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Measurement Reporting Enhancement for 5G Cellular-Connected Aerial Vehicles

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***Abstract*—Measurement reporting is essential in every cellular network to guarantee the best radio resource management and performance to its users. The information in reports is mainly used to perform handovers and interference management between cells. In the case of cellular-connected UAVs, where the UAV impacts a high number of cells due to its flight height, measurement reporting becomes essential. However, applying the same reporting schemes used for terrestrial users, the UAV appears to generate a large number of reports, creating a substantial signalling overhead. To overcome this problem, we introduce in this paper a new measurement reporting scheme adapted for UAVs, which reduces the number of reports compared to LTE-supported aerial vehicles. Our scheme shows a 30% reduction in number of reports compared to LTE, without having a major impact on the network's knowledge about the most relevant cells.**

I. Introduction

Uncrewed aerial vehicles (UAVs) have become increasingly popular in recent years, thanks to the advances in technology that have made them more affordable and easier to operate. One area of growth in the field of UAVs is the use of a cellular network to communicate with a ground controller or other devices. This allows for the UAV to be operated beyond the range of a direct radio link, making it useful for a wide range of applications such as monitoring, search and rescue, agriculture and more [1].

In cellular networks, such as Long Term Evolution (LTE), measurement reports play a critical role in maintaining the connectivity of the user equipment (UE), as they provide the network with information about the signal quality and performance of its users.

The UE actively measures the quality of the downlink signal from the serving and other detectable neighboring cells, represented by reference signal received power (RSRP), reference signal received quality (RSRQ), and signal to interference and noise ratio (SINR). Typically, the UE is responsible of triggering the measurement reports when certain criteria are met, then the network uses these reports to make decisions about handover and radio resource allocation [2]. The configuration of reports triggering is made by radio resource control (RRC) signaling between the UE and its serving base station (BS).

Handover is necessary to maintain a seamless connection as the UE moves between cells, and it is an essential part of the overall performance and functionality of the network. Coordinated radio resource allocation is also used to manage interference between cells in order to improve the performance of the UEs, especially in the presence of UAVs, which experience and cause high interference levels to many neighboring cells.

Some issues arise when trying to generalize the techniques used for terrestrial UEs to aerial ones, mainly because of the different propagation conditions and the different mobility characteristics between the two types. One of the main issues identified in [3] is the increased number of reports generated by aerial UEs compared to terrestrial ones. This stems from the fact that UAVs detect more cells at higher altitudes than terrestrial UEs, because of the increased probability of line of sight (LOS) between the UAV and the BSs. According to experiments conducted in a rural environment, the UE detected on average 5 cells at 1.5 m height, while detecting more than 16 cells at 120 m [3].

Another aspect that has not been yet addressed in the literature is the limited report size.In practice, the UE keeps a list called *CellsTriggeredList* which contains the identities and measurement results of the neighboring cells that fulfill the criteria for the given event, ordered by the quantity that is configured and indicated (i.e. RSRP, RSRQ or SINR) [2]. The measurement report then contains the *CellsTriggeredList*, limited to the first 8 entries, even if it contains more. This can lead to generating multiple consecutive reports that contain exactly the same information. Increasing the report size in this case is not useful for several reasons: 1) The network has a limited ability of coordination with other cells, and the extra information may not be used eventually. 2) The increased signalling overhead causes extra delays and interference to the measurement reports, for all users in the network.

There is an ongoing work by the 3rd Generation Partnership Project (3GPP) to standardize RRC for cellular-connected UAVs in 5G New Radio (NR) [2]. The previous technical specification in [4] provides LTE-support for UAVs, with some enhancements to measurement reporting schemes for UAVs. It also introduces height-based reporting trigger for UAVs.

The problem of increased number of reports generated by UAVs in LTE has been recognized in [3], and several solutions were proposed to reduce this number, such as periodical reporting and adding a prohibit timer between consecutive reports. However, both solutions were discarded from standardization work since periodical reporting has a major drawback regarding reports generated when there is no actual update, and the prohibit timer may cause unnecessary delays, with no evidence on its efficiency.

Another aspect to tackle here is the different channel conditions with respect to height. As UAVs are highly mobile, they could change their height several times during flight, and potentially experience non-LOS (NLOS) conditions. Therefore, it is necessary to study the effect of height on measurement reporting, and evaluate the need to have height-dependent configurations for report triggering.

In [5], the probability of LOS (PLOS) and shadow fading's standard deviation are experimentally modeled based on the UAV's 3D position and the environment (urban, rural, ...). However, these models generate uncorrelated values in space, which is not suitable for cases including mobility. In our work, we add this correlation to the performance evaluation, to generate more realistic results.

