A Multi-Purpose Automated Vehicular Platform with Multi-Radio Connectivity Capabilities

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***Abstract*—Internet access has become commonplace in the modern world. As the number of users and amount of data traffic in the Internet keep rising exponentially, and the requirements of novel applications are becoming more stringent, there is a clear need for new networking solutions. Therefore, one of the key concepts in solving the challenges of the upcoming 5G era of communications will be represented by multi-radio heterogeneous networks, where the users can gain benefits by either being connected to multiple different radio technologies simultaneously or seamlessly changing from one network to another based on their needs. In this work, we propose a multi-purpose automated vehicular platform prototype equipped with multiple radio access technologies, which was constructed to demonstrate the potential performance gains provided by the use of multi-radio heterogeneous networks in terms of network throughput, latency, and reliability. We discuss the potential drawbacks of using multiple radio interfaces at the same time. The constructed vehicular platform prototype constitutes a flexible research framework for communication technologies within heterogeneous networks and becomes helpful for supporting future use cases of industrial IoT applications.**

I. Introduction

A. Machine-Type Communications in 5G Systems

While it is still not completely clear what Internet of Things (IoT) will exactly become in the end [1], one point is apparent: IoT will be a very complex network, which utilizes a multitude of different protocols to connect between various types of networks in order to provide ubiquitous connectivity for IoT smart devices [2]. As such, heterogeneous networks are one of the key enabling technologies and concepts in order to make IoT a reality [3], [4].

Machine Type Communications (MTC) is expected to be tightly related with next-generation 5G mobile systems and IoT. MTC can be roughly divided into two major categories: (i) massive Machine Type Communications (mMTC) and, (ii) ultra-reliable Machine Type Communications (uMTC), which have distinctly different requirements [5]. The former is about deploying possibly billions of low-cost devices and sensors and providing them with wireless connectivity, while the latter is about providing high availability and reliability along with low latencies [6]. Example use cases for mMTC include smart homes, cities, and other environments filled with sensors, while example use cases for uMTC include assisted driving or even self-driving cars, and mission-critical control applications for industry [7].

Hence, the IoT related applications are expected to have highly varying requirements. The next-generation networks (5G and beyond) must be able to satisfy all of these requirements either at the same time or they must be able to adapt to the ever-changing requirements. Multi-radio heterogeneous networks are expected to help enable these stringent requirements and further aid the realization of IoT [3], [8].

The key contribution of this paper is to answer the question of how can we utilize the concept of heterogeneous networks as well as simultaneous connections to multiple radio technologies to improve throughput, latency, and reliability. Following the above, a multi-purpose automated vehicular platform prototype equipped with multiple radio access technologies was constructed to show the potential performance gains provided by the use of multi-radio heterogeneous networks in terms of throughput, latency, and reliability.

B. Multi-Radio Heterogeneous Networks

In the context of communication networks, a heterogeneous network stands for a network which is a combination of other networks using different access technologies (RATs) [9]. In this paper, the focus is on multi-radio heterogeneous networks, in which multiple radio access technologies are used, possibly, even at the same time, forming a multi-connected multi-radio heterogeneous wireless network [10]. Devices in such networks are equipped with multiple radio access interfaces in order to gain benefits related to: (i) throughput, (ii) latency, and (iii) reliability. On the other hand, disadvantages include increased power consumption and complexity.

In heterogeneous networks, the users can reap the benefits by either being connected to multiple different networks simultaneously or smoothly changing from one network to another based on their needs [3]. Fig. 1 describes a generic topology of a multi-radio heterogeneous network. At the center of the figure, there is an LTE cell tower (eNodeB) that is providing cellular connectivity over an area depicted by the largest ellipse [11]. Further, there are other access points providing additional coverage with various radio access technologies such as the Wi-Fi access points and a high-speed millimeter-wave (mmWave) 5G access point.

