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***Abstract*—We consider the important emerging scenario of a private 5G packet core supporting proximity services enabling coverage extension for end-devices through relays using Wi-Fi Direct connectivity. We demonstrate and evaluate the implementation of Device-to-device (D2D) communications using Off-The-Shelf User Equipment through the development of a customized 5G Packet Core with Local Area Network capability and a mobile/server application to allow direct communication, discovery, and relay selection between the end-device and the relay(s). The system was tested in a laboratory-based testbed, and latency, throughput, and jitter measurements were obtained for multiple devices. We conclude that 5G networks are suitable for industrial applications, although current 5G solutions are focused on consumer communications, which require changes in the configuration to have similar capacity and delay both for download and upload traffic.**

***Keywords*—5G, Device-to-Device Communications, Wi-Fi Direct, 5G LAN, End-device, Single-hop.**

I. INTRODUCTION

5G networks have been slowly introduced in our everyday lives, either as Stand-Alone (SA) or as Non-Stand-Alone (NSA), allowing a plethora of benefits to the users, such as improved speeds and lower latency [1]. However, despite the numerous benefits, 5G technology faces significant challenges, such as coverage range and infrastructure cost. In addition, there are applications where network coverage in three dimensions becomes a significant issue. For example, due to the higher frequencies in 5G and the significant coverage shrinkage, network coverage on skyscrapers, specifically in smart cities, is a significant challenge [2]. One approach to address the coverage range and infrastructure cost is the concept of Device-to-device (D2D) communications [3]. Instead of expanding the coverage from each Base Station (BS), User Equipment (UE)s could act as relays enabling single or multi-hop networks, extending the coverage without the need for extra infrastructure [4].

D2D was integrated into 3rd Generation Partnership Project (3GPP) Release 12 to develop a global standard for public safety communications [5], [6]. Within 3GPP Proximity Services (ProSe), D2D was seen as a way to extend conventional cellular services. In Release 13, D2D was consolidated as direct communication between two devices, as one UE was allowed to function as a relay for another UE [7], [8]. The requirements for 5G-related services address D2D in two ways. The first approach uses a direct connection between devices without any network entity in between them. The second approach consists of interposing a relay UE between a UE and the 5G network. The relay UE can use multiple access schemes, such as 5G radio access technology (RAT), Long Term Evolution (LTE), Wi-Fi, and fixed broadband. Thanks to the characteristic of not requiring a fixed network structure [9], D2D has been the candidate for several applications. An example of this can be seen in using D2D as an alternative content delivery method to address highly demanding and efficiently distributed communications, such as emergency services and natural disasters [10], [11], [12]. Furthermore, we observe a revitalized focus on D2D communications in far-edge architecture, thus opening up more efficient and coherent ways of integrating the overall architecture [13], [14], [15].

There are various open issues and challenges that need attention in securing D2D communication in 5G environments [16]. The most critical challenges in D2D communications are within the context of device discovery (synchronization, initial device discovery signals, multicell device discovery, frequency of discovery messages); in interference management (Cell Densification and Off-loading, D2D in mmWave Communication); in security (Balancing Security-Energy Trade-off, Lack of Standardization, Decentralized Anonymity Schemes, Privacy); in power control (One Large or Multiple Small Networks, Optimal Transmission Power); and in mode selection (Mode Alterations Volume, Mode Selection Overhead, Dynamic Mode Selection). Nevertheless, since infrastructure cost is an a significant barrier, implementation of D2D needs to be completed with commercially-available UEs. However, such devices do not have all the required features to support this approach.

