On the Impact of Satellite Communications over Mobile Networks: An Experimental Analysis

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Abstract—Future telecommunication systems are expected to co-exist with different backhauling nodes such as terrestrial or satellite systems. Satellite connectivity can add flexibility to backhauling networks and provide an alternative route for transmission. This paper presents experimental comparisons of satellite and terrestrial cellular networks and evaluates their performances in terms of different Key Performance Indicators (KPIs) including Channel Quality Index (CQI), Modulation Coding Scheme (MCS) index, Downlink throughput, Frame Utilization (FU) and number of Resource Block (RB) utilization ratios. Our experimental satellite network system uses a real satellite backhaul deployment and works in Ka band (with two specific sub-bands on 19 Ghz in downlink and 29 Ghz in uplink). As a benchmark, we compare our system with live terrestrial network in which backhaul connection is cellular backhaul. Our experiments reveal three main observations: First observation is that there exists FU and number of RB utilization problems in the satellite link even though there exists a single test user equipment (UE) with high CQI and MCS index values. Second observation is that in satellite link relatively low number of Protocol Data Units (PDUs) are generated at Radio Link Controller (RLC) layer compared to the Packet Data Convergence Control (PDCP) layer. Finally, our third observation concludes that the excessive existence of PDCP PDUs can be due to existence of General Packet Radio Service (GPRS) Tunneling Protocol-User Plane (GTP-U) accelerator where an optimal balance between the caching size and the number of UEs using satellite eNodeB is needed. For this reason, our experimental results reveal the existence of a trade-off between the supported number of users on satellite link and the GTP-U acceleration rate.

Index Terms—LTE, satellite communications, mobile network, experiments

I. INTRODUCTION

Long Term Evolution Advanced (LTE-A) is already putting a heavy burden on backhaul networks and various advanced techniques are proposed to improve microwave backhaul including Adaptive Modulation and Coding (AMC), interference mitigation and cancellation techniques, higher order modulations, packet header compression, frequency diversity and multiple-input multiple-output (MIMO). This bottleneck problem of backhaul links gains more momentum as the number of small cells inside Mobile Network Operators (MNOs)’ network infrastructure is starting to soar. To carry this enormous amount of data traffic generated inside cells by end-users and Internet of Things (IoT) devices, backhaul links have also need to be redesigned in addition to Radio Access Network (RAN) level improvements. Otherwise, backhaul links will soon be the bottleneck that will put the whole proper operations of end-to-end system into trouble. For these reasons, designing backhaul links is the next critical issue for 5G networks. For backhaul connection, various communication mediums can be considered as candidates such as microwave radio, copper Digital subscriber line (DSL), optical fiber, mmWave or satellite. The choice may depend on many factors including cost, performance, bandwidth demand, capacity and often many more. In particular, satellite point-to-point links that can exploit the benefits of satellite networks can be considered for reliable backhauling without interference with other cells or access links. Satellites can play a key role for reliable service delivery in 5G networks and are already included in several 5G use cases [1].

On the other hand, providing ubiquitous coverage is one of the major requirements that needs to be satisfied within Fifth Generation (5G) networks. Next generation 5G wireless solutions are expected to embrace satellite and cellular solutions [2], [3]. Due to cost per bit reductions of current state-of-the-art satellite technologies, MNOs have started to select satellite technology as a promising backhaul solution inside their cellular infrastructure. In fact, satellite networks can provide MNOs the opportunity to extend their coverage range in rural or remote areas of the country where existing infrastructure is not available (due to challenging topology of the geography) or limited in terms of network capacity. Hence, providing backhaul using satellite links in cellular networks can be a practicable solution to provide low cost and timely delivery of connectivity services for hard to serve areas (such as mountains, islands, etc). For example, seamless integration and convergence with 5G terrestrial systems can support various vertical use cases and drive growth in sectors such as backhaul and trunking, transportation (aero, land, maritime) with mobile communications, media and entertainment with broadband services and public safety during disaster relief and emergency response situations.

