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Deterioration Causes Evaluation of Third Generation Cellular LTE Services for Moving Unmanned Terrestrial and Aerial Systems

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Abstract **– Well-deployed cellular networks offer a cheap wireless solution for the control channel deployment of Remote-Control Vehicles (RCV) and Unmanned Aerial Vehicles (UAV). However, a cellular data transfer service performance is affected by a different kind of User Equipment (UE) mobility. Operating conditions of UAV imply working at different altitudes, variable velocities with accelerations/decelerations and rapidly changed antennas angular position, which lead the wireless signal to be prone to negative effects. Available field measurement studies are not sufficient to provide excessive information on degradation problem causes for UEs moving along a complex trajectory. This paper presents an evaluation of the service quality of live operational 3G and LTE networks for both ground moving and flying UE. It has been found that antennas angular position variations in 3D (for example, during UAV manoeuvers) increase data transfer latency and jitter. Moreover, this effect in conjunction with higher interference at high altitudes may partially or fully block the data transfer service. This paper has been prepared to draw attention to the problem that makes the cellular data transfer service unusable for highly-manoeuvrable UAVs.**

Keywords **– 3G; Antenna angular position variations; LTE; Mobility; Moving equipment; PIFA; RCV; RPAS; UAV.**

I. Introduction

Remote Control Vehicle (RCV) and Unmanned Air Vehicle (UAV) operations are beyond the Radio Line-Of-Sight (LOS) [1]. The actual UAV communication range typically is much less due to radiated power and transmitter consumed power limitations: not more than 15 km [2]. Of course, cellular data transfer service solutions are of RCV and UAV developers' main interests. Such solutions can provide an extended range of operation (limited by the cellular operator coverage), reduced radio transmitter size and power consumption (like typical 3G/LTE USB dongle) and ability to transfer control commands, telemetry and video streaming simultaneously over a high-speed service.

Today 2G, 3G and LTE networks are deployed in most countries. Only 3G and 3G LTE (also called LTE) networks will be discussed here. The main reason to exclude LTE-A (sometimes called 4G or 4G+) from the study is its equipment excessive power consumption. This makes it impossible to be implemented as USB dongle due to USB power supply limitations.

A 3G network has been introduced in third generation partnership project (3GPP) Release '99 (R99). 3G technology utilises Wideband Code Division Multiple Access (WCDMA), requires new base stations (called NodeB) and is called Universal Mobile Telecommunications System (UMTS). First improvement was done by a significant increase of UMTS network performance within existing NodeB by introducing High Speed Packet Access (HSPA) according to the third generation partnership project (3GPP) specifications Release 5 and 6 [3]. In addition to higher data rates, this technology also provides low jitter – below 20 ms and latencies below 100 ms [4]. The primary technological features that help reduce RTT are the following: short transmit time interval (TTI) of 2 ms and hybrid automatic repeat request (HARQ) implementation in the NodeB. Each received data packet in HSDPA downlink is acknowledged automatically by the NodeB. Furthermore, NodeB is responsible for immediate acknowledgments of uplink packets in HSUPA. Now the NodeB HARQ mechanism is responsible for retransmission of all lost transport blocks in downlink and all lost packets in uplink. The main idea of work shift from the Radio Network Controller (RNC) to the NodeB is to speed up acknowledgement and lost transport blocks retransmission by shifting it into hardware that is closer to the radio interface. Further improvement in 3G networks was done by implementing HSPA+ standard according to 3GPP Release 7 [5]. HSPA+ is sometimes referred as 3.5G network and utilises Multiple Input Multiple Output (MIMO) solution downlink. The UE must meet at least Cat 15 to be able to operate in HSPA+ mode. The simultaneous use of 64QAM modulation and MIMO downlink technology is possible starting from 3GPP Release 8 [6]. These networks are usually referred to as 3.9G networks. Here the UE must meet Cat 19 or 20 with the maximum downlink speed of 35.28 Mbps or 42.20 Mbps, respectively. The final improvement was done in Release 9 [7] by allowing Dual Cell (DC) in downlink (DC-HSDPA) and uplink (DC-HSUPA) simultaneous operation called DC-HSPA+ or 3.99G network. Here the UE can be configured with two uplink and two downlink frequencies from the same NodeB. The UE must meet Cat 25/26 or Cat 27/28 to support DC-HSPA+ operation with maximum data rates of 55.9 Mbps or 84.40 Mbps, respectively.

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The Long Term Evolution (LTE) technology was also implemented in 3G networks starting from 3GPP specification Release 8 [8]. LTE uses the same MIMO and DC operations as described above. The key difference between conventional 3G DC-HSPA+ network and 3G LTE network is the use of scalable channel bandwidth (up to 20 MHz) and more spectrum-efficient OFDMA instead of WCDMA. This makes 3G and 3G LTE incompatible to each other: LTE requires its own eNodeB stations instead of existing NodeBs. The UE must meet LTE Cat. LTE Cat from 1 to 5 (specified in 3GPP Release 8) does not support Carrier Aggregation (CA).

