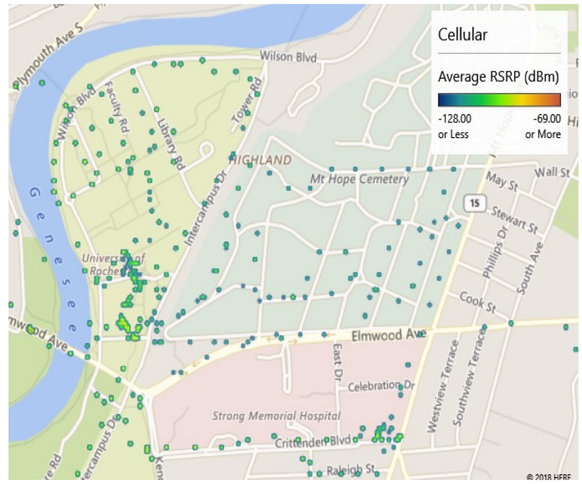

Figure 2: Average Cellular Reference Signal Received Power.

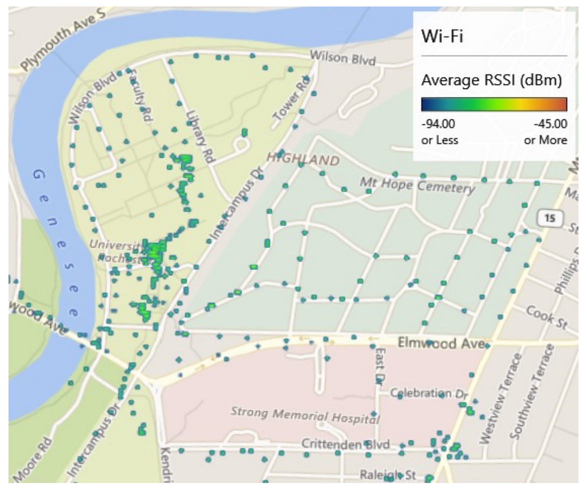

Figure 3: Average Wi-Fi Received Signal Strength.

A summary of selected Wi-Fi and cellular recorded data is shown in Table I.

These results show that, for optimizing the next generation wireless networks, a hybrid architecture must be considered to benefit from both the cellular and Wi-Fi networks coverage areas and their intrinsic capabilities for indoor and outdoor communications.

A histogram of the total and open number of available access points scanned at each location is shown in Figure 4. From this figure, we can see that the maximum number of APs was 66 recorded near College Town, which is an area full of stores and restaurants. Furthermore, the average number of scanned APs was 15, which suggests a high accessibility of Wi-Fi APs in this area. However, about 10% of the locations have only 0-2 Wi-Fi APs, and for more than 20% of the locations, all of the available access points are private and unaccessible due to security restrictions.

We note that an increasing number of ISPs started utilizing

Table I: Summary of selected Wi-Fi and cellular recorded data

Parameter	Value
Wi-Fi	
Average number of access points per location	15
Minimum RSSI	-94 dBm
Average RSSI	-77 dBm
Maximum RSSI	-45 dBm
Cellular	
Average number of base stations per location	6
Minimum RSRP	-128 dBm
Average RSRP	-100 dBm
Maximum RSRP	-69 dBm

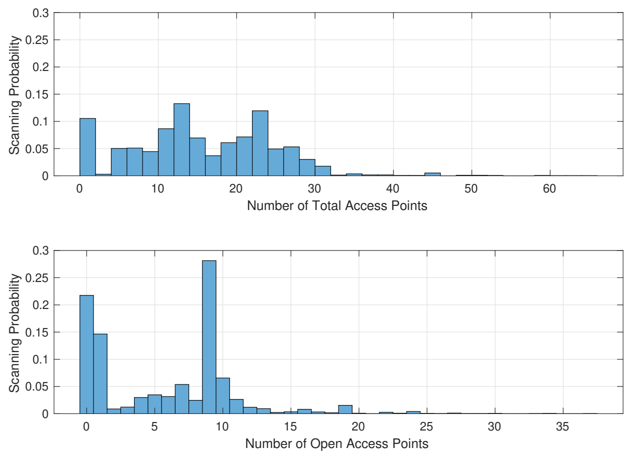

Figure 4: Probability mass function of the number of APs scanned per location.