Satellites can also complement the next generation 5G terrestrial systems and provide substantial economic and societal benefits. For example, MNOs can have the option of not building a new cellular backhaul infrastructure in rural or remote areas depending on return-of-investment over infrastructure. The usage of satellite network for backhaul can reduce the infrastructure investment cost while providing coverage to large-geographical areas of the country.

It is inevitable that satellite networks will integrate with other networks including 5G cellular networks. Support for satellite communications is considered to be an essential capability of the 5G technology. Moreover, satellites can be
used to support the key usage scenarios of 5G including enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC) and Ultra-reliable low latency communications (URLLC). For example, satellites can be used to carry high bandwidth High Definition (HD) content via High Throughput Satellites (HTSs) in geosynchronous (GEO), medium Earth orbit (MEO) and low Earth orbit (LEO) in eMBB scenarios, can scale to support future IoT communications in mMTC scenarios and can play a role in low latency by delivering same content to mobile base stations (BSs) or multicasting the content to caches in individual cells in URLLC scenarios. However, the success of satellite also depends on their capabilities to provide cost/bit compared to terrestrial systems as well as adequate throughput to provide 5G services for backup and offloading purposes. Moreover, large delays experienced by satellite links are one of the significant impediments for the utilization of this technology in traditional cellular networks, either in LTE or 5G in future.

II. MOTIVATION AND RELATED WORK

Satellite communication can be performed with four different satellite categories High Earth Orbit (HEO), LEO, MEO and GEO satellites that are orbiting at different attitudes around the Earth. In general, GEO and MEO satellites are used for communication purposes especially for satellite backhaul applications. There exists several works on providing satellite integration to cellular networks [4], [5], [6], [7], [8], [9], [10], [11].

Different satellite-5G integration use cases as well as the latest initiatives and challenges in future 5G terrestrial and satellite integration are summarized in [4]. The authors have investigated the impact of impairments in a typical satellite channel in Long Term Evolution (LTE) waveform design as well as L1 and L2 procedures. HTSs use frequency reuse and multi-beam technology to provide high capacity communication with reduced costs [12]. The paper in [3] uses a real-time simulator for satellite back-hauling of moving evolved Node-Bs (eNodeBs) where LTE network and satellite links are emulated. The authors in [13] are proposing a new radio resource management algorithm for multimedia content distribution over satellite networks.

The authors in [8] are studying the integration of satellite and terrestrial communication networks and validate such integration with a testbed including a satellite emulator for backhaul support. The paper in [9] studies the key technical challenges (mostly related to PHY/MAC layers) as well as architectures for incorporation of satellites into 5G systems. The paper in [10] presents several enabling techniques to reuse the existing terrestrial air interface for transmission over satellite links. The paper in [11] proposes a Downlink (DL) scheduling strategy in an integrated terrestrial-satellite network to enhance spectrum efficiency, fairness and capacity. The authors in [14] have reviewed the benefits of integration of satellite and terrestrial links to provide a network with wireless backhaul. The paper in [15] identifies the technical challenges associated with the convergence of satellite and terrestrial networks in order to provide a similar end user quality-of-service (QoS) as in high bandwidth terrestrial networks.

Performance evaluations and research challenges of multisatellite relay systems with cooperative transmission in Time Division Multiple Access (TDMA)-based architecture is given in [16]. For delivering TV services, Rajeev Kumar et al. in [17] are investigating usage of different wireless links (including Satellite, WiFi, and LTE/5G millimeter wave (mmWave)) to improve TV distribution penetrations.

Standardization bodies including The 3rd Generation Partnership Project (3GPP) [18], European Telecommunications Standards Institute (ETSI) [19], International Telecommunication Union (ITU) [20] as well as 5G Infrastructure Public Private Partnership (5G PPP) [21] have considered satellite networks in conjunction with terrestrial communication systems. For instance, 3GPP Release 15 has recently drafted a technical study on New Radio (NR) to support Non-Terrestrial Networks (NTNs) [18]. European Commission (EC) funded 5GPPP projects have also been launched in H2020 framework. SANSA (Shared Access terrestrial-satellite backhaul Network enabled by Smart Antennas) project is investigating utilization of extended Ka band for backhaul operations to improve spectrum efficiency. SaT5G (Satellite and Terrestrial Network enabled by Smart Antennas) project is focusing on plug-and-play integration of satellite communications into 5G network for eMBB use case. ESA ARTES SATis5 (Demonstrator for Satellite-Terrestrial Integration in 5G Context) is building a large Proof-of-Concept (PoC) testbed to enable satellite-terrestrial convergence into 5G context focusing on eMBB and mMTC scenarios.