II. Our Multi-Purpose Vehicular Platform

In this section, the multi-purpose automated vehicular platform prototype developed to evaluate the performance im-

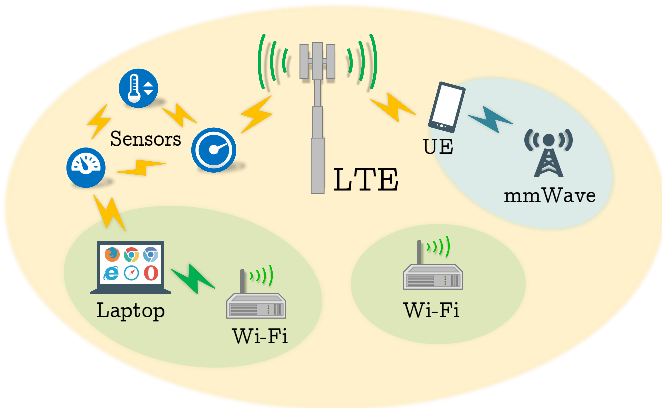

Fig. 1. A generic heterogeneous network topology depicting devices connected to multiple radio access technologies at the same time.

provements provided by heterogeneous networks is presented. The vehicular platform is equipped with multiple radio access technologies in order to show the potential performance gains of multi-radio heterogeneous networks and demonstrate use cases for heterogeneous networks.

A. Design of the vehicular platform

The design of multi-purpose automated vehicular platform embodies the key concepts of the IoT vision and 5G mobile networks. The envisioned key concepts are heterogeneous networks, mobility, autonomous operation and sensors, which are described in Table I.

TABLE I
ENVISIONED KEY CONCEPTS FOR THE MULTI-PURPOSE AUTOMATED VEHICULAR PLATFORM

Heterogeneous networks	**Mobility**
Multiple radio access technologies	Moves on wheels, physically
Multi-connectivity	Roaming between networks
Improved performance	Ubiquitous connectivity
Autonomous operation	**Sensors**
Various modes of autonomous operation	Proximity sensors
Initially: pre-programmed instructions	Positioning data
Ideally without human intervention	Signal coverage mapping

In this work, the focus is on the heterogeneous network aspect of the developed demonstrator. For this purpose, the vehicular platform was designed to function in three different modes, which have distinct latency and throughput requirements:

1) Automated mode: where the vehicle follows a predefined route or pre-scripted commands and sends keep-alive messages periodically. In case the vehicle detects a problem or an obstacle, it may try to navigate around it, or it can notify the operator supervising the platform's operation and change the operating mode into either semi-automated or manual mode. This operating mode is not delay sensitive and the throughput requirements are low assuming no large amounts real-time data is transmitted during the operation.

2) Semi-automated mode: where the vehicle follows a predefined route or pre-scripted commands and streams video to the remote operator instead of keep-alive messages. The operator can follow the operation of the vehicle and intervene if deemed necessary. The operator can either alter the route or switch the operation into manual mode at any point. This operating mode is not very delay sensitive as the video does not have to be streamed perfectly in real-time. Throughput requirements are higher, but adaptive, as the throughput requirements can be controlled by adjusting the quality of the video stream.

3) Manual mode: where the vehicle is controlled by the operator remotely. The operator is constantly aware of where the vehicle is owing to the video stream and positioning data. This operating mode is highly delay sensitive due to the real-time controls and real-time video feedback. Throughput requirements in this mode are on the same level as the semi-automated mode, but still adaptive, as the throughput requirements can be controlled by adjusting the quality of the video stream.

In summary, varying delay sensitivity and unbalanced upload/download throughput requirements make the developed platform to be an excellent basis for testing radio access technology switching and splitting techniques in heterogeneous networks. In each mode, the multi-purpose automated vehicular platform can utilize all radio access technologies simultaneously to maximize performance and satisfy requirements of the applications under test.

III. Prototype Structure and its Implementation

At the core of the platform is a Raspberry Pi 3 model B single-board computer. The two motors of the vehicular platform are controlled via the Raspberry Pi's GPIO (General Purpose I/O) pins. The GPIO pins are connected to a custom power feeding circuit built by other members of the research group. This custom-built circuit features a connection to an external 7.2 V battery pack, a voltage regulator which converts and stabilizes the battery voltage to the correct 5V voltage for the Raspberry Pi. The battery pack provides power to both the Raspberry Pi and the motors.

The platform is equipped with three radio access technologies: Wi-Fi and Bluetooth Low Energy (BLE) via the built-in chips on the Raspberry Pi, and an external ZTE MF831 USB LTE modem. However, Bluetooth is not used in any of the current testing scenarios. A Raspberry Pi Camera Module v2 is installed to the front of the vehicle. A real-time video stream is suitable for creating a testing environment that is intended for testing applications, which require high throughput and low latency. Other video and audio outputs are not used in the current implementation of the platform.