LTE-Advanced (LTE-A) was officially introduced in 3GPP Release 10, but finished in Release 11. The LTE-A is usually referred to as 4G (or 4G+) technology [9]. Both 3G LTE and 4G LTE-A use the same eNodeBs and spectra. The LTE-A speed improvement is done by introducing CA and 8 by 8 MIMO. UE must meet at least LTE Cat 6 to be able to use CA. LTE Cat 6 device power consumption is higher than USB power supply limit, so the LTE Cat 6 device cannot be implemented as USB dongle.

The key differences between 3G and LTE for the end user are the following: UE must support LTE Cat to be able to operate in LTE cells; 3G and LTE (3G LTE and 4G LTE-A) use different cells (so typically 3G and LTE have different coverage and operating bands); UEs in 3G HSPA+ and above networks are operating in a low-speed channel (original UMTS) at idle and are switched in high speed channel (HSPA+) as soon as traffic exceeds threshold, which is set by the cellular operator (usually 64 bps); there is no low-speed channels in LTE, so its starting time is reduced; overall network latencies and maximum speeds of 3G and 3G LTE are comparable: LTE provides slightly lower RTT (due to different backhaul [10]) and slightly greater theoretically available maximum data rate; finally, in 3G only a limited number of users can be allocated in a high-speed channel (HSPA+), so in highly loaded 3G network some users may be left in a low-speed mode (called UMTS); whereas LTE has no such mechanism and overloaded LTE cell usually cause a high number of dropped packets.

Regardless of the LTE technology benefits, sometimes LTE service performance is decreased due to the overload, while conventional 3G HSPA+ networks provide comparable, or even better performance because typically they are less loaded [11], [12]. The LTE cells are more loaded because modern UE automatically selects LTE cell in case it is available; 3G cell is selected if LTE service fails or if there are no LTE service at all. This makes LTE cells highly loaded in dense urban areas, while 3G cells become less loaded. In rural areas, both 3G and LTE are relatively low loaded; hence, typically LTE provides greater performance compared to 3G service [13].

As mentioned above, 3G and LTE data transfer services promise a cheap and lightweight solution for the UAV and RCV remote control wireless channel implementation. Available field studies [14], [15] stated that cellular network coverage up to 300 m height above ground level (AGL) is sufficient to promise possible UAV control over cellular data transfer services. However, the all-inclusive field study by Fung Po Tso et al. [16] noted ground moving UE downlink and uplink throughput degradation, even if the signal strength was sufficient. Our preliminary experiments also confirm service quality deterioration as soon as the UE starts to move. The data in [16] is statistical representation of throughput, Round Trip Time (RTT) and Energy per chip to Interference plus Noise ratio (Ec/Io) measurements and is not suitable to provide excessive information on degradation problem causes. The field studies performed in Riga also reported poor cellular data transfer service performance during flight even if the signal strength was sufficient [17].

The data transfer service quality considerably depends on UE ability to detect its useful signal against all other signals (considered as interference). This means that the cellular network data transfer service mainly depends on the overall signal strength indicator (called Received Signal Strength Indication (RSSI), expressed in dBm) and useful signal strength indicator (called Received Signal Code Power in 3G networks (RSCP) or Reference Signal Received Power (RSRP) in LTE networks). In rural area, the regional morphology has a major impact; in urban area, the signal is affected by shadows from buildings and signal multiple reflections (multipath). Consequently, if the UE is placed above the earth surface, the signal strength must be defined by the cell carrier frequency, distance between Base Station and UE, as well as NodeB (or eNodeB) array pattern only (here PIFA antennas are considered as omnidirectional). At a higher altitude, RSSI and RSCP (RSRP) levels become increased as the UE and the selected Base Station (BS) obtain LOS path without interfering objects at all. However, RSSI also increases because UE obtains LOS with more BSs that were previously shaded. This increases difference between an overall signal strength indicator (RSSI) and a useful signal strength indicator (RSCP in 3G or RSRP in LTE). More BSs at the same band cause higher interference and make signal detection process more complicated. This effect is measured by the UE and indicates via wireless signal performance indicators, such as: Energy per chip to Interference power ratio in 3G networks (Ec/Io, expressed in dB, its value is always below 0 dB) or Reference Signal Received Quality (RSRQ, in dB, always less than 0 dB) and Signal to Interference and Noise Ration) (SINR, in dB, can be negative or positive) in LTE networks.

Many research papers and field studies are devoted to ground (terrestrial) cellular communications. At present, few research papers are available to better understand the potential of cellular data transfer service for small UAV. The same problem is stated in all these papers: high downlink channel interference as flying UAV obtains LOS path with many BSs and other UEs [18]–[20]. UE Automatic Modulation and Coding (AMC) mechanism reports increased interference via Channel Quality Indicator (CQI) to BS to request slower modulation and coding scheme. This leads to slower data rates, but helps keep BER at 0.1 % [6]. Cellular data transfer services (3G and LTE) at higher altitudes will operate in slower modulation and coding scheme due to high interference. Interference level values represented in [18] (as well in our preliminary testing) are not below minimum acceptable limits (we use cisco requirements as a reference [21]) and the data transfer service should be able to operate correctly, keeping BER at 0.1%.

