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Integration of Unmanned Aerial Vehicles and LTE: A Scenario-Dependent Analysis

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Abstract*—Commercial applications of Unmanned Aerial Vehicles (UAVs) are expected to be one of the disruptive technologies that can shape many activities spans from goods delivery to surveillance. To maximize the effectiveness of such UAV applications, it is very important to enable beyond-line-of-sight (BLoS) communications. Hence, integrated UAV with LTE network can be used to extend UAV operations beyond visual line-of-sight (BVLOS) communications. This paper investigates the ability of Long- Term Evolution (LTE) network to provide coverage for UAV in such rural area, in particular for the Command and Control (C2) downlink. The system design carried out takes into consideration the dependency of the large-scale path loss on the height of the UAV in the simulation environment, which is obtained from industrial measurements, and a real-world communication infrastructure layout and configuration. Key performance factors for the quality of service (QoS) of the channel are the signal strength and throughput performance levels at the UAV vehicle. Results show that UAV height is a very critical factor in terms of delay and jitter performance for urban micro scenarios, and less affective in urban macro scenarios. Furthermore, the number of the available LTE base stations for backhaul connections, fluctuates as the UAV ascends to higher altitudes and average throughput performance is less sensitive to the change in parameters and communication environments when the application type is set as a 1080p-quality video feed. Besides, mobility performance is explored for different system parameters such as hysteresis margin, time-to-trigger under various communications scenarios. Finally, the finding presented in this paper can be a roadmap to facilitate UAV-LTE integration in the near future.

***Index Terms*—LTE, UAV, handover, BLOS**

I. INTRODUCTION

Establishing long-distance communications between Unmanned Aerial Vehicles (UAVs) and Ground Control System (GCS) is the key for unlocking the real potential of UAVs. As the commercial applications of UAVs span from inter-city package delivery to wide-area surveillance for hazard prevention [1] [2], it is critically important to fully connect UAV and GCS during the flight operation. In addition to seamless connectivity requirements, UAV-GCS communications needs reliable capability to establish beyond-line-of-sight (BLOS) data link. Even though satellite-variant communications protocols are widely used to enable BLOS links for commercial and military aircraft, UAVs are much smaller in size and severely battery-limited devices to generate satellite transmit power. Nevertheless, UAVs are able to fly at considerably lower altitudes in comparison to commercial aircraft. Hence, this can paves the way to enable cellular communications between UAV and GCS due to shorter communications distance [3] [4]. Providing connectivity to aircraft such as UAV is a significant challenge for tomorrow's aviation communication systems. [5]. The key challenges that technology needs to address are the high coverage and uninterrupted connectivity during mobility to ensure continuous control and tracking of autonomous flying vehicle.

Cellular communications is widely available and quite robust technology. Nowadays, Long Term Evolution (LTE) [6] is the most well-establish cellular technology. Due to the wide availability of LTE networks, it is much easier to establish a communications network for UAVs that is capable of establishing BLOS links [7]. Nevertheless, the LTE networks are designed and optimized to handle terrestrial LTE communications which is realized by establishing a wireless connection between ordinary user equipment (UE) and a base station, also known as eNB. Hence, this leads to unique communications complications over LTE-UAV integration such as higher interference, weaker signal strength due to side lobes of antenna patterns [8].

Furthermore, the distribution and heights of eNBs are designed to optimize blockage probability caused by buildings and foliage between ground UE and eNB. Hence, the probability of establishing a LOS link between eNB and UAVs will be shaped by dissimilar dynamics/challenges of wireless communications such as height of UAV and high mobility. For instance, it is found that path loss exponent decreases as the UAV increases its height, approximating freespace for horizontal ranges up to tens of kilometers at UAV heights around 100 km [7]. Therefore, those phenomenons arise issues on communications performance of LTE-UAV integration. As a result, this paper aims to estimate performance metrics of the LTE-UAV integration scenario by employing full-stack LTE simulations by analyzing impact of different communications factors such as communications environment, size/type of eNB, height of UAV, transmit power etc. As a simulator, the well-known discrete event simulator NETSIM with C++ is used.