The platform also features an infrared proximity sensor connected to the GPIO pins, which allows the platform to detect obstacles in front of it and automatically brakes before crashing into them. This feature works in both automatic and manual modes. An obstacle in the sensor's range also prevents the operator from manually accelerating. The effective range

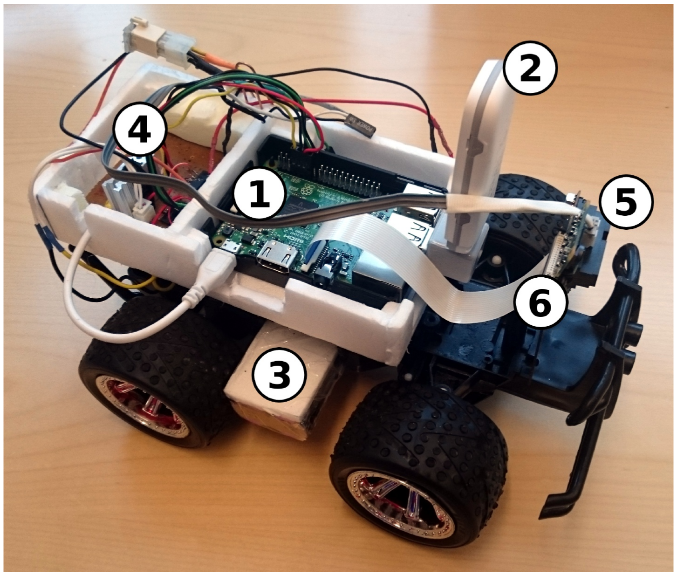

Fig. 2. A photo of the latest iteration of multi-purpose automated vehicular platform prototype. (1) Raspberry Pi, (2) LTE modem, (3) battery pack, (4) power feeding circuit, (5) proximity sensor and (6) camera are shown mounted on the platform.

of the proximity sensor is approximately 30 to 50 centimeters, which is judged to be sufficient when driving at slow speeds.

A photo of the latest iteration of multi-purpose automated vehicular platform prototype is displayed in Fig. 2. The figure shows the Raspberry Pi connected to the power feeding circuit via the GPIO pins. Power is supplied from the circuit via the micro-USB cable. The LTE modem is connected upright to one of the Raspberry Pi's USB ports near the front. The battery pack is mounted at the bottom of the platform and the proximity sensor and camera are mounted at the front of the platform. The technical details and features of the multi-purpose vehicular platform prototype are summarized in Table II.

TABLE II
TECHNICAL SPECIFICATIONS AND FEATURES OF THE MULTI-PURPOSE VEHICULAR PLATFORM PROTOTYPE

Framework	Disassembled radio-controlled car 4 wheels and 2 motors
Computing unit	Raspberry Pi 3 model B
Operating system	Raspbian Jessie Lite (Linux-based)
Radio access technologies	BCM43438 Wi-Fi IEEE 802.11 b/g/n ZTE MF831 LTE USB modem Bluetooth Low Energy
Battery	2-cell 7.2 V LiIo battery pack
Camera	Raspberry Pi Camera Module v2, 8 Megapixels
Video stream	Up to 720p @ 30 fps tested working smoothly
Video compression	Hardware encoded H.264 MJPEG and raw formats also available
Sensors	Infrared proximity sensor

A custom application written in Python 3 is responsible for outputting signals via the GPIO pins to control the motors according to the instructions it receives from the remote client controlled by the user. The application also monitors the input from the proximity sensor so it can send the signal to brake if the sensor detects an obstacle in front. The wireless (Wi-Fi) driver and the LTE modem are periodically polled for the current signal level and the information is forwarded using the respective RAT along with the latency measurement from that RAT. Video feed received from the camera is encoded in hardware with minimal latency and sent to the remote client via one RAT at a time using UDP (User Datagram Protocol). The RAT used can be changed at will in less than a second or the change can be automated based on the latency and signal strength measurements of each RAT.

Likewise, on the user side, a custom remote client application written in Python 3 receives the measurements and the video data from the platform and displays them to the user.