In this paper and within the framework of the EU-funded project IoT as part of Next Generation Internet (IoT-NGIN) [2], we present some real implementation challenges of D2D communications using common, commercially-available UEs

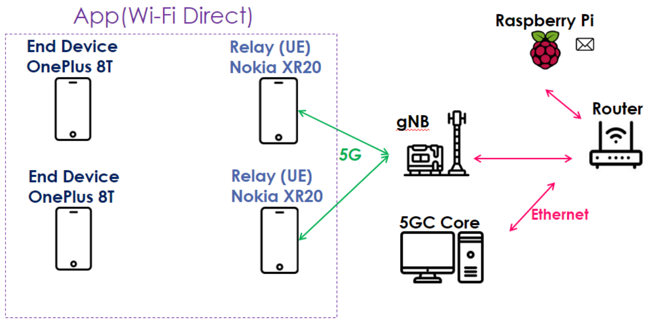


Fig. 1. Overall architecture of the experimental setup.

in an attempt to test the end-to-end functionality and performance of single-hop D2D communications. A customized 5G Packet Core (5GC) and a mobile and server application have been developed and used in these experiments to allow the implementation of a 5G Local Area Network (LAN) so that multiple relays could be identified. The end-device and the relay are connected through Wi-Fi Direct since there are no commercially-available UEs that can act as a 5G Time Sensitive Network (TSN) bridge. Finally, the application was also capable of performing a relay selection, ensuring the power efficiency of the network.

II. EXPERIMENTAL SETUP

An end-to-end experimental setup was implemented involving 4 UEs (2xOnePlus 8T & 2xNokia XR20), a laboratory-based BS (Amarisoft Callbox Mini) with a gNodeB (gNB) that is compliant with 3GPP Release 16 having 20 MHz MHz bandwidth, a 5GC (CUMUCORE OY) running on a Linux-based PC and a custom-made mobile/server application running on a Raspberry Pi 400. Custom SIM cards and settings were used in the mobile phones to connect to the BS and the 5GC properly. Both PLMN-00101 and PLMN-99999 were tested with custom and programmable SIM cards. The connection between the BS, 5GC, and the Raspberry Pi was achieved through Ethernet connections to a 1 Gbps router (MikroTik RouterOS). The gNB and Relay devices were connected with 5G New Radio (NR) in the Stand-alone mode. The End-Devices and Relay devices were connected with Wi-Fi through the developed mobile/server application. The overall experimental setup and configuration demonstrating the end-to-end, single-hop, D2D functionality of the test-bed and the multiple relays and multiple end-devices situation are shown in Figure 1. The exact configuration was used to test the relay selection capability of the mobile/server application.

III. 5G PACKET CORE

Most verticals are currently utilizing Wi-Fi, but 5G brings new benefits tailored for industrial networks, like coverage thanks to the higher transmission power of 5G base stations both indoors and outdoors. Mobility is another major advantage of 5G. Thus, private networks or Non-Public Networks (NPN) are suitable for Industrial communications that are facing a new era of transformation targeting increased automation and efficiency. The industrial network requires ultra-reliability; hence they are mostly based on wired fixed LAN. Wi-Fi has been the de facto replacement for some of the wired technologies, although exposing some shortcomings. NPNs are being considered a key connectivity solution after the latest releases of 5G have defined new features tailored for Industry 4.0 applications. The higher coverage and reliability of NPNs will enable the management of wireless communications on the shop floor without any external interference. With NPN, industrial applications can exchange data locally inside the NPN without external networks to guarantee the strong security requirements of industrial scenarios. NPNs, by default, bring the usage of edge computing with data processing on-premise.

The deployment of NPNs follows strong optimization to guarantee indoor coverage based on areas that require high-availability connectivity. This is translated into high customization, where NPN owners have total control over the network deployment and configuration, ensuring high efficiency and Quality of service (QoS). Therefore, NPNs provide very high reliability, thanks to the integration of time synchronization mechanisms and the use of a dedicated spectrum. This paper focuses on a 5G feature named 5GLAN, designed specifically for connecting wireless devices with fixed LAN. The 5GLAN is a new feature in 5G where the NPN administrator can go to the network management system and create a 5GLAN group. The group includes the list of the General Public Subscription Identifier (GPSI) or the Subscriber Permanent Identity (SUPI) of all UEs that are supposed to use this 5GLAN group to support private communications. The 5GLAN group can use IP or Ethernet type of communication. In addition, the NPN administrator may also indicate any of the following additional information: requested QoS, IPv4 or IPv6 communication, static or dynamic IP address, additional IP services (e.g., DNS, Dynamic DNS, DHCP, IMS, egress to the Internet), additional Ethernet services (e.g., multiple IEEE 802.1Q VLANs). After the 5GLAN group is created and the mobile devices part of the group is selected, the 5G network will start managing the traffic between wireless and wired devices as native Ethernet communications.