Unfortunately, field studies on real working equipment indicate temporary data packets loss that leads to massive resends made by HARQ mechanism, causing “spikes” in RTT (latency) and jitter. This leads to periodical freeze in UAV telemetry feedback (e.g., real time artificial horizon display) and jittering in video channel.

The goal of our field study is to find factors that, together with increased interference, sometimes cause excessive data transfer jitter or even cause cellular data transfer service to fail when 3G or LTE is used in flying UAV.

II. Experimental Section

A. Testbed

Network and ground server selection: LMT cellular network operator has the least loaded cellular network in Latvia [12]. The LMT cellular network operators’ cellular data transfer service is used to reduce (or even exclude) data transfer quality deterioration due to cellular network overload. The testing results in [12] show that the google free DNS server (IP: 8.8.8.8) is more trusted than the server hosted at RTU building (IP: 213.175.90.193). The use of google free DNS server helps avoid limitations that can be caused by the ground wired network segment service quality.

UE setup: request messages are sent from the portable computer, which is equipped with mobile broadband USB dongle Huawei E3372. It uses its own PIFA antennas; external antennas were not connected. The Huawei E3372h is Cat 24 device (supports 64QAM modulation and can operate in dual cell DC-HSPA+ mode) and LTE Cat 4 device. By default, its operational mode is HiLink (CdcEthernet). In this mode, the device operates as a NAT server and emulates a virtual network card (NDIS) on the local computer. All configurations as well as network information can be displayed by accessing a gateway address (default gateway ip: 192.168.8.1) via web browser. It makes network information logging task complicated. The device has been reprogrammed into Stick mode (RAS) (firmware 21.315.01.00.143_M_01). The Stick mode enables access to the set of standard serial AT-commands and reports. Under the Stick mode, the device operates as a standard PPP modem, emulates two virtual serial ports and uses local computer resources (by means of modem running software) to operate. The modem software blocks any further access to the serial ports because serial ports can be accessed only individually. The access problem can be solved by using MS Windows 8 operation system, which has built-in driver (Huawei 1.0.17.0) and allows access to the internet without installing the Huawei modem software. This retains internet access and allows access to the serial port for control and monitoring purposes simultaneously.

The following data has been captured: network performance indicators, such as RSSI, RSCP, Ec/Io (or RSSI, RSRP, SINR and RSRQ in LTE mode) reported by dongle; ground speed, GPS coordinates and altitude (from the Global Sat BU-353-S4 GPS receiver) and network RTT (based on ping report). As BS is responsible for immediate acknowledgments of TCP packets (see introduction for more details), the time interval between sending a TCP packet from the dongle and receiving a corresponding ACK message cannot be used as RTT measurement [6]. This is the main motivation why the standard utility “ping” was chosen. The “ping” settings are: 32 Byte packets, periodic and timeout are 1 sec, destination is 8.8.8.8.

To simplify simultaneous data capturing from the USB dongle and GPS receiver NMEA messages, as well as to perform data decoding and real-time visualization, a virtual instrument (vi) was developed in the LabVIEW environment. A vi generated report can be exported into MS Excel.

Fig. 1. Data acquisition system.

B. Cellular Network Performance for the Flying UE

It is proven that interference increases at higher altitudes, but usually is still in acceptable limits to operate with slower modulation and coding (see Introduction section for more details). We assume that influence of increased interference can be redoubled by the fact that flying UE antennas have angular position variations, causing antenna polarization variations, as well as Doppler shift variations.

This experiment was done to check 3G network performance in case of rapid horizontal and vertical speed elevations, as well as tilt and roll changes (UE antenna angular rotations) when UE is flying. This was done by placing UE in lightweight Cessna 172N airplane.

Fig. 2. Visualized GPS coordinates of the horizontal flight path.

A ground run, one take-off, one go-around, two flares and one ground roll were performed in Spilve airfield in Riga. GPS data visualization is done by online resource [22].

A strong crosswind at the take-off/landing causes additional complexity for the pilot and causes various types of airplane position and angle elevations. The Metres Above Sea Level (MASL), ground speed and coordinates measurements were reported by GPS receiver once per second. Unfortunately, this results in low gust resolution, whereas angular position (tilt and roll) was not measured at all and not represented here.

The experiment data can be divided into two parts. The first part contains reference data captured from the stationary aircraft, and the experimental results are shown in Fig. 3. The first plot shows RTT in time (blue curve); the second plot shows network performance indicators: RSSI (left *y* axis, blue curve in dBm); Ec/Io (right *y* axis, red curve in dB).

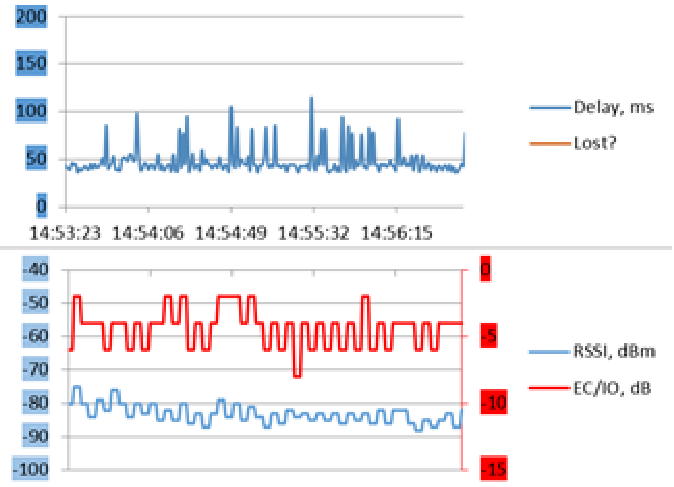

Fig. 3. Network performance for the immovable UE placed on the ground.