There also exists various works investigating satellite communication in Ka band [22]. The authors in [22] are investigating beam tracking methodology in Ka-band for UAV-satellite communication systems. An Uplink (UL) signal-to-interference-plus-noise ratio (SINR) probabilistic model for Ka band in HTSs is studied in [7]. The authors in [6] are focusing on extending the LTE broadband service using a mega-constellation of LEO satellites that are deployed in Ka-band. The paper in [23] provides an overview of advancements in many satellite based communication systems utilizing Ka band frequency band.

To compensate for the excessive latency existent in satellite links, GPRS Tunneling Protocol (GTP)-U accelerator is considered to be a viable solution by satellite modem vendors [24], [25]. The patent [26] have applied acceleration function to GTP Protocol Data Units (PDUs) for traffic flows over satellite links via utilization of caching, pre-fetching and web acceleration methods. GTP-U accelerator is mainly useful for satellite links to mitigate the effect of long propagation delays that the signal experiences. GTP-U acceleration method can be applied at a Very Small Aperture Terminal (VSAT) modem.

Although most of the above papers have investigated the cellular satellite integration aspects, there exists some limitations of the considered scenarios. For example, some of the papers investigate performance over satellite emulators testbed implementations or work on virtualized environments of real-time simulators. These results lack the relevant realistic

* https://sansa-h2020.eu/
† http://sat5g-project.eu/
‡ https://artes.esa.int/projects/satis5
requirements including combined effect of LTE radio link with satellite backhauled-Evolved Packet Core (EPC). The aim of this work is to show how the performance of satellite link behaves in a real-time operational network and in comparison with terrestrial live network. To that end, we have deployed a satellite test-bed environment and monitored some of the key key performance indicators (KPIs) that can give insight into for utilization of network resources such as number of resource blocks (RBs), Frame Usages (FUs) ratios, Channel Quality Indicator (CQI), Modulation Coding Scheme (MCS) index, Packet Data Convergence Control (PDCP) throughput, number of PDUs in Radio Link Controller (RLC) and PDPC layers and MIMO Transport Block (TB) usage. More specifically, a satellite-based test eNodeB that connects a test user equipment (UE) to EPC is considered. In this context, the impact of satellite link latency is investigated on the resource allocation schemes of satellite eNodeB scheduler.

Another important contribution of the paper is to complement the literature works on integrated satellite-terrestrial networks by presenting an end-to-end complete and realistic validation results of the considered satellite based backhaul system, supported by actual wide range of KPI measurements. Regarding that aspect, our proposed analysis works around the deployment of a satellite-based eNodeB architecture that combines further analysis and several KPI comparisons with an operational terrestrial live cellular network. Benefits, challenges and opportunities of an operational satellite backhaul deployment are also widely discussed. Furthermore, the experiments are evaluated at minutes-level which provides a fine grained characterization of the insights into the satellite backhaul deployment scenario. The analysis results of our experimental evaluations are laid on the trade-offs and the savings observed when comparing the KPIs of satellite based backhaul network of the experimental set-up with the live terrestrial network. All these considerations have allowed us to serve the goals of understanding the behaviour satellite links under different real operating conditions. Our contributions can be summarized as follows:

- proposing a new satellite based backhaul architecture and experimenting it in real-world experimental set-up
- performing a real-world experimentation trial of the proposed satellite based backhaul architecture with link that utilizes Ka band,
- revealing three distinct observations based on the problems of FU and RB utilization, existence of excessive number of PDCP PDUs and the trade-off between the support for higher capacity and GTP-acceleration rate using the satellite-based backhaul link.