The User Plane Function (UPF) that handles the user data in the 5G network is configured to route the traffic based on detected MAC addresses. The UPF learns the MAC address(es) connected interface between the 5G core network and the fixed LAN based on the source MAC addresses of the download (Download (DL)) traffic received on the LAN interface. The UPF learns the MAC address(es) of UE(s) and devices connected to the 5G network based on the source MAC address contained within the Uplink (UL) traffic received on a data session through the interface with the base station. The UPF forwards DL unicast traffic (with a known destination address) on a packet data (Protocol Data Unit (PDU)) Session determined based on the source MAC address(es) used by the UE for the UL traffic. The UPF forwards UL unicast traffic (with a known destination address) on a port (PDU Session) determined based on the source MAC address(es) learned beforehand. The UPF responds on behalf of the UEs as part of the 5GLAN group to Address Resolution Protocol (ARP) requests and/or IPv6 Neighbour Solicitation requests based on local cache information for the Ethernet PDUs. The UPF responds to the ARP and/or the IPv6 Neighbour Solicitation Request by providing the MAC address corresponding to the IP address sent in the request. With this mechanism, 5G can deliver with the 5GLAN seamless Ethernet communications between fixed LAN and 5G-connected devices.

IV. MOBILE & SERVER APPLICATION

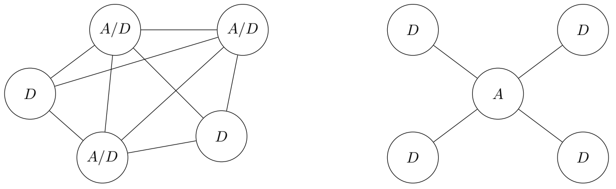
A. Mobile Application

We developed an Android application that relies on Google's Nearby Connections Application Programming Interface (API) to establish D2D links among mobile devices [17]. This API provides tools to perform neighbor discovery before triggering a direct connection between two or more devices. All this without the need for a conventional network infrastructure. Nearby Connections uses Neighbor Discovery Protocol (NDP) with Bluetooth Classic or Bluetooth Low Energy (BLE) to exchange beacons for mutual discovery [18]. In theory, the line-of-sight coverage range of Bluetooth Classic can reach up to $100\,\mathrm{m}$, while that of BLE can reach up to $20\,\mathrm{m}$. The trade-off is that Bluetooth Classic consumes more energy than BLE. Nearby Connections defines two roles for devices to execute NDP: `advertiser` and `discoverer`. Advertisers regularly throw beacons in the air while discoverers listen to the medium to detect the advertisers around it. Advertisers and discoverers cannot establish connections with devices playing the same role. A device can play either one or both roles; however, it will retain the role with which it has established the connection. Therefore, the choice of a device's mode has thus a direct impact on the formation of the network. Note that during the connection establishment procedure, devices will automatically accept connection requests if they come from devices running the same application. Once the devices have discovered each other and established the connections, Nearby Connections uses Bluetooth Classic, Wi-Fi Direct, or Wi-Fi Aware as the link technology for data transfers.

The effective link technology will depend on which topological strategy one decides to use. Nearby Connections defines three strategies (depicted in Figure 2), namely `CLUSTER`, `STAR`, and `POINT_TO_POINT` Figure 2.

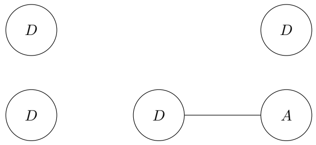
The goal of the `CLUSTER` strategy (Figure 2a) is to interconnect as many devices as possible. To do so, it allows each device assigned as a discoverer to connect to more than one advertiser. In addition, this strategy uses Bluetooth Classic for the communication link. In this strategy, contrary to the others, a device can act simultaneously as an advertiser and a discoverer, thanks to Bluetooth's flexibility. However, this flexibility comes with a cost, which is a much lower throughput when compared with the other strategies.