Wi-Fi hotspots to offload data from the cellular network in order to optimize the spectrum [20]. Hence, we expect to see an increase in the number of open Wi-Fi APs in the near future.

B. RSSI Level vs. Download and Upload Speeds

In this section, we present the average download and upload speeds with respect to the received signal strength and frequency range for Wi-Fi.

Figure 5 shows the average download and upload speeds with respect to the RSSI for the 2.4 GHz and 5.8 GHz frequencies. It is worth noting that these results are obtained through extensive experiments (over 1000 runs).

It is clear from Figure 5 that for the same received signal level, a higher bandwidth results in higher download speeds on average. Moreover, the average download speed on the range -64 dBm to -53 dBm RSSI for the 2.4 GHz frequency was about 14.64 Mbps, while for the same RSSI range, the 5.8 GHz Wi-Fi reached an average download speed of about 27.78 Mbps, which is almost double the download speed for the 2.4 GHz frequency. This is due to the higher number of channels, larger bandwidth in the 5 GHz frequency Wi-Fi, in addition to the higher interference from other devices in the 2.4 GHz frequency Wi-Fi compared to the 5 GHz.

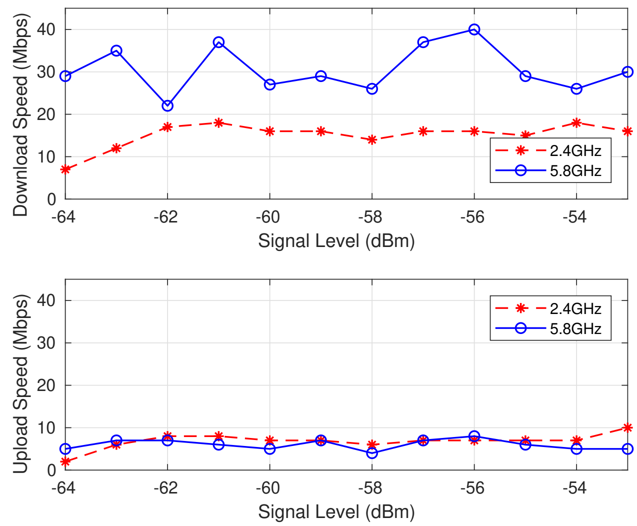

Figure 5: Average download and upload speeds with respect to the received signal strength indicator (RSSI).

On the other hand, a higher frequency doesn't necessarily result in higher upload speeds, as the average upload speeds were about 6.89 and 6.24 Mbps for the 2.4 GHz and 5.8 GHz, respectively. This may be due to Internet traffic and server limitations.

Based on these results, we can conclude that, on average, the 5.8 GHz frequency Wi-Fi results in a higher download speed compared to the 2.4 GHz Wi-Fi regardless of the received signal strength (RSSI).

C. Wi-Fi vs. D2D Ad Hoc Network

In this section, we present a comparison in terms of the average upload and download speeds between a direct Wi-Fi connection, a direct cellular connection, and one-hop, two-hop and three-hop D2D Wi-Fi Direct networks with Wi-Fi and Cellular connections from the Gateway node.

Figure 6 shows that the average upload speed of the direct Wi-Fi connection to the Internet server was about 9.03 Mbps, while the average upload speed of the cellular network reached an average of about 7 Mbps. Furthermore, the 1-hop, 2-hop, and 3-hop Wi-Fi upload speeds were about 6.62 Mbps, 4.65 Mbps, and 2.92 Mbps, respectively. On the other hand, the 1-hop, 2-hop, and 3-hop D2D networks with cellular network as the gateway to the Internet reached lower upload speeds compared to the D2D networks with Wi-Fi as the Internet gateway technology.