To summarize, we aim in this work to introduce a new reporting scheme for UAVs in 5G networks, which enhances measurement reporting by reducing the number of reports while keeping the network updated with the latest changes. Our contributions in this paper are summarized as follows:

- Model spatially-correlated LOS and large-scale shadow fading for UAV performance evaluation.
- Develop the concepts of relevant cells and reporting accuracy to measure the performance of the reporting schemes.
- Propose a new measurement reporting scheme for UAVs in 5G NR.
- Study height-dependent parameters for reporting enhancement.

The rest of this paper is organized as follows. Section II describes the framework of our study, which is used for performance evaluation. Section III reviews the reporting events related to interference detection, and proposes enhancements to the existing reporting scheme in LTE. Performance of reporting schemes is then evaluated in section IV, then section V concludes the paper.

II. Study framework

We consider a rural environment with three-sector macro sites. The basic network layout is illustrated in Figure 1, and the associated numerical values in Table I. Six replicas of this layout are then simulated around the main one to create a larger network. The simulation follows the 3GPP model in technical report TR 36.777 [5] for aerial vehicles in LTE.

The considered BS antenna is a cross-polarized panel array antenna and its pattern follows the model described in [6] for 5G NR. We index the simulated cells (BSs) as BS_i: $i \in 1, \ldots, 336$, and denote the antenna gain of BS_i in the UAV's direction by $A(\theta_i)$, where θ_i is the angle between the UAV's LOS to BS_i and BS_i's mainbeam: $-180^o \leq \Theta_i \leq 180^o$. All BS antennas are downtilted with $\theta_{downtilt}$ to optimize the performance for terrestrial users.

We consider one UAV, moving in a circular path, illustrated in Figure 1, with a fixed altitude denoted by h_{UAV},

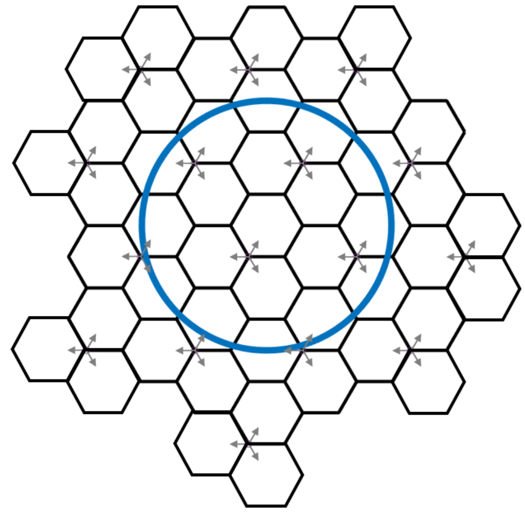

Figure 1: Network layout and UAV's circular path

Table I: System model

Network parameters	
Network layout	Grid of uniform hexagonal cells, 3 sectors per site, $n_{sites} = 7 \times 16$ macro sites
Inter-site distance	ISD = 1732m
BS antenna height	$h_{BS} = 35$m
Carrier frequency	$f_c = 4$ GHz
System bandwidth	10 MHz UL, 20 MHz DL
DL subcarriers	$N_{SC} = 1200$
BS max Tx power	$P_{max}^{DL} = 43$ dBm
Shadow fading	$\sigma_{LOS} = 4.2 \exp(-0.0046 h_{UAV})$ dB
	$\sigma_{NLOS} = 8$ dB
	$D_{decorr} = 100$ m, $\rho = 0.3$
BS antenna pattern	Cross-polarized panel array antenna [6]
Panel size	8×2
Down-tilt	$\theta_{downtilt} = 3^o$
UAV parameters	
UAV height	$h_{UAV} = \{20, 50, 100, 120\}$ m
UAV speed	30 km/h
UL power control	Open loop power control (OLPC)
UAV max Tx power	$P_{max}^{UL} = 23$ dBm
OLPC parameters	$P_0 = -100$ dBm, $\alpha = 1$, $M = 50$
Noise floor (UL)	$P_N = -104$ dBm
Measurement reporting configuration	
A3 offset	*offset* = 3 dBm
A4 threshold	*thresh* = $\{-87, -82, -77\}$ dBm

and a constant speed of around 70 km/h. The UAV is equipped with an omni-directional antenna.

The simulation time step is approximately 330 ms and equivalent to every 6 m traveled by the UAV. In each time step, the UAV measures the RSRP of detected cells and updates its *CellsTriggeredList*, if needed. It also decides whether to trigger a report or not based on the updates and the reporting scheme, as will be discussed later in section III.

The channel model depends on several factors, notably the probability of LOS (PLOS) which affects the experienced pathloss and shadow fading. The channel conditions and PLOS are mainly different below and above rooftop level, where BS antennas are usually located.