The `STAR` strategy (Figure 2b) focuses on establishing a star topology using an advertiser as the root and discoverers as leaves. Here, the advertisers can connect to more than one device, whereas discoverers are limited to communicating with a single advertiser. For this purpose, the advertiser acts as an access point that maintains Wi-Fi Direct connections with the leaves. The `STAR` strategy is more rigid than `CLUSTER` but leads to better transfer rates.



a) Cluster Strategy

b) Star Strategy



c) Point-to-Point Strategy

Fig. 2. Nearby Connections's available strategies: (a) `MESH` with two devices set as discover-only (D) and three devices set as advertiser/discover (A/D), (b) `STAR` with one advertiser (which becomes the root) and four discoverers (which become leaves), and (c) `POINT_TO_POINT` with one advertiser and four discoverers (only one discoverer could connect to the advertiser)

Finally, in the `POINT_TO_POINT` strategy (Figure 2c), a link is established between two and only two devices. In this strategy, advertisers and discoverers have to decide with whom they wish to communicate, as they will not be able to communicate with other devices within range (nor advertise or discover) after establishing a direct link. The advertiser functions as a single-link access point, where a Wi-Fi Aware or Wi-Fi Direct access point will be established if the devices support them. This strategy allows for the highest link performance.

Considering that the `CLUSTER` strategy offers low throughput and given that `POINT-TO-POINT` allows single link communications, we adopt the `STAR` strategy in our mobile application.

B. Server Application

In order to communicate the D2D network with the outside, we have implemented a Transmission Control Protocol (TCP) socket in which the relay devices between the D2D network and the 5GLAN network act as clients, while a Raspberry Pi inside the LAN acts as a server. When a client connects to the server, the server registers the new client with its unique ID in a registration table. The server then asks the new client for the devices connected via D2D, returning a JSON with the requested list. Likewise, if an already registered relay has updated its table of connected D2D devices, it will notify the server with a new JSON. Finally, the server generates a routing table where it redirects the traffic of each non-client device to its corresponding Relay, which will then forward the traffic through its D2D link.

V. RESULTS & DISCUSSION

A. Experimental Methodology

Three main tests were performed in this work: testing the 5G network and its specifications; the Wi-Fi Direct and its specifications; and the complete, end-to-end communication. The parameters that were used to test the connections between the devices were Round Trip Time (RTT), throughput, and jitter. RTT is the duration in milliseconds it takes for a network request to go from a starting point to a destination and back again to the starting point. RTT is typically measured using a ping. The ping is set to repeat the measurement 1000 times. Also, the packet size is the default, which is $64\,\mathrm{B}$ [19].

TABLE I. RELAY DEVICE TO 5GC - DOWNLOAD

	RTT (ms)	**Throughput** (Mbps)	**Jitter** (ms)
Phone 1 (SN ced5e14e)	23.23	129.36	0.15
Phone 2 (SN 406f972f)	23.21	96.84	0.19
Average	23.22±0.1	113.10±16.26	0.17±0.02

TABLE II. RELAY DEVICE TO 5GC - UPLOAD

	RTT (ms)	**Throughput** (Mbps)	**Jitter** (ms)
Phone 1 (SN ced5e14e)	25.03	3.51	5.53
Phone 2 (SN 406f972f)	25.58	1.35	8.05
Average	25.31±0.27	2.43±1.08	6.79±1.26

Throughput is defined as the amount of data per time unit delivered over a physical or logical link or passing through a certain network node. It shows the data rate that the network can handle. The measurement method is iperf3 [19]. Jitter is IP Packet Delay Variation. The variation in packet delay is called jitter. The meaning concerns with the variation of a metric (e.g., delay) concerning some reference metric (e.g., average delay or minimum delay). The measurement method is iperf3 [19].