Moreover, in LTE architecture, each UE is assigned to a single eNB which typically provides the best signal quality. Nevertheless, if the UE moves away from one position to another, LTE architecture assigns another eNB that has the typically best channel condition. Hence, the transition from one eNB to another is technically called handover. Nevertheless, UAVs are particularly mobile vehicles that change abruptly their locations at relatively high speeds. Additionally, high mobility of UAVs causes more challenging handover optimization compared to UE [9]. Hence, an UAV that needs to communicate with eNBs regularly has to deal with frequent handovers. Evidently, this phenomenon will have a negative impact on communications quality. Therefore, there will a room for research to improve handover performance by tuning handover-related parameters. Hence, in addition to performance metrics, this paper explores handover performance of LTE-UAV integration for various cases. As a result, the following contributions are provided in this paper.

- An comprehensive quality-of-service analysis that takes into account throughput, packet loss rate, jitter and delay is provided for the integration of LTE and UAV through full-stack LTE simulations. Moreover, video transmission is set as application type to match with real-world requirements. Hence, the outcome of the simulations will help system designers to facilitate the integration of LTE and UAV.
- In addition to typical wireless communications parameters such as transmit power, modulations and protocols, the impact of UAV height during the flight on system performance is investigated for various communications scenarios, namely rural macro, urban macro and urban micro scenarios.
- The urban micro scenario is the most sensitive one compared to other scenarios in terms of wireless communications. Furthermore, the delay and jitter performance are the most varying key performance indicators. Nevertheless, increasing UAV height up to 120m significantly compensates the degradation in delay/jitter performance. Even though, the increase in UAV height generates considerably higher path loss, the resulting change in throughput performance is minor.

II. SYSTEM MODEL

The integration of UAVs into LTE cellular networks, either as aerial users or as communication platforms, brings new design opportunities as well as challenges. As most of commercial UAV applications are based on sending real-time video capture, this paper focuses on the performance of video transmission over the LTE network as in [10]. Accordingly, unicast transmission, i.e., only data transmission from UAV to GCS, is simulated as in most real-life applications. In the simulation, 1080p video quality is set as standard where Gaussian distribution is used to generate bits of each pixel where the mean and standard deviation of bits of each pixel is adjusted as 0.52 and 0.23, respectively. Accordingly, 30 frames per second and 921600 pixels per frame are used to form 1080p video quality. Moreover, Non-Real-Time Polling Service (nrtPS) is used as quality-of-service which is able to handle delay-tolerant data streams consisting of variable-size packets. Furthermore, nrtPS is an appropriate option when a minimum data rate guarantee is needed.

Fig. 1 illustrates the simulation environment where the campus of Cranfield University is set as the simulation background. Plus, the runway corridor of Cranfield Airport is used as the flight path of UAV. Accordingly, the total flight trajectory and the distance between two eNBs are set as 1 km. Additionally, the distances between UAV to eNB1 at the start point and UAV to eNB2 at the endpoint of the flight are set as 300m. Furthermore, the speed of the UAV is set as 10m/s, hence 100s simulation time is required to complete flight trajectory. Besides, as the UAV will reach the middle point between two eNBs around the 50th second of the flight, a handover event will be carried out by LTE architecture around that time with a standard deviation that depends on channel characteristics and handover parameters. In addition, GCS is in a stationary position and associated with eNB1. Furthermore, when a packet is sent by UAV, at first it reaches the associated eNB then is forwarded to Evolved Packet Core (EPC). Afterward, EPC forwards to the packet eNB1 and eNB1 delivers to packet GCS through a wireless channel. Similarly, if the UAV transmits a packet to the eNB2 at first, then eNB2 forwards packet to EPC, afterwards EPC passes the packet to the eNB1. Finally, the packet reaches GCS through eNB1.