When the UAV is located above rooftop level, i.e., $h_{UAV} > 40$ m, it is assumed that PLOS = 1 to all BSs, while it does not often experience these conditions below this height, mainly because of obstacles between the UAV and the BSs, such as buildings.

PLOS below rooftop is not explicitly modeled in 3GPP for cases including mobility. The experimentally derived formulas in [5] provide the PLOS based on the UAV's distance from the BS and the environment. We use these formulas in our simulations to create a spatially-correlated map for each site. Each map is of the size of the network layout, filled with boolean values indicating LOS/NLOS conditions. These boolean values are the same every d_{decorr} m, where d_{decorr} is the de-correlation distance and it depends on the considered environment.

To model large-scale shadow fading, we consider the bi-dimensional correlated model in [7]. This model creates both site-to-site and spatially correlated shadow fading maps. In this method, we generate $n_{sites} + 1$ maps of the layout size, consisting of random values drawn from a Normal distribution $\mathcal{N}(0, \sigma^2)$. The n_{sites} maps are cross-correlated with the remaining one, with a correlation factor ρ, to create site-to-site cross correlation. To introduce spatial correlation, the resulting maps are then filtered with a 2D finite impulse response (FIR) filter, that has properties such as the de-correlation distance D_{decorr}. The parameter σ depends on LOS conditions, and can take two values as indicated in Table I. Consequently, we generate two sets of maps for LOS and NLOS, when the UAV is below rooftop, then choose the appropriate value based on the boolean PLOS map. We denote the shadow fading for the (x, y) UAV coordinates to BS_i by $SF_i(x, y)$.

The pathloss also has two formulas for LOS and NLOS cases, indicated in [5]. We denote the pathloss between the UAV and BS_i by $PL(d_i)$, where d_i is the distance between the UAV and BS_i.

A. RSRP estimation

We consider that measurement reports are configured based on RSRP. Downlink (DL) RSRP is the received power at the UE, when the BS transmits a reference signal with a fixed power. The reference signal is considered to be the maximum transmit power of the BS over the overall bandwidth: P_{max}^{DL}.

In this case, the RSRP to BS_i depends on the pathloss, shadow fading, and the antenna gain in the UAV's direction, as described in eq. (1), where N_{SC} is the number of subcarriers within the transmission bandwidth.

$$RSRP_i = P_{max}^{DL} + A(\theta_i) - PL(d_i) - 10\,\log_{10}(N_{SC}) \quad (1)$$

B. Power control

The UAV uses open loop power control (OLPC) to adapt its uplink (UL) transmit power. In OLPC, the UE is able to increase or decrease its power level based on estimations of the channel conditions to the serving BS, without any required feedback from the BS. We evaluate in eq. (2) [8] the UAV's transmit power when it is connected to BS_i, where M is the number of used resource blocks (RBs), P_{max}^{UL} is the maximum UAV transmit power, and α is the pathloss compensation factor. P_0 is a parameter that controls the desired power per RB (PRB) at the receiver. Eq. (2) evaluates the

$$\begin{aligned} P_{Tx}(UAV_i) = \min(&P_{max}^{UL},\ P_0 + 10\log_{10}(M) \\ &+\alpha\,[PL(d_i) + SF_i(x,y) - A(\theta_i)]\,) \end{aligned} \quad (2)$$

The received power at the serving BS (BS_i) can be then evaluated from eq. (3). From eq. (2 - 3), we can infer that $S_i(UAV_i) = P_0 + 10\log_{10}(M)$ if OLPC fully compensates for the pathloss: $\alpha = 1$.

$$S_i(UAV_i) = P_{Tx}(UAV_i) - PL(d_i) - SF_i(x,y) + A(\theta_i) \quad (3)$$

Furthermore, we can evaluate the interference from the UAV to a neighboring cell BS_j: $j \neq i$, from eq. (4).

$$S_j(UAV_i) = P_{Tx}(UAV_i) - PL(d_j) - SF_j(x,y) + A(\theta_j) \quad (4)$$

C. Relevant cells

One of the key objectives of measurement reporting is to keep the network updated about the cells that are causing interference, or being interfered to the most, by the UAV. RSRP levels alone do not provide this information, therefore, we introduce the concept of relevant cells, where a relevant cell suffers from 3 dB interference-over-thermal-noise (IoT) ratio, from UL UAV interference. To obtain the relevant cells, we compare the values obtained from eq. (4) to the thermal noise level as follows:

$$S_j(UAV_i) - P_N \geq 3 \text{ dB} \quad (5)$$

III. Measurement reporting for interference detection

Two of the most commonly used measurement events, that target the optimization of mobility and resource allocation, are events A3 and A4 [4]. Event A3 is triggered when the RSRP of a neighboring cell becomes an *offset* better than the serving cell, and event A4 is triggered when the RSRP of any neighbor cell becomes higher than a threshold. In our study, we focus on event A4 for interference detection and resource management, since event A3 is mostly used for handovers. The reports in event A4 are sent every time a new cell, or set of cells, trigger the event for a time period, denoted by time-to-trigger (TTT). TTT can be configured from a set of values ranging between 0 and 5120 ms [2]. In our case, the considered time step in simulation replaces the TTT.