The client-side application receives inputs from the user to instruct the vehicular platform to drive forward or backward, turn left or right, or force changing the RAT used to stream video data. The application sends the commands using UDP transport protocol to the vehicular platform either via a specified RAT or duplicated over all the available RATs for increased reliability and lower latency. If instructions are duplicated, they are marked with an ID so that the platform does not execute the same command twice.

For the final phase of testing, Multipath Transport Control Protocol (MPTCP) support was added to both the platform and the remote client. MPTCP was used only for testing throughput improvements in general since the custom application only uses UDP for communication.

IV. Testing Scenarios and Obtained Results

The first phase of testing setup consists of utilizing Jolla smartphones in a simple heterogeneous network with LTE and Wi-Fi as the radio access technologies of choice. The second phase incorporates the multi-purpose vehicular platform described in Section II into the testing scenarios and introduces a refined and expanded test network. During the third phase, MPTCP performance on the local server and on the vehicular platform was evaluated.

A. Tested applications

The baseline logical topology of the test network is shown in Fig. 3. The UE can connect to a device acting as the server using either Wi-Fi or LTE, or both. The LTE side is routed to an Evolved Packet Core (EPC).

Throughout the testing phases, various applications were used to obtain results. This section introduces all of the applications utilized. The primary testing applications were custom-made Python scripts because the readily available testing applications are not made with multipathed heterogeneous networks in mind, and as such, they are generally limited to measuring one path at a time. While in some cases it is possible to launch an instance of the application for each available RAT, combining the results in a meaningful way can be tricky.

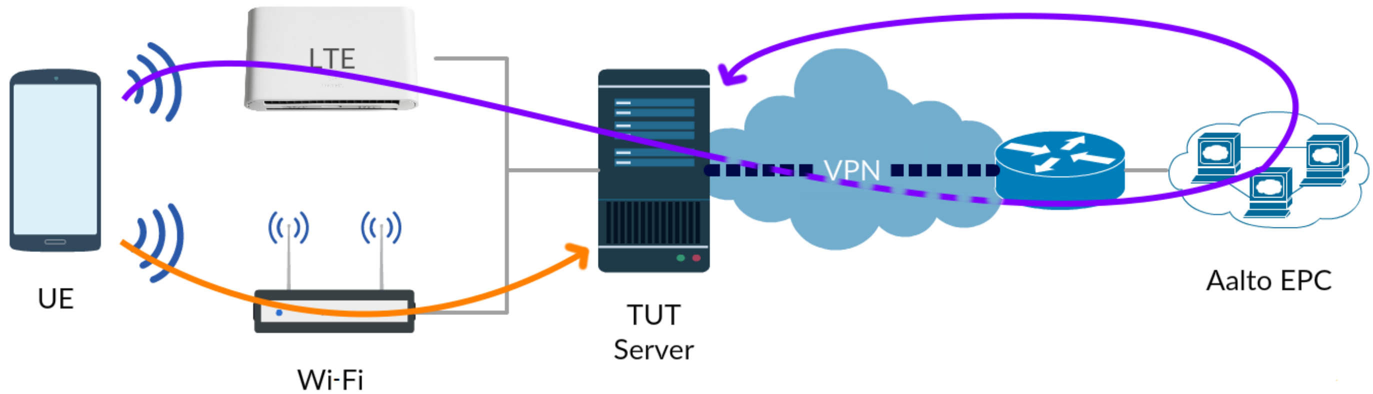

Fig. 3. Baseline logical topology for the test network detailing the path for the connections over Wi-Fi and LTE.

Applications that use TCP can use MPTCP if the devices at both ends of the connection support MPTCP and are configured to use it [12], [13]. However, applications that do not use TCP, such as live video streaming or ping, cannot utilize this option. Custom multipath aware applications that use UDP were created to solve this problem.