The structure of the paper is as follows. Section III presents system model and concepts. Section IV presents the experimental analysis results of one-day satellite based eNodeB measurements and comparing the results with terrestrial based eNodeBs. The paper ends with the conclusions and future works in Section V.

III. SYSTEM MODEL AND ARCHITECTURE

Fig. 1 show the end-to-end system architecture of the utilized testbed for live network site. This traditional mobile network consists of RAN, transport and core networks. In LTE, access network is called Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and core network is EPC with all Internet Protocol (IP)-based connection. E-UTRAN is composed of eNodeBs, UEs whereas EPC includes Packet Data Gateway (P-GW), Serving Gateway (S-GW) and Mobility Management Entity (MME). A schematic view of the architecture is depicted in Fig. 1.

A. General architecture with satellite based backhaul network

Fig. 2 represents the high-level architecture and key components with a GEO satellite based backhaul for mobile network communication. We consider a GEO satellite that can provide Internet service to UEs. LTE’s BS eNodeB is connected to the VSAT modem with an Ethernet cable. VSAT enables communication with satellite. The traffic from eNodeB goes through VSAT modem that performs optimization as well as modulation of signal to be transmitted over the satellite link. In this setup, S1 interface between eNodeb and EPC is transported via satellite. In addition, VSAT modem is capable of both IPsec setup and data acceleration. A 120cm antenna is set-up on the site for satellite access. LTE supports satellite transmission over S1 interface. The ground station has redundant 9.2m Ka antennas, one VSAT hub and one firewall. After the traffic is received by the ground station, VSAT hub transmits traffic to firewall. The firewall is used to encrypt the satellite traffic and establish a new IPsec tunnel with the security gateway in the mobile core network. Mobile Cell Site Routers (CSRs) are installed at eNodeB locations to transfer traffic to the mobile IP/MPLS backhaul network. However due to this topology in which eNodeB S1 traffic is received via satellite, mobile CSR is installed on the ground station where the VSAT hub is located. The CSR is connected to a mobile Mobile Backhaul Aggregation Router (MBAR) via a leased circuit over a carrier of a stationary operator. Links from many CSRs are collected in the MBAR and forwarded to the LTE security gateway. The purpose of the security gateway is to terminate IPsec tunnels set up and encrypt S1 traffic. Security gateway is connected to EPC. EPC is connected to the Internet via a high-capacity Internet router as given in Fig. 2.

B. Ka band

HTSs are characterized by many small beams with high gains that also allow multiple frequency re-use. Ka band frequency utilization is getting common in HTSs. In fact, classical frequency bands such as C and Ku-band are getting congested due to increase of the number of satellite communications systems. For this reason, utilization of Ka bands can provide higher bandwidths compared to L-/S-bands and is more suitable for broadband services due to usage of high frequencies. Moreover, higher frequencies avoid the interference with terrestrial communication systems, enable the reduction of system components both in ground and space segments and enable higher antenna gains and directivity. However as the frequency increases, small perturbations on the atmosphere (e.g. rain attenuation) on the propagating waves can have higher impact on link quality. This affects the QoS.
experienced by end-users at high percentage of time. For this reason, it is critical to observe the effect of Ka band utilization over satellite links on various KPIs using experimental trials and compare it with legacy terrestrial networks.

IV. EXPERIMENTAL RESULTS

In this section, our focus is to obtain empirical assessments of different KPIs under the satellite-based backhauling set-up and compare them with a terrestrial live 4G cellular mobile radio communication network. For this reason, a real-time prototype of satellite-based backhaul is deployed and tested. Observations of different KPIs can yield insights to identify involved deployment trade-offs while accounting for actual network deployment conditions.