A. Handover Events in LTE

Seamless mobility is a key technique needed to support UAS connection during movement in wireless communication networks. Handover is one of the key processes in wireless communication networks that guarantees seamless connection and reliable communication services during the mobility of users. Mobility procedures enable the maintenance of ongoing data link connectivity while UAS aircraft moves across different base stations networks. The handover mechanism [11] is triggered by different set of events where Table I summarizes the key events and handover types with the corresponding explanations. Nevertheless, the handover decision is made by eNB in LTE architecture [12]. Specifically, this paper investigates A3 handover event which takes place when neighbor cell provides a better signal than the serving cell by some pre-set offset, which is called hysteresis margin, for a

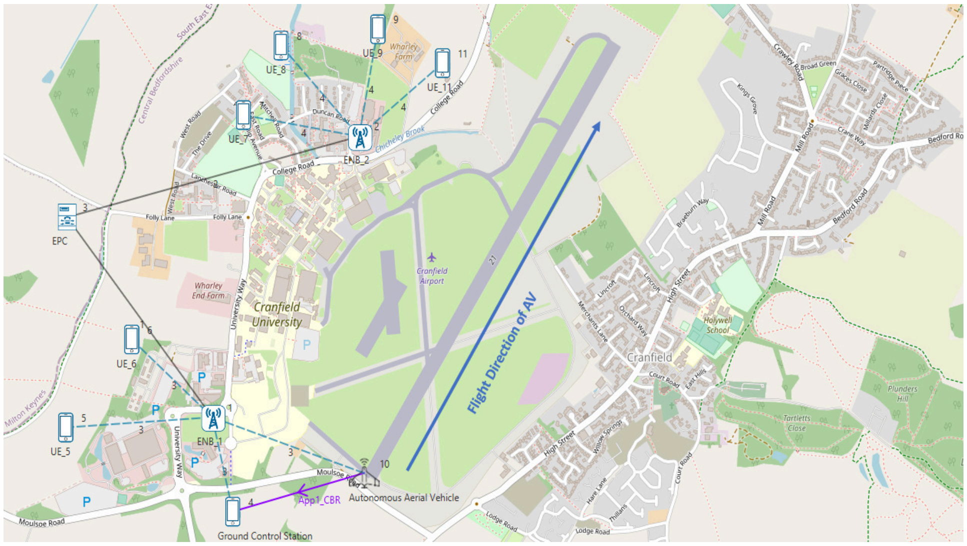


Fig. 1: Simulation layout of UAV-GCS communications through LTE network at Cranfield University. The UAV flies diagrammatically along the runway of Cranfield airport.

specified duration [13]. Namely, A3 handover takes place if the following statement holds,

$$\text{RSRP}_{\text{neigh.}} > \text{RSRP}_{\text{serv.}} + H_{\text{margin}} \text{ and Duration} > \text{TTT}, \tag{1}$$

where $\text{RSRP}_{\text{neigh.}}$ and $\text{RSRP}_{\text{serv.}}$ are Reference Signal Received Power of neighbour and serving cells, respectively. Additionally, H_{margin} and TTT are hysteresis margin and Time-to-Trigger, respectively.

B. Channel Model

Due to air-ground interaction of UAV-GCS, resulting channel behaviour is fundamentally different than terrestrial LTE communications. As a result, 3GPP [14] [15] proposed a channel model for UAV-eNB communications based on field measurements. Hence, 3 different scenarios emerged which depend on the size of the base station and the urbanization level of the environment, namely Rural Macro (RMa), Urban Macro (UMa) and Urban Micro (UMi).

The channel model that is embedded into the simulation has 3 factors, namely Line-of-Sight (LOS) probability, shadowing, and path loss. Essentially, the probability of forming LOS link between UAV and eNB increases if UAV reaches a higher level or communicates with macro base station. Secondly, the impact of shadowing, which is a mathematical model that depends on the scenario and height of UAV, is also included in the simulation. Thirdly, the path loss model [15], which takes into account the scenario, the height of UAV, communications distance, and carrier frequency, is added to the simulation. Furthermore, the heights of RMA, UMa, and UMi base stations are considered as 35m, 25m, and 10m, respectively

TABLE I: Handover Events in LTE

Event	Description
A1	Serving cell rises above offset
A2	Serving cell falls below offset
A3	Neighbouring LTE cell rises above serving cell + offset
A4	Neighbouring LTE cell rises above threshold
A5	Serving cell falls below threshold 1 Neighbouring LTE cell rises above threshold 2
A6	Neighbouring LTE cell rises above secondary cell + threshold