On the ground RSSI level is satisfactory: −84 dBm. The Ec/Io is in perfect-to-good of −4 dB … −6 dB limits. RTT values are small and stable: 45 ms in average. None of packets were lost.

The second part contains two paths. The first path (take-off, horizontal flight and approach) was done by inexperienced pilot, while the go-around and further flight was done by the more experienced flight crew and the flight was much more stable.

At the beginning of the ground roll of the airplane, RSSI level is satisfactory: −78 dBm. Then the airplane is accelerated up to 120 km/h. The RSSI and Ec/Io values are not affected, whereas RTT becomes less stable. The take-off takes place at 14:59:56. This results in larger RSSI values: at the top altitude of 300 m the RSSI value increases up to −62 dBm, while the Ec/Io drops down to −10 dB … −18 dB. The RTT values become unstable and the majority of them exceed 1 sec (are considered as lost) and the data transmission almost failed regardless of high RSSI values and Ec/Io is poor, but still acceptable. Further speed, flight direction and altitude changes have no noticeable effect on almost failed data transfer. A go-around occurs at 15:05:00. The flight path, speed and altitude are almost the same compared with the previous path. The Ec/Io values are in −8 dB … −22 dB limits, but the data transmission did not fully fail here. The RTT values are unstable again, but the number of lost packets decreased significantly.

We comprehend such difference as the second flight path was more stable that caused less UE antenna position and angular orientation elevations.

The touch-down and braking take place at 15:09:48. Then the RSSI drops to −70 dBm, the Ec/Io values are again at perfect level of −4 dB and the RTT becomes stable.

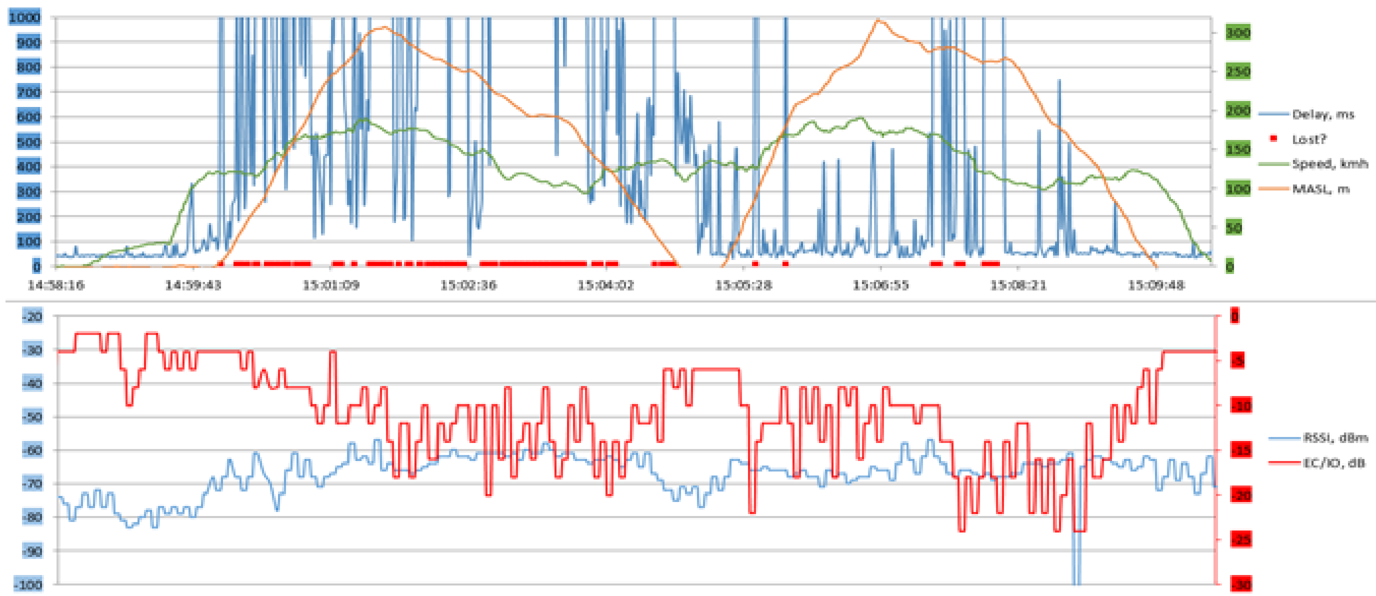

Fig. 4. Network performance during ground roll, two laps with one take-off and one go-around, as well as one landing.

C. Dependence of Network Performance on Altitude

The following experiment was made to check cellular network coverage above the ground surface near to Spilve airfield, which was used in field study in the section 2B. Our field study yields comparable results with [18] and will be represented here for comparison.