In the presented work, the deployed satellite system constitutes a single satellite eNodeB where a single test UE is connected including an EPC for end-to-end system implementation. Fig. 3 shows the experimental test site locations of the utilized live LTE and satellite networks. The KPI performance differences between these two network systems enable us to determine the differences between a satellite-based and terrestrial-based backhaul mobile system and to evaluate their comparative performance gains to outline the involved trade-offs.
A. Satellite components and configurations

Our satellite system is HTS and uses Ka band frequencies between 19.828.662 kHz - 19.891.412 kHz for DL and between 29.590.047 kHz - 29.594.041 kHz for UL. Therefore, the spectrum bandwidths are 70 Mhz and 4 Mhz for DL and UL respectively.

The DL link transmission is between the satellite and the eNodeB whereas UL is vice-versa. Usually, dedicated bandwidth for DL is higher than UL. The total bandwidth is summation of UL and DL bandwidths. In this paper, we have used GEO satellite which is 35.786 km away from Earth. Together with calculations, one-way propagation delay of GEO satellite transmission can be calculated as

\[ T = \frac{d}{c} = \frac{35.786\text{km}}{3e5\text{km/s}} = 119\text{ms} \]  

Hence, the communication delay between two ground stations through the satellite is around \( 2T = 238\text{ms} \).

B. Testbed network functions

To perform experimental end-to-end tests over the considered systems, we used a notebook with SIM card as an iPerf [27] client and a UE with TEMS[28] tool which installed on UE to collect radio parameter KPIs. An File Transfer Protocol (FTP) server located on the Internet is used to download a file via UE. The same tests were conducted both in the live and in the satellite test sites. iPerf tool is used to generate a UDP flow between the iPerf client the iPerf server. The principle objective of the deployed experimental test system is to allow realistic evaluations of the trade-offs that could be provided by applying satellite-based backhaul in a real-operator environment. Fig. 4 shows different types of network devices that is used during experimental trials. These components are:

1) Satellite antenna: After the line right angle towards the satellite has been adjusted, it is fixed positioned to the ground to combat environmental effects.
2) Sector antenna: A sector antenna is a directional antenna for outdoor enviroment that provides high gains. Sector antennas consist of an array of dipoles. Performance of these antennas are dependent on the size and shape of the reflector.
3) Baseband Unit (BBU): A BBU is a unit that processes baseband. The BBU is connected with Remote Radio Unit (RRU) via optical fiber. The BBU is responsible for communication through the physical interface.
4) RRU: A RRU performs radio frequency (RF) downlink and uplink channel processing. The RRU communicate with BBU via a physical link. It communicates with wireless mobile devices via air interface.
5) VSAT modem: An equipment that performs traffic acceleration and security protocols is selected and it is also compatible to operate with LTE. It is connected to the satellite antenna and eNodeB.
6) iPerf Client: iPerf works in a client/server mode. A client sends data to the server for the test. Additionally, the deployment complies with the relevant features of LTE standards.

Table I presents the iPerf measurements delay responses of UL and DL links from the satellite test eNodeB. Bandwidth setting for iPerf test is limited to 50 Mbit/s in order to transfer approximately 60 MBytes of data. The results indicate that User Datagram Protocol (UDP) traffic has low completion time compared to Transport Control Protocol (TCP) traffic. In the iPerf tests, it is seen that tests with TCP were completed in both UL and DL by approximately 3 percent later than UDP. This demonstrates how TCP is affecting the applications used by the end-user connected to a satellite eNodeB. Differences between UL and DL test completion durations are caused by hardware differences between iPerf server and client. It is also related to the high number of tests performed by the server at the same time.

C. Performance in the Downlink

DL number of RBs distribution: Fig. 5 shows the differences of number of RB utilization ratios in DL between live LTE (eNodeB) and satellite test eNodeB DL performances. In Fig. 5, RBs DL Probability Distribution Function (PDF)
Table I: Test Completion Results of the iPerf measurements taken from the satellite test eNodeB.

| Protocol | Upload Test Completion Time (s) | Download Test Completion Time |
|----------|---------------------------------|------------------------------|
| TCP      | 11.35                           | 11.13                        |
| UDP      | 10.98                           | 10.89                        |

Fig. 4: Installed equipment and connections on the satellite test site. Left: Satellite and Sector antennas. Right: RRU, BBU, VSAT modem and Iperf client.