The following applications were used for producing results:

- *Ping duplicator* – A simple custom Python application which on the client side sends a numbered UDP packet via each available RAT at specified intervals for a predetermined amount of time. Information about which RAT was used and when the packet was sent is also included in the packet. On the server side, the server simply echoes the packet back to the source. If the client receives a packet back, it calculates the round trip time (RTT), i.e. how long it took for the packet to travel back and forth. Finally, the client plots a scatter plot detailing the RTT for each packet that was not lost on the way.
- *Vehicular platform control application* – The metrics gathered by the application are detailed. On the platform side, the application keeps track of the RTT and the signal strength for each RAT in one-second intervals and reports the metrics to the remote client. On the remote client side, the application monitors the bitrate of the video it receives and the throughput of each RAT. All connections of the application use UDP.
- *iPerf* – This application is used to measure the maximum available throughput on each RAT. The application supports TCP, UDP, and SCTP (Stream Control Transmission Protocol) by default. When both the client and the server support MPTCP and they are configured to use it, the underlying network stacks of the operating systems automatically convert TCP connections to MPTCP connections, so iPerf can be used to measure throughput in multipathed networks in this case.

During the testing process, applications were run on both the UE and another device located in the TUT network with one end acting as a client and the other as a server depending on the application. Testing scenarios were run through at least five times to ensure that the results were coherent.

B. *Refined Test-Bed Architecture*

For the second phase of testing, the multi-purpose vehicular platform prototype detailed in Section II was built. Additionally, the Wi-Fi portion of the testing network was expanded from one access point to three access points – the Wi-Fi part of the test network was now composed of three Cisco Air-LAP1142N wireless access points. The LTE part of the test network still consisted of the two Ericsson RBS 6402 indoor picocell base stations. The access points and base stations were relocated to an L-shaped corridor as shown in Fig. 4, as it was not possible to create large enough coverage holes in the previous test network setup. In the refined testing scenario, the Wi-Fi AP2 is turned off in order to create a coverage hole in the Wi-Fi part of the test network. Other improvements over the initial testing scenario include the ability to measure the signal strengths of the Wi-Fi and LTE connections and larger control over the data flows from the vehicular platform to the remote client and back.

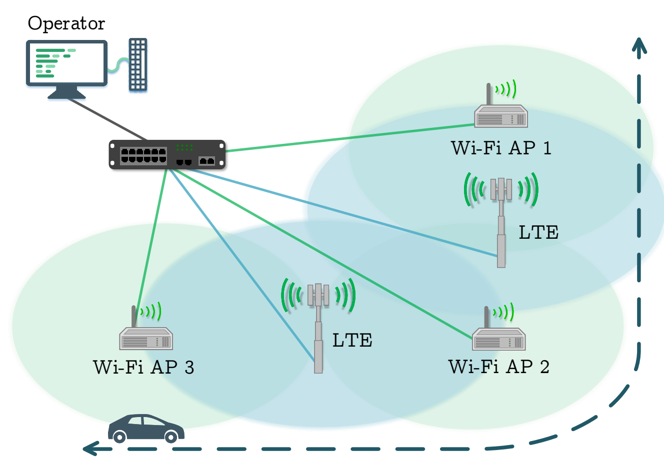

Fig. 4. Simplified logical topology of the refined test network. Approximations of the physical locations of the APs and BSs are shown, and the path of the vehicular platform is marked with a double-headed arrow.

At the beginning of the refined testing scenario, after the vehicular platform has established connectivity to one of the

Wi-Fi access points and to one of the LTE base stations, the remote client establishes at least four connections to the vehicular platform:

- a control connection, which is used to transmit instructions such as *turn left* or *change video stream to LTE* to the vehicular platform;
- a connection for the video stream, which is used solely to transmit the video data from the vehicular platform to the client;
- two telemetry connections, one for each RAT, which are used to measure the latency and transmit other telemetry information such as signal strength.

The RATs used for the control connection and video stream can be chosen and changed freely. Alternatively, the control connection can be duplicated over all available RATs for improved reliability and lower latency. In this scenario, video is streamed over Wi-Fi at the beginning and control connection is duplicated over both RATs.