As shown in Figure 7, the average download speed of the direct Wi-Fi connection was about 19.77 Mbps, and in contrast to the cellular upload speed, using the LTE cellular network results in an average download speed of about 35 Mbps, which is much higher than the Wi-Fi connection average download speed. Moreover, the download speed for a 1-hop, 2-hop, and 3-hop D2D Wi-Fi networks reached an average of about 12.08 Mbps, 7.94 Mbps, and 7.38 Mbps, respectively.

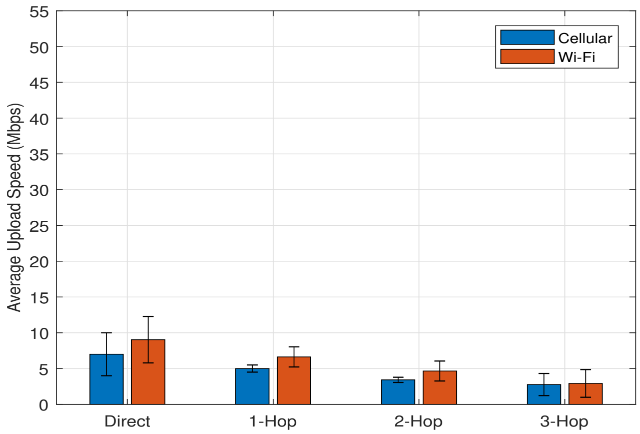

Figure 6: Average upload speeds for direct Wi-Fi, direct cellular, 1-hop, 2-hop, and 3-hop Wi-Fi Direct D2D networks with Wi-Fi and cellular connections from the Gateway node.

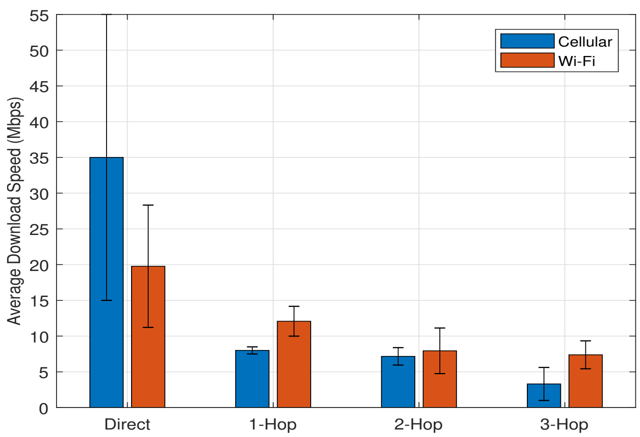

Figure 7: Average download speeds for direct Wi-Fi, direct cellular, 1-hop, 2-hop, and 3-hop Wi-Fi Direct D2D networks with Wi-Fi and cellular connections from the Gateway node.

Based on these experimental results, the LTE cellular network results in the highest download speeds compared to Wi-Fi and multi-hop D2D networks. On the other hand, the upload speeds of the direct Wi-Fi connection were higher compared to the cellular network, on average. Furthermore, the network switching time in the multi-hop D2D cellular network between the Wi-Fi Direct network and cellular (and vice versa) leads to much lower performance compared to a direct cellular connection. This creates a trade-off between the higher download speeds of the cellular network and the no-switching delay of using the Wi-Fi network.

V. Conclusions

In this paper, we have evaluated the accessibility and quality of wireless networks around the University of Rochester in Rochester, NY. Experimental results show that Wi-Fi networks cover almost the entire movement route. Nevertheless, and due to security restrictions, open and accessible Wi-Fi networks are not as available as private Wi-Fi networks. Furthermore, we have created a D2D network using Wi-Fi direct and shown that we can extend access to the Internet through a 1-hop, 2-hop, and 3-hop Wi-Fi Direct connection at the expense of a decrease in upload and download speeds. Finally, we have shown that even for a 3-hop D2D Wi-Fi network we can achieve average upload and download speeds of about 62% and 64% less than the direct Wi-Fi connection, respectively.

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