C. Simulation Parameters

Throughout the simulation, unless the otherwise stated, the transmit power and antenna gain of UAV are set as 23 dBm and 0 dBm, respectively. Plus, inter-band carrier aggregation is simulated and it is observed use of intra-band carrier aggregation did not cause major change in system performance at physical layer. Besides, bandwidth of uplink and downlink channels is adjusted as 20 MHz. Plus, it is observed that 5 MHz and 10 MHz LTE band allocations are not able to support 1080p video transmission in this setup. Moreover, downlink and uplink MIMO layer counts are set as 2 and 1, respectively. In addition, QAM64 is used as modulation technique. Also, UDP is implemented as a transport layer protocol. Furthermore, Round Robin scheduling is used at the data link layer. Additionally, some critical handover setting are employed. For instance, UE/UAV measurement report interval, hysteresis margin and TTT are set as 240 ms, 3dB and 320ms, respectively.

III. SIMULATION RESULTS

The simulation results are investigated and analyzed under 4 headline, namely throughput, packet loss rate, delay and jitter. Simply, throughput is defined as the delivered data rate which excludes protocol overhead. Similarly, packet loss rate is the ratio of lost packets and total transmitted packets. Additionally, delay is defined as the average time to send a packet from application layer of source node to application layer of destination node. Similarly, jitter describes the variance in delay

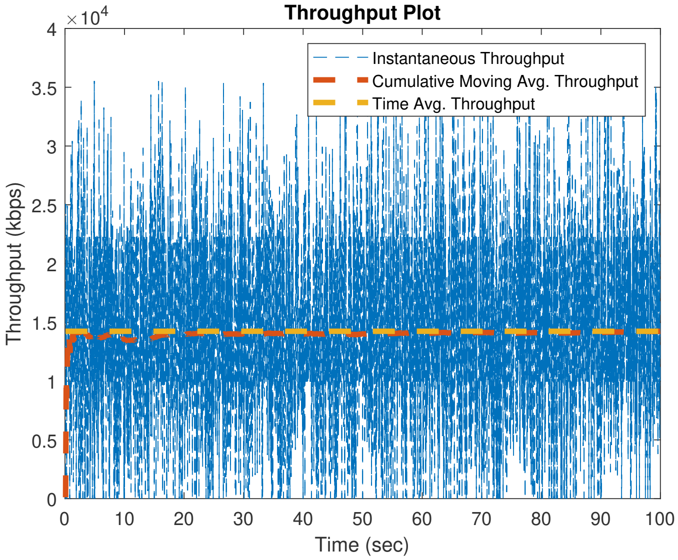


Fig. 2: Throughput vs time plot of RMa scenario in which UAV height is 25m.

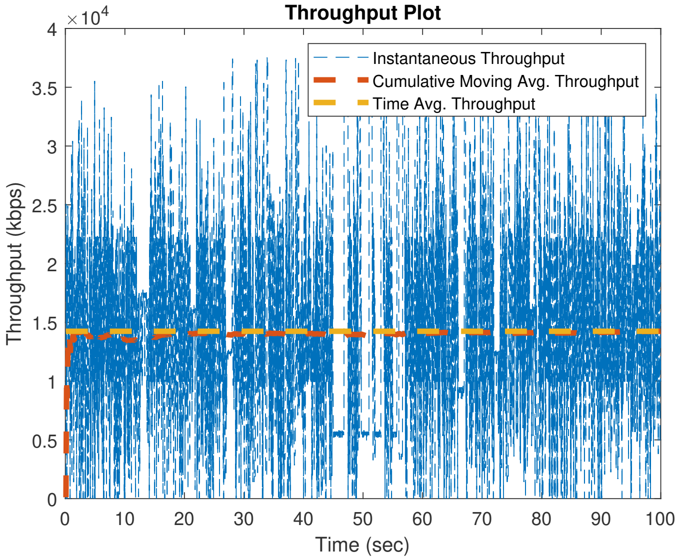


Fig. 3: Throughput vs time plot of UMa scenario in which UAV height is 25m.

that could be caused by network congestion or deep fade in wireless channel. Hence, the simulations of RMa and UMa and UMi are carried out accordingly.