represents the percentage of number of RB measurements at a specific value in DL direction. $RBs_{DL}$ Cumulative Distribution Function (CDF) represents the percentage of number of RB measurements at least as good as a specific value in DL direction. Similarly, Fig. 6 shows the boxplot for the number of RBs in DL for both live and satellite eNodeBs. The median values of number of utilized RBs for satellite and live eNodeB are 76.92 and 43.53 respectively. In eNodeB live network, the variance of RB is observed to be narrower than satellite test eNodeB. Although RF conditions seems not good in live eNodeB, the scheduler utilizes RBs as many as possible in which up to 50 RBs are used for a given bandwidth of 10 Mhz. In satellite test eNodeB, RB utilization variance is larger.

DL FU ratio distributions: Fig. 7 shows the FU ratios in DL direction of both live and satellite eNodeBs. Similar observations with DL RB utilization is also observed in Fig. 7. Similarly, Fig. 6 shows the boxplot for the FU ratio (%) in DL for both live and satellite eNodeBs. The median values of FU ratio for satellite and live eNodeB are 60.66 and 66.87 respectively. Fig. 6 clearly validates the higher FU ratio in live eNodeB compared to satellite eNodeB. The variance on FU ratio is narrower on live eNodeB and is concentrated at higher values. This is again due to usage trend of maximum FU policy of the scheduler even though the RF conditions are not as good as satellite eNodeB. There exists higher variance on FU ratio for satellite eNodeB due to existence of not full transmit buffer and irregular PDU receptions due to delays in satellite links. Similar to Fig. 5, satellite eNodeB cannot schedule the PDUs appropriately at Medium Access Control (MAC) layer due to existence of incomplete transmit buffer. This in turn reduces the FU ratios as well as DL PDCP throughput even though there exists only one test UE inside satellite eNodeB.

D. KPI Relationship analysis

In this section, we investigate the relationship between different LTE performance KPIs by varying one of them and observe its affect on the remaining KPIs. The KPIs that we are observing are DL throughput, CQI, FU ratio, number of RBs, Block Error Rate (BLER), number of RLC and PDCP packet numbers, MCS and MIMO TB usage. In the following analysis, in order to put on the same graph metrics with different ranges, some metrics have been normalized to percentage, so that 100% corresponds to the maximum value of the metric. For instance “RBs DL (in %, normalized to 30)”, means that the maximum value of “RBs DL” in the graph is 30. In that case 50% would correspond to “RBs DL = 15”.

MCS and CQI values: Comparing average CQI values on top subfigures of Fig. 10 marked with dark blue colors for both satellite and live eNodeBs, we can observe that satellite communication link quality is high and mean CQI value of 14.96 is observed during the evaluation time interval. This
Fig. 5: Normalized histogram and CDF of DL # of RB distributions (a) eNodeB in Live Network (b) Satellite Test eNodeB

Fig. 6: Boxplot comparisons of number of RBs and the FU ratio (%) in DL for live and satellite eNodeBs.

Fig. 7: Normalized histogram and CDF of DL FU ratio distributions (a) eNodeB in Live Network (b) Satellite Test eNodeB

indicates a good RF medium conditions in satellite backhaul network and there is no problem with RF signal quality for satellite UE. On the other hand, terrestrial live network’s CQI values fluctuate and radio conditions are slightly lower than satellite eNodeB with an mean CQI value of 9.92. Red colored marks in third row of Fig. 10a and Fig. 10b show the MCS index values over the observation duration. MCS index in live eNodeB network is fluctuating between 0 and 25 values. This shows that radio conditions are variable and worse than satellite network. In comparison, satellite network MCS index is almost constant at maximum MCS index of 25 which indicates high modulation usage in satellite eNodeB with very small decreases at certain time intervals in DL. Note that there are many real-UEs in eNodeB live network as well one test UE in satellite eNodeB. This is also another effect that can have a negative impact on average CQI value of UEs in live eNodeB.