The starting location for the vehicular platform is at the end of the corridor, past Wi-Fi AP1. The operator controlling the vehicular platform from the remote client starts driving slowly along the corridor towards Wi-Fi AP2, which has been turned off. When the vehicular platform approaches the corner in the corridor, the operator changes the video stream to LTE from Wi-Fi. This could be set to be done automatically based on the telemetry data, but in this scenario, the changes are done manually for the sake of consistency. When the vehicular platform approaches Wi-Fi AP3, the operator changes the video stream back to Wi-Fi. After driving past Wi-Fi AP3, the operator turns the vehicle around and starts driving back along the same route while changing the video stream to LTE and back at the appropriate locations. The test ends when the vehicular platform returns to the starting location. The objectives of this refined testing scenario are:

- to show that in heterogeneous networks it is possible to compensate for interruptions, congestion, coverage holes or other problems in one RAT by sending the data via other RATs instead;
- to show that by duplicating data over multiple RATs, it is possible to achieve lower overall latency when compared to a single RAT. This objective could not be realized in the initial testing scenario.

V. Main Practical Results

A. First and Second Phase Test Scenarios

Fig. 5 shows the signal strength levels for Wi-Fi and LTE as a function of time from the same test run as in the previous figure. It can be noticed that while the polling rate for Wi-Fi and LTE signal strengths are the same (one second), the LTE USB modem seems to update its RSSI value erratically (i.e., at random intervals) when compared to the built-in Wi-Fi chip of the Raspberry Pi. From the figure, it can be roughly seen when the vehicular platform approaches the Wi-Fi AP1, continues past it to LTE BS1, turns around the corner to LTE BS2, reaches the range of Wi-Fi AP3 and drives past it to turn around and backtrack through the same route in reverse. In general, the connection with a relatively stronger signal is used.

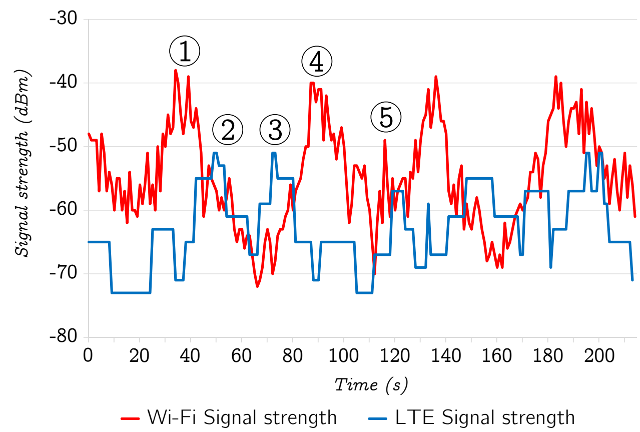

Fig. 5. Signal strengths in dBm for Wi-Fi and LTE as a function of time. The graph shows roughly when the platform reached each access point and base station along the path: ① Wi-Fi AP1, ② LTE BS1, ③ LTE BS2, ④ Wi-Fi AP3 and ⑤ the turning point past Wi-Fi AP3. After point ⑤ the platform turned around and traversed the same path in reverse.

Fig. 6 shows the latency metrics collected from a different testing run as the previous two figures, and as such, this figure is not directly comparable with them. As the general flow of the testing scenario is the same, similar patterns can be noticed. A 10-second moving average for the RTT was used to smoothen out the graph, which is the reason why the x-axis starts from 10 instead of 0. The main point of this figure is to show that when duplicating data over multiple RATs, it is possible to achieve noticeably lower overall latency than when compared to a single RAT. Thus, the second objective of this testing scenario was fulfilled.

In conclusion, it was shown that by directing the heavier data flows, such as video streams, at opportune moments to another RAT, it is possible to achieve better performance in terms of latency and a more stable or better quality connection in terms of signal strength. A future research challenge is to utilize the results obtained from this testing scenario and develop a solid algorithm to automatically change the heavier data flows optimally. While sending redundant copies of large amounts of data to the Internet is undesired from the network's point of view as it causes congestion, low amounts of important traffic, such as control signals, could be duplicated constantly to consistently improve reliability and latency. In a separate network environment, such as the intranet of a factory, even large amounts of mission-critical data could be duplicated freely, as it would not cause congestion to the Internet.