A. Rural Macro Scenario

For the RMa scenario, two cases are simulated, namely 25m and 100m UAV height cases. The key results of those cases are outlined in Table II. Furthermore, the throughput plot of 25m UAV height case is shown in Fig. 2 which simultaneously illustrates instantaneous, cumulative moving average, and time-average throughput. It is found that the performance difference between the two cases is very minor due to fact that the blockage probability in a rural environment with macro base stations is very low and similar. Hence, no major abrupt signal degradation is observed. Plus, the handover takes place seamlessly for both cases in RMa scenario as there is no unusual pattern at the 50th second of the simulation in Fig. 2.

B. Urban Macro Scenario

Similar to RMa scenario, 25m and 100m UAV height cases are simulated for UMa. It is found that the 100m-height UMa scenario performs very similarly with the corresponding RMa scenario due to the low blockage probability. Nevertheless, the 25m-height case shows considerably worse performance than the 100m-height case as illustrated in Fig. 3. Clearly, there is a major degradation in throughput around the 50th second of the simulation. Mainly, at this time, the distance between UAV to eNBs reaches the maximum level. According to the 3GPP [15] [14], the probability of establishing LOS link decreases with an increase in communications distance which explains the decrease in throughput at 50th second. Moreover, the ping-pong effect is observed during handover event at the same time. Additionally, there is not major handover performance difference between 25m-height and 100m-height UMa cases.

Additionally, as Table II shows, there is no difference in average throughput performance between 25m-height and 100m-height UMa cases. Nevertheless, there are significant differences in delay between the aforementioned cases where 25m-height case shows approximately five times worse delay performance than 100m-height case. Similarly, the jitter performance of the 25m-height case is worse than the 100m-height case. Consequently, it is possible to infer that increasing UAV height during the flight could be a solution to improve

TABLE II: Summary of key numerical results of simulated cases

Application Case	**Control Parameter**	**Packet Loss Rate (%)**	**Throughput (Mbps)**	**Delay(microsec)**	**Jitter(microsec)**
RMa-25m	UAV Height	0.331567702	14.237516	9249	613
RMa-100m	UAV Height	0.331567307	14.237516	9240	613
UMa-25m	UAV Height	0.330749016	14.237714	47741	783
UMa-100m	UAV Height	0.330748020	14.237635	9240	613
UMi-25m	UAV Height	0.334023759	14.237172	6314956	1499
UMi-100m	UAV Height	0.330749016	14.237732	42464	894
UMi-25m	TCP-BE	44.649404772	7.905367	11189113	2063
UMi-25m	EIRP-20 dBm	1.430243887	14.080349	7332497	1528
UMi-25m	EIRP-10 dBm	14.324543379	12.236881	13636460	1659
UMi-25m	Hysteresis Margin-1dB	6.112307302	13.410574	6960287	1554
UMi-25m	TTT-640ms	10.640457809	12.763168	9983833	1594
UMi-25m	M.R. Interval-1024ms	0.492848781	14.214616	7189497	1521

delay and jitter performance. Accordingly, the increased path loss due to an increase in UAV height causes compensable results.

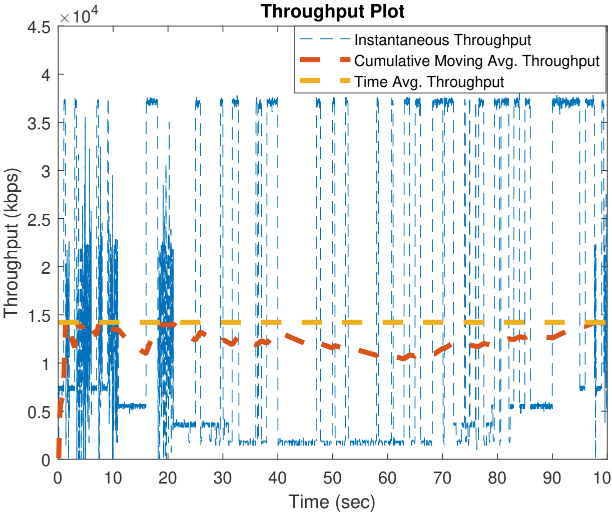
C. Urban Micro Scenario

In Fig. 4a-b, throughput results of 25m-height and 100m-height cases of UMi scenario are illustrated. It is observed that there is a substantial difference between the aforementioned cases. The decrease in flight height, blocking impact of large buildings of an urban environment, and size of micro base stations cause NLOS links between UAV and base stations. This phenomenon leads to deep fading for the 25m-height case as illustrated in Fig. 4a. On the other hand, increasing UAV height to 100m significantly reduces this effect, as seen in Fig. 4b, and provides a more sustainable wireless communications performance.