KPI relationship analysis based on number of RBs for LTE in DL: Fig. 8 shows the average percentage values for CQI, MCS index and FU ratio on the right y-axis as well as average throughput values on left-y axis versus increasing number of RBs on x-axis. Note that in Fig 8a and Fig 8b CQI values are normalized with respect to maximum value of 10.5 and 15 and DL MCS index values are normalized with respect to maximum value of 16 and 28 respectively. Number of DL RBs is related to load in the cell. As the number of RBs increases, throughput values of both satellite and live eNodeBs also increase accordingly as expected. For example in Fig. 8a together with 50 total number of RBs (for 10 Mhz of bandwidth), around 18,000 Mbps can be achieved, whereas in Fig. 8b the throughput raises above 140,000 Mbps with 100 number of RB utilization (for 20 Mhz of bandwidth).

Average MCS index and CQI values are at relatively maximum levels for satellite eNodeB in Fig. 8b. (Note that there exists high fluctuations in Fig. 8b at the beginning for average MCS index values which are due to small number of averaged sample data at low number of RBs.) Due to RF conditions of live eNodeB, CQI and MCS index values fluctuate between...
60% to 100% in Fig. 8a. Comparing DL FU ratio distributions when the number of RBs increases in Fig. 8 we can observe that there exists slower trend of increase in satellite eNodeB than live eNodeB. This is related to transmit buffering problem encountered in satellite eNodeB which is also discussed in more detail in subsequent sections.

Comparing DL FU ratio distributions when the number of RBs increases in Fig. 8, we can observe that there exists slower trend of increase in satellite eNodeB than live eNodeB. This is related to transmit buffering problem encountered in satellite eNodeB which is also discussed in more detail in subsequent sections.

KPI relationship analysis based on LTE DL FU ratio:
Fig. 9 shows the relationship between FU ratio and other related KPIs. On the other hand, Fig. 10a and Fig. 10b (second rows marked with yellow colors) depict the FU ratio for both eNodeBs in live and satellite networks respectively. We can observe from Fig. 10 that in live eNodeB, DL FU percentages are lower than satellite eNodeB. This is due to existence of real UEs connected to the live eNodeB. The scheduling of UEs at each transmission time interval (TTI) (i.e. every 1 ms) may allow some UEs to have no resource allocations during this allocation interval. However interestingly, the same trend of DL FU percentage fluctuations are observed with satellite backhaul network as well as depicted in Fig. 10b. Note that in satellite eNodeB, the FU percentage is not expected to fall to zero values since there exists only one test UE in the satellite network. Additionally, the radio conditions are observed to be good (from observations of CQI and MCS index values as discussed previously) in satellite eNodeB.

Last row subfigures marked with black colors in Fig. 9 and Fig. 10 show DL PDCP throughput values. We can infer that as expected DL PDCP throughput values of both live and satellite eNodeBs increase in correlation with the increase in FU ratios. At the same time, satellite eNodeB yields higher average DL PDCP throughput values compared to live eNodeB due to existence of only single UE. Light blue marked subfigure in fourth rows of Fig. 10a and Fig. 10b depict the DL BLER percentage. In general for live eNodeB network, as expected when BLER percentage increases, MCS index drops and as a result throughput decreases. Moreover, there exists other UEs inside the cell which have an effect on increase in BLER values. When satellite network results are investigated in DL direction, the error detection for PDUs sent by test UE by Hybrid automatic repeat request (HARQ) is realized very late due to end-to-end latency in the network. This makes BLER higher.