All network parameters and network RTT were recorded simultaneously to exclude possible misunderstanding of the obtained experimental results. RTT values are averaged. Measurements were done using firewatch tower. To exclude impact of the UE antennas directivity and possible shadows, the dongle was placed horizontally at 2 m above tower wood floor, keeping the same axial direction for all altitudes. Measurements were obtained both in 3G (DC-HSPA+) and 3G LTE modes.

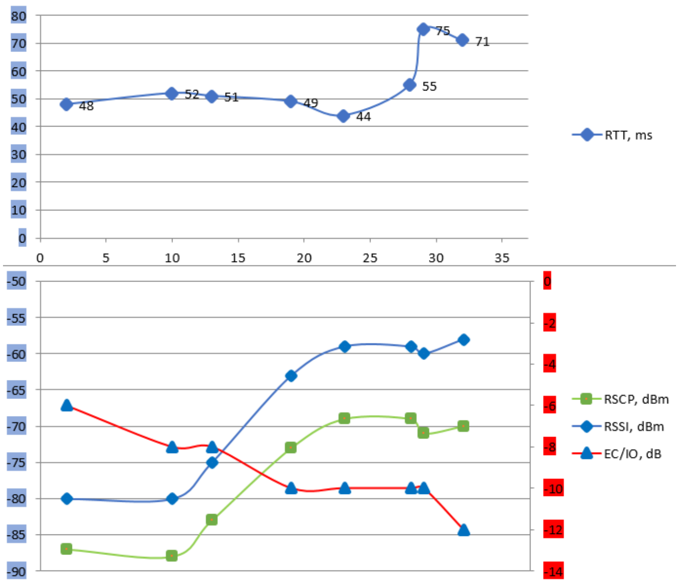

Fig. 5. Network performance for the static UE at different altitudes in 3G HSPA+ mode of operation.

Averaged RTT values are shown in the first graph, in milliseconds. Network performance indicators are shown in the second graph: RSSI and RSRP are in the left *y* axis, in dBm, Ec/Io is in the right *y* axis, in dB. Altitude is in the *x* axis and represented in meters.

On the ground RSSI is −80 dBm and Ec/Io is −6 dB. At higher altitude Ec/Io monotonically decreases to −12 dB at the 32 m altitude. RSSI and RSCP levels become increased starting from 10 m altitude. True Line-of-Sight (LOS) between UE antennas and the base station (NodeB) without interfering objects at all is available when dongle is placed above trees, starting from 13 m. Ec/Io becomes decreased even though RSSI and RSCP increase. RSCP increases as the UE and selected NodeB obtain true LOS path without interfering objects at all. However, RSSI also increases because the UE obtains LOS with more NodeBs that were previously shaded. This causes Ec/Io to decrease. Minimal Ec/Io level during this experiment was −12 dB, which was still enough to operate. None of packets were lost during this experiment.

Averaged RTT values are shown in the first graph, in milliseconds. Network performance indicators are shown in the second graph: RSSI and RSRP are in the left *y* axis, in dBm, RSRQ and SINR are in the right *y* axis, in dB. Altitude is in the *x* axis and represented in meters.

In LTE mode, RSSI and RSRP also become increased at higher altitudes because UE obtains LOS communications between its antennas and eNodeBs. Higher altitude causes SINR also to decrease; however, SINR becomes less affected compared to Ec/Io in 3G DC-HSPA+ mode. We comprehend such difference as LTE cell operation in Riga is distributed between 4 bands, whereas all 3G cellular operators operate at the same B1 band and there are at least 7 NodeBs (3G) accessible at the top altitude of 32 m. More BSs at the same band cause higher interference. It should to be noted that there is no effect on RTT values in LTE mode.

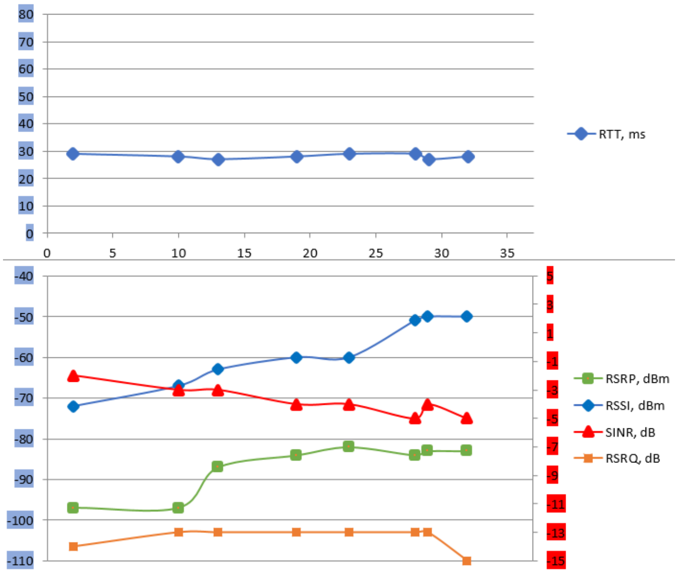

Fig. 6. Network performance for the static UE at different altitudes in 3G LTE mode of operation.