iperf3 was installed on the server and the other device (client) to exchange messages. The bandwidth was set to $200\,\mathrm{Mbps}$ which is higher than devices can support, allowing the devices to reach their maximum speeds. In addition, the reporting intervals are set at $1\,\mathrm{s}$, so the system presents bandwidth, jitter, and loss reports every second. Another parameter is the length of the test, which is set at $1000\,\mathrm{s}$. Moreover, for this test, it was decided to use User Datagram Protocol (UDP) to establish low-latency and loss-tolerating connections. On the other hand, TCP protocol, as a connection-oriented protocol, guarantees the reception of all packets. Therefore, TCP is safer and more reliable than UDP but is slower and requires more resources. In conclusion, the UDP is better suited for applications that need fast and efficient transmission. The gNB and 5GC operate in a Linux operation where the libraries for these parameters are installed. The Android terminal emulator and Linux environment application were installed on the phones, with Android as their operating system. This app is a terminal emulation and Linux environment application that works directly with no rooting or setup is required.

B. Experimental Results

1) 5G Network: The first set of tests focused on the 5G Network side between the relay devices and the 5GC. The 5GC and the Relay device are connected through the gNB using 5G NR in SA mode. Two Nokia XR20 mobile phones were used as relays, and they were placed near the BS during the tests. It must be noted here that these tests were not performed in an anechoic chamber; hence, a significant amount of Electro-Magnetic Interference (EMI) was expected. Tables I and II show the obtained results.

RTT times, both download and upload, are adequately stable comparing the two relays. In terms of throughput and jitter, it appears that Phone 2 has lower capabilities, both in the download and the upload direction. From this, it becomes obvious that although the devices are the same, there is a significant deviation between their capabilities, something that will eventually affect the overall end-to-end performance of D2D communication. This highlights, again, the erratic behavior of UEs in terms of stability and huge variation between devices. A test on the throughput with both PLMN 001-01 and 999-99 was also performed to investigate whether the nature of the network would make a significant difference. The download and upload throughputs for PLMN 001-01 were measured to be approximately $(86.8 \pm 27.1)\,\mathrm{Mbps}$ and $(2.52 \pm 1.79)\,\mathrm{Mbps}$, respectively. In the case of PLMN 999-99, the download and upload throughputs were measured to be approximately $(77.77 \pm 16.27)\,\mathrm{Mbps}$ and $(3.70 \pm 2.33)\,\mathrm{Mbps}$, respectively. No significant difference between the two network types was observed, at least not to the level that could be measured with the external noise levels.

2) Wi-Fi Direct Network: The second set of tests is related to the Wi-Fi Direct side of the network. In this test, two OnePlus8T mobile phones were used as end-devices, and two Nokia XR20 phones were used as relays. The connection between the end-devices and the relays was achieved through the custom mobile/server application described in the previous section. Figure 3 shows the obtained results. It is clear from the measurements that this side of the network experiences much higher RTT times, approximately $(87.60 \pm 13.49)\,\mathrm{ms}$ in the download mode. On the other hand, in the upload mode, the RTT times are approximately $(21.37 \pm 1.77)\,\mathrm{ms}$. Hence, upload RTT times are similar to those of the 5G network, but the download side experiences approximately triple RTT times. It is also interesting that for the download RTT, the relay plays the most significant role since both measurements using relay number 1 show higher RTT times. In the upload mode, RTT times are significantly stable.

In terms of throughput, it is obvious that in the download mode, the Wi-Fi Direct side of the network shows speeds of approximately $(48.93 \pm 19.63)\,\mathrm{Mbps}$, which is significantly slower than 5G. It is important to state that in the download mode, the throughput is mostly defined by the end-device and not the relay since both experiments with end-device number 2 show much slower throughput. In this case, end-devices have two different Android versions (End-device 1 Build: KB2003 11 C.33, Baseband ver: Q V1 P14, Kernel:4.19.157-perf+; End-Device 2 Build: KB2003 11 C.20 Baseband ver :Q V1 P14, Kernel:4.19.157-perf+), which can significantly affect the network performance. In terms of the upload mode, speeds of $(41.54 \pm 16.31)\,\mathrm{Mbps}$ have been recorded, showing much higher throughput than 5G.