When we compare the number of RB utilization ratio in percentages at a given FU ratio in percentages in Fig. 9, a higher RB utilization ratio percentage in live eNodeB is observed compared to satellite eNodeB. For example, at 32% FU RB utilization percentage is around 70% for satellite eNodeB, whereas it has reached to 90% for live eNodeB. Fig. 9b shows that the number of utilized RBs can decrease as FU ratio increases. For instance, the number of RBs usage percentage is lower when FU ratio is 74 compared to the case when it is 72. This result is in contrast with the expectations and the observation results of live eNodeB in Fig. 9a. The main reason is again due the transmit buffer not being filled...
Fig. 9 also shows the effect of increase in MCS and its impact on PDCP throughput, FU and CQI. The effect of jitter and latency in satellite based backhaul can be extracted from these KPIs of satellite eNodeBs. The transmit buffer does not become full due to satellite backhaul link originated latency. For this reason, PDCP PDUs are kept inside transmit buffer until it becomes full so that it can be scheduled later. The PDCP PDUs in the transmit buffer are scheduled to be transmitted with sufficient number of DL RBs and consecutive TTIs at high FU ratio over the satellite link. Due to existence of only one UE in satellite eNodeB and the impact of latency and jitter of the satellite links, the FU ratio has wide variance as also observed in Fig. 9b and Fig. 6. On the other hand, GTP-
U accelerator yields satisfactory UE throughput in contrast to this large variance in FU ratio as also observed from Fig. 9b. Note that there is only one test-UE inside satellite network and there is a tendency that DL FU ratio is expected to be worse in case the number of UEs increases.

Number of PDUs in the protocol stacks of RLC and PDCP layers are marked with light blue and yellow colors in third rows of Fig. 11a and Fig. 11b. For more detailed examinations, Fig. 12 shows the box plot of the number of PDUs in the protocol stacks of RLC and PDCP layers for both live and satellite eNodeBs over the same observation duration. We can observe that the median number of DL RLC PDUs are around 897 for live eNodeB and 1314.5 for satellite eNodeB. On the other hand, median number of DL PDCP PDUs (that are
The scheduler at the satellite eNodeB is concatenating PDCP PDUs and sending them to MAC layer as one Service Data Unit (SDU). However, this process of scheduler is delayed due to effect of satellite link. Under normal circumstances, schedulers are expected to segment PDCP PDUs at the RLC layer. However, this kind of segmentation does not appear in satellite eNodeB where RLC PDUs are segmented at the PDCP layer. For this reason, in case there exists many UEs inside satellite eNodeB the occurrence of too many PDCP PDUs can create a transmit buffering problem.

The third observation is that the excessive existence of PDCP PDUs can be due to existence of GTP-U accelerator. GTP-U accelerator technique includes a caching method. Therefore, we observe that there can be a trade-off between the number of UEs that can be supported within a eNodeB with satellite backhaul link and the caching size related to the GTP-U accelerator’s performance. Large caching size increases the capabilities of the GTP-U accelerator in terms of providing lower latencies, on the other hand it can decrease the number of UEs that can be scheduled over the satellite eNodeB due to existence of large number of PDCP PDUs compared to RLC PDUs. Lower caching size on the other hand, adversely affects the GTP-U’s accelerator, but decreases the number of PDCP PDUs in the buffer of the scheduler. Therefore, for higher performance gains in terms of lower latency and higher number of UEs for satellite eNodeB, an optimal balance between the caching size and the number of UEs using satellite eNodeB is needed since GTP-U acceleration is a fundamental requirement for satellite links to decrease latency.

V. Conclusion

It is inevitable that satellite networks will integrate with other networks including 5G cellular networks. In this paper, we investigated various KPIs performances of both satellite and terrestrial cellular networks in a an experimental set-up to observe the effect of backhaul satellite links on cellular network performance. The comparative experimental performance evaluations were performed in terms of CQI values, MCS index, PDCP throughput, RB and FU utilization ratios as well as BLER and MIMO TB utilization. Our experimental results indicate three main observations: First one is the existence of FU and RB utilization ratio problems in satellite links due to existence of delays in satellite links even though there exists high MCS index and CQI values. Second one is that compared to live terrestrial networks, our numerical results revealed that total number of PDCP packets outnumbers the total number of RLC packets in satellite networks. Our final result designate that there will be a trade-off between the number of UEs that can be supported with satellite eNodeB and the caching size related to the GTP-U accelerator. Therefore, an optimal balance between the caching size of the GTP-U accelerator for latency reductions and the number of UEs using satellite eNodeB needs to be adjusted before deployment of satellite backhaul network in an operational environment.
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