D. Dependence of Network Performance on Angular Position of UE Antennas

Making experiments in the air is too expensive. Such experiments do not allow making simultaneous measurements for the stable and not stable flights. The following experiments were done to prove that rapid antenna angular position variation in 3D (for example, during unstable flight) is one of the causes of unreliable data transfer over mobile cellular networks. To consider the impact of possible UE rapid changes in its angular position, two UE USB dongles were used simultaneously. The first dongle was securely fastened to a wood holder 1.5 meter apart from the car body in horizontal position. The second dongle was also fastened to a wood holder and was manually jiggled, tracing out an "8" 0.5 m long trajectory simultaneously with 180° angular rotation. Both dongles were registered within the same cell.

The experimental results for the DC-HSPA+ mode of operation are shown in Fig. 7. The first plot shows RTT in time for the first dongle with fixed angular position (left *y* axis, in ms and blue criss-cross marks); RTT in time for the second shaky dongle (left *y* axis, in ms and green square marks); ground speed (right *y* axis, in km/h and red curve). The second plot shows network performance indicators. Fixed dongle: RSSI (blue curve, left *y* axis, in dBm); Ec/Io (right *y* axis, in dB and red curve). Shaky dongle: RSSI (green square marks, left *y* axis, in dBm); Ec/Io (orange square marks, right *y* axis in dB). During the experiment, the cell was not changed.

The Huawei 3372h dongle approaches its noise floor at RSSI = −90 dBm. In this case, Ec/Io value becomes decreased because the denominator Io also implies spectral density of noise. A lot of retransmissions made by HARQ can be observed here. None of packets were lost during this experiment.

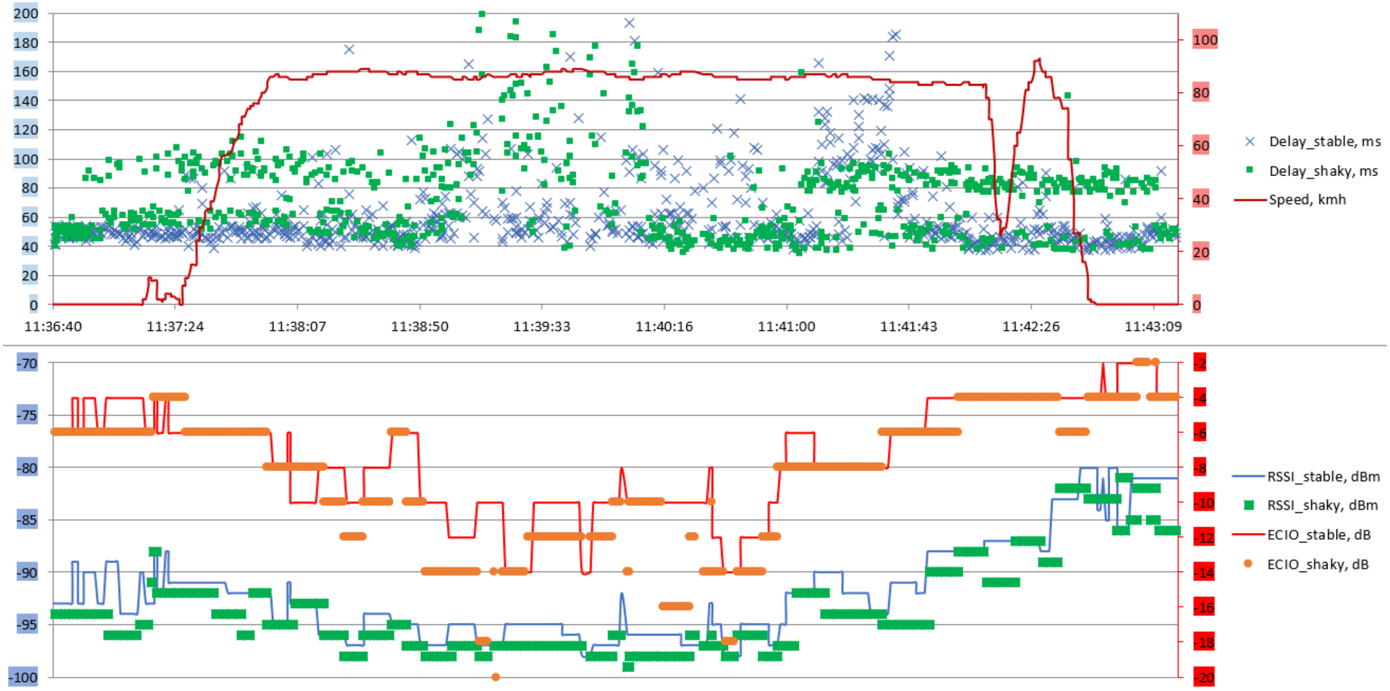

Fig. 7. Network performance for the movable UE with fixed and with jiggled antennas in 3G HSPA+ mode.