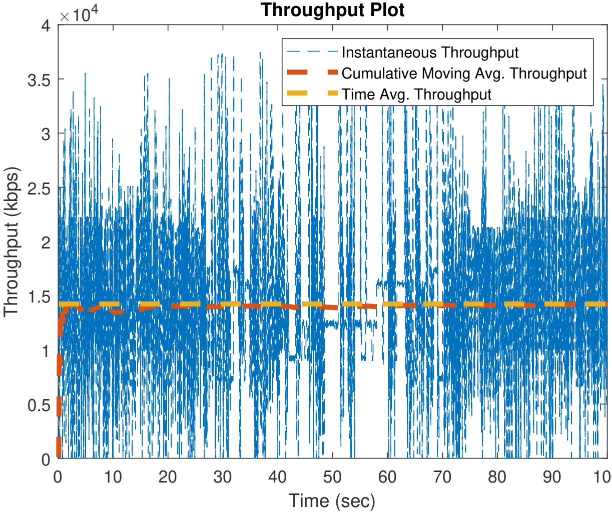
Additionally, Table II summarizes the key numerical results of 25m-height and 100m-height cases of the UMi scenario. Both of the cases are able to deliver 14.23 Mbps throughput, however, the delay performance of the 100m-height case, and accordingly jitter performance, is significantly better than the 25m-height case. For instance, average delays of 25m-height and 100m-height cases are approximately 6.3 and 0.042 seconds. On the other hand, both cases are able to illustrate a very low packet loss rate.

In order to observe the impact of acknowledgment messages on the performance of the communications, TCP is also simulated, and key numerical results are summarized in Table II where best-effort (BE) is employed as quality-of-service. As a result, TCP is not able to deliver 30 frame-per-second 1080p video quality due to the fact that the resulting average throughput is approximately half of the UDP cases. Moreover, delay and jitter performance of TCP cases are much worse. Yet, TCP could be a powerful protocol to deliver command and control messages to UAVs.

Additionally, Table II shows the impact of Effective Isotropic Radiated Power (EIRP) which is the sum of transmit power, antenna gain, and cable losses. In addition to 23 dBm EIRP which is the maximum limit that is allowed by LTE architecture, two more EIRP cases are simulated, namely 20 dBm and 10 dBm where UDP is implemented as transport layer protocol and UAV height is set as 25m. It is found that decreasing EIRP from 23 dBm to 20 dBm slightly deteriorates every key parameter. Yet, a 3dBm drop in EIRP means transmission power is halved. Hence, considering that UAVs are battery-limited vehicles, it could be a reasonable trade-off to use half-power in the exchange for slightly worse performance. Moreover, it is observed that 10 dBm EIRP has a more visible impact on system performance. For instance, the packet loss rate is increased up to 15% and average throughput decreased by approximately 2 Mbps. Nevertheless, 10 dBm EIRP means 20 times less transmission power compared to 23 dBm EIRP. So, it could be used as battery-saver mode.



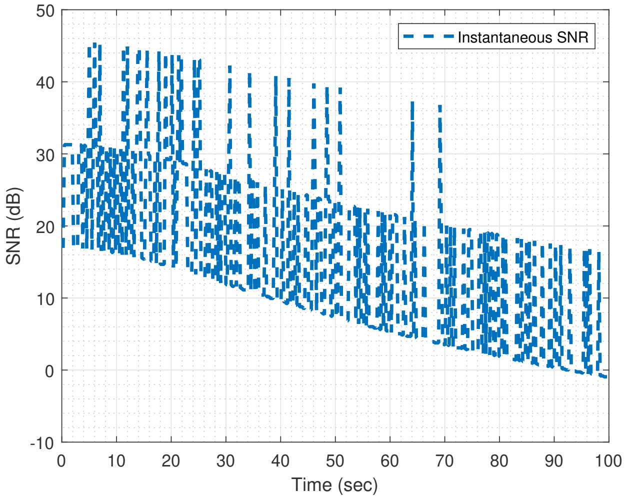
(a) Throughput vs time plot of UMi scenario in which UAV height is 25m.