3) End-to-End D2D Communication Testing: In this last set of tests, the end-to-end setup of this D2D communication was demonstrated. The end-devices (OnePlus 8T) and the relays (Nokia XR20) connect to each other through Wi-Fi Direct using the custom mobile/server application. The relay is also connected to the 5G BS using 5G NR. Initially, device and relay discovery are achieved through the mobile/server application, and secondly, message exchange from the server (Raspberry Pi) to the end-device is demonstrated using the configuration shown in Figure 4. The average overall transmission time during the end-to-end testing for sending a message from the server to the end-devices has been measured to be approximately $91\,\mathrm{ms}$ with a $28\,\mathrm{ms}$ standard deviation.

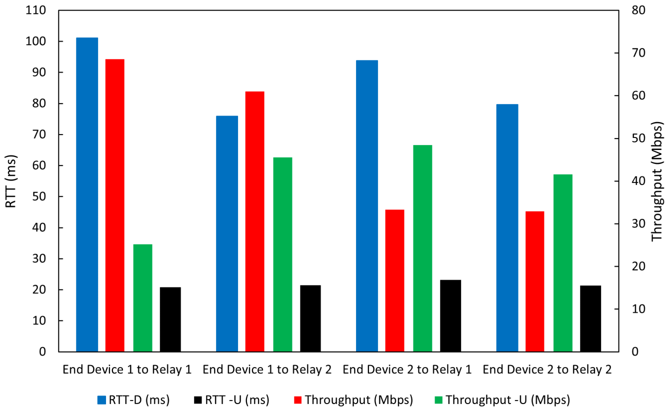


Fig. 3. End-device to relay (D-Download, U-Upload).

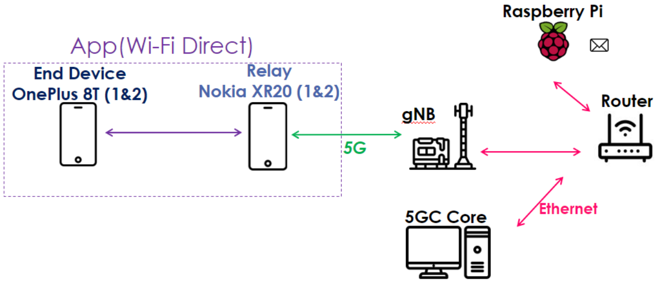


Fig. 4. End-to-End Testing setup

Compared with the RTT times for the individual segments of travel, the total time is calculated to be approximately $112\,\mathrm{ms}$. Acknowledging that RTT times involve the bi-directional travel of the packet and the non-symmetric RTT times for both the 5G and Wi-Fi Direct, it is expected that this method would give higher times than the real ones. However, the calculated and measured values are significantly close to each other, confirming the correct order of magnitude in transmission time.

VI. CONCLUSION

In this paper, it has been demonstrated that D2D communications with everyday devices are possible; however, there are several remaining implementation challenges to using this technology in a seamless environment. It has been demonstrated that although, in some cases, 5G technology can provide improved performance, offloading the network using D2D with OTS UEs still needs further development of specific technologies that are not yet up to the required level. It has been shown that RTT values of the 5G network are approximately $25\,\mathrm{ms}$ with throughputs of approximately $140\,\mathrm{Mbps}$ download and less than $5\,\mathrm{Mbps}$ upload, whilst the jitter was less than $0.3\,\mathrm{ms}$ download and approximately $30\,\mathrm{ms}$ upload. 5G networks are suitable for industrial applications, but currently, 5G is focused on consumer communications, which require changes in the configuration to have similar capacity and delay both for download and upload traffic. Wi-Fi Direct generally has higher RTT times and lower download throughputs compared to the 5G network. Finally, the message transmission from the server application to the end device has been measured in the order of $100\,\mathrm{ms}$.

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