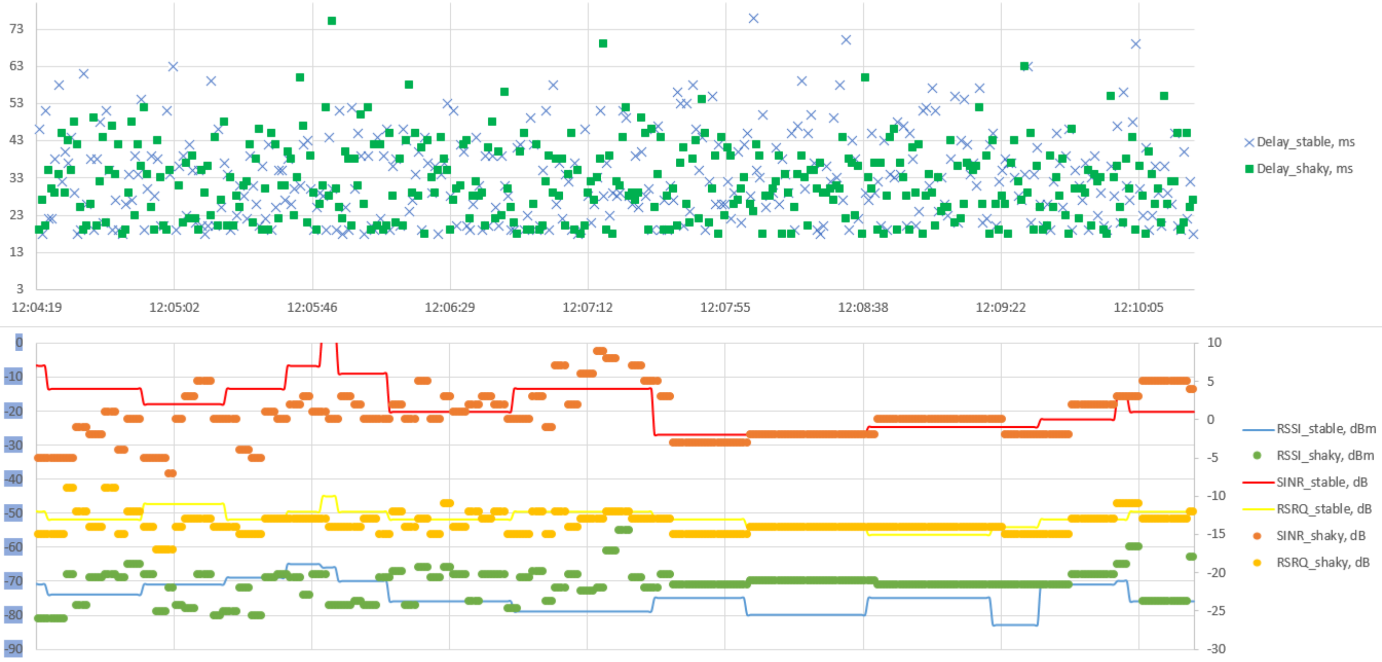

Fig. 8. Network performance for the movable UE with fixed and with jiggled antennas in LTE mode.

The experimental results for the 3G LTE mode of operation are shown in Fig. 8. Both dongles are fastened and second is jiggled as described above. The ground speed is 90 km/h. Operating frequency choice of both dongles was made automatically. Since there are a lot of LTE cells and its sectors, dongles have many possible options to select the desired cell and band. To obtain comparable results, only part where both dongles were operating in the same cell is shown in Fig. 6. Fixed dongle SINR (red curve) and RSRQ (yellow curve) both in dB are shown in the second plot right axis, RSSI (blue curve, dBm) in the left axis. Shaky dongle's SINR (orange dots) and RSRQ (light-orange dots) both in dB are shown in the right axis, RSSI (green dots, dBm) in the left axis. RTT, in milliseconds, is shown in the first plot. Please note that there is no noticeable difference between RTT of both dongles and no packets were lost during this experiment.

III. Discussion and Conclusion

Deterioration causes of 3G DC-HSPA+ (Cat 24) and LTE (LTE Cat 4) used on moving terrestrial and aerial systems are in the focus of this paper. LTE-A (LTE Cat 6 and above) UE is excluded from this paper due to excessive power consumption, which makes it impossible to implement it as a USB powered dongle.

This paper tends to show that UE PIFA antennas angular position variations make the wireless signal prone to negative effects and these effects are not fully compensated by AMC, particularly in DC-HSPA+ mode. This leads to an increased number of resends made by HARQ, which results in an increased jitter and average RTT.

The effect of rapid angular position variations of UE built-in PIFA antennas is aggravated at higher altitude due to stronger interference. In this case, data transfer service can be partially interrupted, even if the wireless signal parameters are not below their acceptable limits. Note that there is only one difference between the first and second path of the flight, described in Section 2.B: the second flight path was much more stable, while flight trajectory and wireless signal parameters were almost same for both paths.

This problem is less common for terrestrial vehicles because their antennas typically are securely fixed and have no rapid angular position variations, whereas 3G and LTE services are able to effectively compensate accelerations/ decelerations within limits applicable to a typical terrestrial vehicle.

This paper has been written to draw attention to the problem, which makes the cellular data transfer service, in addition to increased interference at high altitudes, even more unusable for highly-manoeuvrable UAVs due to antenna rapid angular position variation in 3D. In our opinion, this problem should be discussed simultaneously with a high interference problem to make oncoming 5G cellular services suitable for highly-manoeuvrable UAVs.