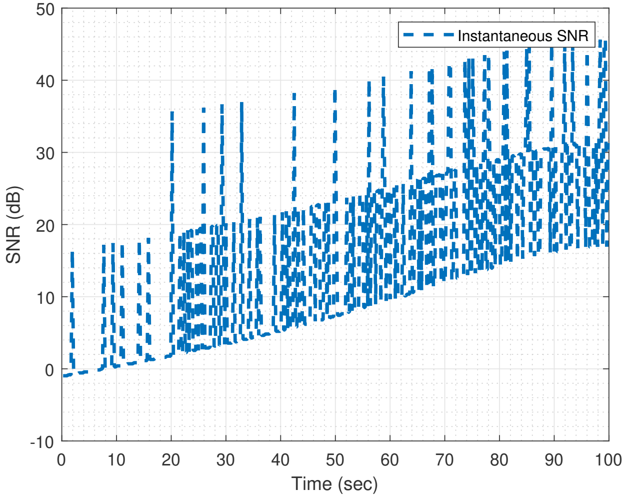
(b) Throughput vs time plot of UMi scenario in which UAV height is 100m.

D. Handover Performance under Urban Micro Scenario

As the most performance differences occur in cases that are simulated within UMi scenario and given that 25m-height UMi case provides the worst performance, the handover analysis is carried out for this case in order to observe the worst case scenario. Moreover, in heterogeneous cellular networks, it is preferred act to offload communications burden from macro eNBs to micro eNBs which makes UMi scenario research-wise more interesting. Accordingly, Fig. 5a and 5b illustrate measured signal-to-noise-ratio (SNR) performance at eNB1 and eNB2, respectively where hysteresis margin, TTT, UE measurement interval are set as 3 dB, 320ms and 240ms, respectively. To carry out a handover from eNB1 to eNB2, the conditions presented in (1) are set as the requirements that trigger handover. Clearly, when an UAV moves towards the destination, the measured SNR of eNB1 deteriorates as communications distance gets larger, accordingly the prob-



(a) SNR vs time plot measured at eNB1. During the flight, the UAV moves away from the eNB1.



(b) SNR vs time plot measured at eNB2. During the flight, the UAV moves towards the eNB2.

ability of establishing LOS links decreases. Simultaneously, measured SNR at eNB2 increases because of the identical factors. Moreover, measured SNR ranges from -5 dB to 45 dB. Plus, considering that the handover event occurred around the 50th second of the simulation, it is possible to see the effect of ping-pong around 20-30 seconds at Fig. 5b and 65-70 seconds at Fig. 5a. Also, Table II shows the key results when the hysteresis margin is set 1 dB. It is found that 1 dB case causes more fluctuation in performance and ping-pong effect. Nevertheless, the average performance difference between 3 dB and 1 dB hysteresis margins is minor.

In addition to hysteresis margin, TTT is one of the key factor that has an impact on handover decision. Unsurprisingly, it is found that increasing TTT delays handover decision whereas decreasing TTT causes a ping-pong effect. For instance, Table II shows the case in which TTT is increased to 640ms. It is observed that this action considerably deteriorates the communications performance for each parameter. Secondly, handovers are initiated by the periodic measurement reports which are sent by UE in LTE architecture [12]. Table II shows the key results of the case in which UE measurement report interval is increased from 240ms to 1024 ms. Hence, it is found that increasing measurement report interval slightly postponed the handover. Yet, the impact of this action on system performance is minor and slightly deteriorating.

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CONCLUSION

In this paper, a scenario-dependent UAV-LTE integration analysis is presented by means of full-stack LTE simulations with an appropriate aerial channel model. Additionally, the simulation is built on uplink video transmission from UAV to LTE base station. As a result, the throughput, packet loss rate, delay, and jitter performance are investigated for different communications environments and various base stations types. Consequently, the impact of UAV height, transport layer protocol, transmit power on the metrics of quality-of-service is investigated. In addition, handover performance analysis in an urban environment for micro base stations is specifically examined. Accordingly, the impact of hysteresis margin, Time-to-Trigger, and interval of measurement report on handover performance is explored.

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