B. Third Phase Test Scenarios

For the third and final phase of testing, the vehicular platform and the local server were upgraded to support MPTCP and configured to use MPTCP instead of TCP whenever possible. The test network is otherwise identical to the one

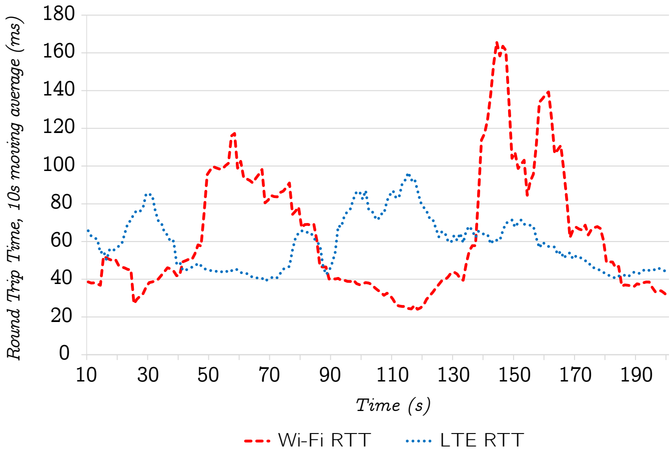

Fig. 6. Round trip time measurements for the second phase testing scenario. A 10-second moving average was used to smoothen out the graph, which is the reason why the x-axis starts from 10 instead of 0.

used in the second phase, except that the Wi-Fi AP2 has been re-enabled. The technical specifications of the final test network and testing scenario are listed in Table III.

TABLE III
TECH. SPEC. OF THE FINAL TEST NETWORK AND TESTING SCENARIO

User equipment	Multi-purpose vehicular platform Laptop
Server	Virtual machine located in TUT's network
LTE base stations	Two Ericsson RBS 6402 indoor pico base stations
Wi-Fi access points	Three Cisco Air-LAP1142N access points IEEE 802.11 b/g/n
Testing application	iPerf with MPTCP (see Section IV-A)
Metrics	Maximum throughput

The objective of the final testing scenario is to demonstrate the potential performance gains from utilizing multipath protocols in terms of throughput. The application used to measure throughput is *iPerf* with MPTCP as the transport protocol. The starting location for the vehicular platform in this scenario does not matter as long as it has connectivity over both Wi-Fi and LTE. The throughput test is run for a period of one minute. The network stacks of the operating systems of the UE and the server automatically convert TCP connections to MPTCP connections as they are configured to do so. Finally, to get a point of reference, the same testing scenario was repeated with only the Wi-Fi connection active and only the LTE connection active.

After the first few trial runs of the testing scenario, it was noticed that the Raspberry Pi was unable to fully harness the improved throughput provided by the use of MPTCP as seen from the sample results shown in Fig. 7(a), which display the throughputs for the Wi-Fi only trial, LTE only trial and MPTCP trial. The throughputs for the Wi-Fi sub-flow and the LTE subflow in the MPTCP trial can be seen in Fig. 7(b).

The throughput appears to cap at around 40 Mbps for both the MPTCP trial and Wi-Fi only trial. It was assumed that the throughput is limited by the hardware of the Raspberry Pi. In order to verify this theory, a more powerful UE was needed. Thus, a laptop was upgraded to include MPTCP support. The same LTE USB modem was used for the laptop to keep the testing environment as similar as possible.

The results from one of the iPerf connection tests by using the laptop as a client in Wi-Fi only trial, LTE only trial and MPTCP trial are shown in Fig. 8(a). The throughputs for the Wi-Fi subflow and the LTE subflow in the MPTCP trial can be seen in Fig. 8(b). The results confirm the hypothesis of the vehicular platform lacking the resources to process the full amount of traffic that would be possible by using MPTCP with all of the available RATs. Nevertheless, the objective of the final testing scenario was accomplished.

The results also show that the throughput of MPTCP does not quite reach the theoretical maximum calculated by summing up the results of the Wi-Fi only and LTE only trials. Methods to improve this ratio while keeping the operation of the protocol fair might be an interesting research topic for the future.

VI. Conclusion

In conclusion, it was observed that the hardware of the Raspberry Pi is not able to handle the full amount of throughput that would be available by the use of MPTCP. A laptop was used as the UE for the throughput performance test instead and it was shown that by utilizing a multipath protocol to transfer data over multiple RATs, it is possible to achieve significantly better throughput at the cost of increased energy consumption. The exact possible drawbacks or benefits of utilizing multiple RATs at the same time from the energy efficiency point of view remain to be determined in future research.