References

[1] M. Paredes and P. Ruiz, "Challenges in Designing Communication Systems for Unmanned Aerial Systems Integration into Non-segregated Airspace," *2014 IEEE Military Communications Conference*, pp. 1435–1439, 2014. https://doi.org/10.1109/milcom.2014.237

[2] F. Dimc and T. Magister, "Mini UAV communication link systems," *Promet Glob. Zb. Ref. Conf. Proc.*, p. 9, 2006.

[3] H. Holma and J. Reunanen, "3GPP release 5 HSDPA measurements," *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, pp. 2–6, 2006. https://doi.org/10.1109/pimrc.2006.254116

[4] M. Jurvansuu, J. Prokkola, M. Hanski, and P. Perala, "HSDPA performance in live networks," in *IEEE International Conference on Communications*, 2007, pp. 467–471. https://doi.org/10.1109/icc.2007.83

[5] H. Holma, A. Toskala, K. Ranta-aho, and J. Pirskanen, "High-speed packet access evolution in 3GPP release 7," *IEEE Commun. Mag.*, vol. 45, no. 12, pp. 29–35, 2007. https://doi.org/10.1109/mcom.2007.4395362

[6] R. Stuhlfauth, *High Speed Packet Access*, First Edit. Munchen: Rohde&Schwarz GmbH&Co. KG2012, 2012.

[7] M. Kottkamp, "HSPA + Technology Introduction," *Rohde Schwarz White Pap.*, 2012.

[8] D. Astely, E. Dahlman, A. Furuskär, Y. Jading, M. Lindström, and S. Parkvall, "LTE: The evolution of mobile broadband," *IEEE Communications Magazine*, vol. 47, no. 4, pp. 44–51, 2009.

[9] A. Roessler, M. Kottkamp, and J. Schlienz, "LTE- Advanced (3GPP Rel.11) Technology Introduction," *Rohde Schwarz White Pap.*, pp. 1–38, 2013.

[10] E. Metsala and J. Salmelin, *Mobile Backhaul*. John Wiley & Sons, 2012. https://doi.org/10.1002/9781119941019

[11] M. Laner, P. Svoboda, P. Romirer-Maierhofer, N. Nikaein, F. Ricciato, and M. Rupp, "A Comparison Between One-way Delays in Operating HSPA and LTE Networks," *10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, May 14–18, 2012.

[12] D. Brodņevs and A. Kutins, "An Experimental Study of Ground-Based Equipment Real Time Data Transfer Possibility by Using Cellular Networks," *Electr. Control Commun. Eng.*, vol. 12, no. 1, pp. 11–19, 2017. https://doi.org/10.1515/ecce-2017-0002

[13] D. Brodnevs and A. Kutins, "Cellular networks selection for the remote control vehicles' control channel setup with parallel redundancy," *J. Mod. Technol. Eng.*, vol. 3, no. 1, pp. 63–74, 2018.

[14] N. Goddemeier, K. Daniel, and C. Wietfeld, "Coverage evaluation of wireless networks for unmanned aerial systems," in *2010 IEEE Globecom Workshops, GC'10*, 2010, pp. 1760–1765. https://doi.org/10.1109/glocomw.2010.5700244

[15] J. A. Romo, G. Aranguren, J. Bilbao, I. Odriozola, J. Gómez, and L. Serrano, "GSM / GPRS Signal Strength Measurements in aircraft flights under 3,000 meters of altitude," *WSEAS Trans. Signal Process.*, vol. 5, no. 6, pp. 219–228, 2009.

[16] F. P. Tso, J. Teng, W. Jia, and D. Xuan, "Mobility: A double-edged sword for HSPA networks: A large-scale test on hong kong mobile HSPA networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 10, pp. 1895–1907, 2012. https://doi.org/10.1109/tpds.2011.289

[17] J. Jelinskis, R. Babrovskis, and P. Jelnskis, "Mobile Application Based Traffic Advisory System for General Aviation – Is It Possible ?," in *2015 Advances in Wireless and Optical Communications (RTUWO)*, 2015, pp. 155–158. https://doi.org/10.1109/rtuwo.2015.7365741

[18] B. Van Der Bergh, A. Chiumento, and S. Pollin, "LTE in the sky: Trading off propagation benefits with interference costs for aerial nodes," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 44–50, 2016. https://doi.org/10.1109/mcom.2016.7470934

[19] X. Lin *et al.*, "The Sky is Not the Limit: LTE for Unmanned Aerial Vehicles," *IEEE Commun. Mag.*, vol. 56, no. 4, pp. 204–210, 2018. https://doi.org/10.1109/mcom.2018.1700643

[20] DOCOMO and Ericsson, "RP-170779: Study on Enhanced LTE support for Aerial Vehicles," 2017. [Online]. Available: http://www.3gpp.org/ftp/tsg_ran/tsg_ran/TSGR_75/Docs/.

[21] Cisco and/or its affiliates, "LTE Antenna Guide. Cisco Integrated Services Router (ISR G2) and Connected Grid Router," pp. 1–23, 2016.

[22] Schneider Adam, "GPS Visualizer," 2016. [Online]. Available: http://www.gpsvisualizer.com/. [Accessed: 23-Oct-2017].

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