Improved throughput potential was demonstrated by using MPTCP [14] to transmit data over LTE (Long Term Evolution) and Wi-Fi simultaneously and measuring the maximum throughput. Even though the throughput of MPTCP did not quite reach the theoretical maximum calculated by summing up the results of the Wi-Fi only and LTE only trials, the ability to utilize the nearly full capacity of each available radio access technology on demand is going to be significant in the future mobile networks in terms of user experience. The exact possible drawbacks or benefits of utilizing multiple RATs (radio access technologies) at the same time from the energy efficiency point of view remain to be determined in future research.

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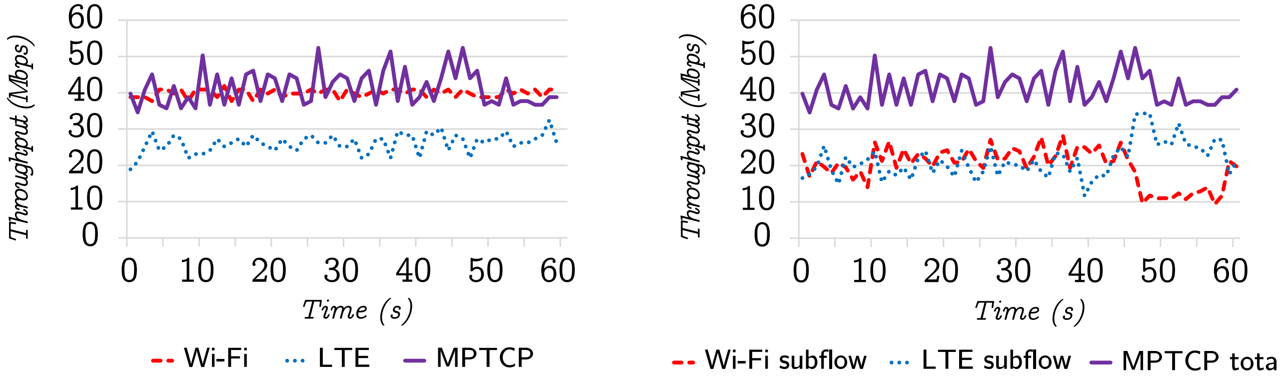
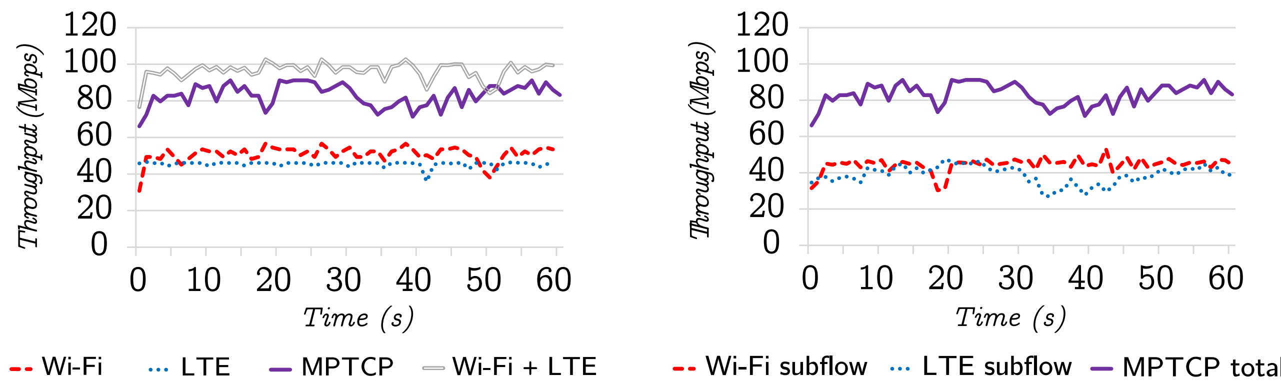


(a) Separate throughput measurements

(b) MPTCP subflow throughputs and total throughput

Fig. 7. Samples of throughput measurements on the mobile platform by using MPTCP. Throughputs are limited by the processing power of the mobile platform.



(a) Separate throughput measurements

(b) MPTCP subflow throughputs and total throughput

Fig. 8. Samples of throughput measurements on a laptop by using MPTCP. The "Wi-Fi only + LTE only" series displayed with a gray line is a theoretical maximum MPTCP could have possibly reached in this particular case if it had performed as well as the sum of its parts.

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