A. LTE support for aerial vehicles

As mentioned earlier in this paper, A4 event suffers from an increased number of reports due to the large number of cells fulfilling the criteria simultaneously. The proposed solution in LTE is the multi-cell trigger mechanism. In multi-cell trigger, a report is only sent if the number of cells triggering the event at the same time becomes higher than a configured threshold, denoted by *NumberOfTriggeringCells*. No further reports are sent if the number of cells increases beyond the *NumberOfTriggeringCells*.

This solution decreases the number of reports drastically, to the point where it stops providing useful information to the network. Hence, *ReportOnLeave* can be optionally configured, to send a report whenever a cell stops fulfilling the criteria and leaves the *CellsTriggeredList*.

Using multi-cell trigger with *ReportOnLeave* performs almost equally to the original reporting scheme in terms of number of reports, as cells leave the *CellsTriggeredList* at the same rate as they are added.

B. 5G NR enhancement

The recent work in 3GPP release 18 for UAV support in 5G NR has led to an agreement to enhance multi-cell trigger mechanism by sending a report for previously reported cells only [9]. This is mainly for *ReportOnLeave*, which will be exclusively sent if a reported cell stops fulfilling the condition.

This method does not take into account the dynamics of measurement reporting. Since reports are limited to the 8-best-RSRP cells, these reported cells could still be triggering the event, but has changed their RSRP-order with other cells, hence the 8-best-RSRP cells to be reported could change without triggering any report, because the originally reported cells has not left *CellsTriggeredList*yet.

C. Further potential enhancement

To reduce the number of reports while maintaining the network's knowledge of the UAV's *CellsTriggeredList*, we propose a scheme where the reports are triggered when the *CellsTriggeredList* changes by a certain threshold, called *NumberOfChangedTriggeredCells*. *NumberOfChangedTriggeredCells* is a parameter that can be configured depending on the scenario and the reporting requirements (number of reports or accuracy). This scheme targets both entry an leave events, and hence provides a better attunement with its parameter.

D. Reporting accuracy

Until now, the efforts in 3GPP standardization target reducing the number of reports, regardless of the affected network performance by this reduction. As indicated in section I, due to the limited report size and the limited network capability of coordinating a high number of cells, we only consider the top 8 cells in both network's *CellsTriggeredList*and relevant cells, to evaluate the accuracy.

We define the accuracy as the average match percent between the relevant and reported cells. The accuracy is first evaluated at every time step as the division result of the number of common cells between the two lists and the number of relevant cells. Afterwards, the instantaneous accuracy values are averaged over the total number of time steps. The probability of having an error in 1 cell out of 8 is 12.5%, which means that a minimum accuracy of 87.5% is required to ensure having on average 7 accurate cells out of 8, all the time. In our scenario, we consider the LTE's accuracy as a baseline, and set the same target to our scheme ±2%, as long as the accuracy of LTE reporting is above 87.5%. We consider that this 2% accuracy difference is negligible in front of the reduction of reports number.

IV. Performance evaluation

In this section, we are interested in evaluating the performance of the different report triggering schemes, in terms of number of reports and accuracy. We also study the benefit of defining a set of height-dependent configurations to the events triggering.

We focus on event A4 with a configured threshold *thresh*, as it is the principle event used for interference detection, and consider that event A3 is always being executed for handovers, with $Offset = 3$ dBm.

One important observation when the UAV's altitude changes is the difference in RSRP levels. The RSRP experienced by UAVs is usually higher than that of terrestrial UEs, due to the increased PLOS. It is also observed that the RSRP gap between serving and neighboring cells becomes smaller at higher altitudes.

We show in Figure 2, the cumulative distribution function (CDF) of the RSRP from the serving and neighboring cells, considering the UAV's circular path, for $h_{UAV} = 20$ m and $h_{UAV} = 100$ m. We only consider the 8-strongest neighbors which can be included in the report, due to the limited report size.

This difference in RSRP with respect to the UAV's height affects greatly event A4 triggering. For instance, setting a relatively high threshold to trigger the event for all heights, results in detecting very few cells below rooftop, compared to a UAV at 100 m of altitude.

Based on Figure 2, we consider two different RSRP thresholds for below and above rooftop levels: -87 and -77 dBm, where these thresholds capture the 8 strongest neighbors with 99% probability, for $h_{UAV} = 20$ and 100 m, respectively. We also include a threshold value in-between, in order to evaluate the necessity for defining

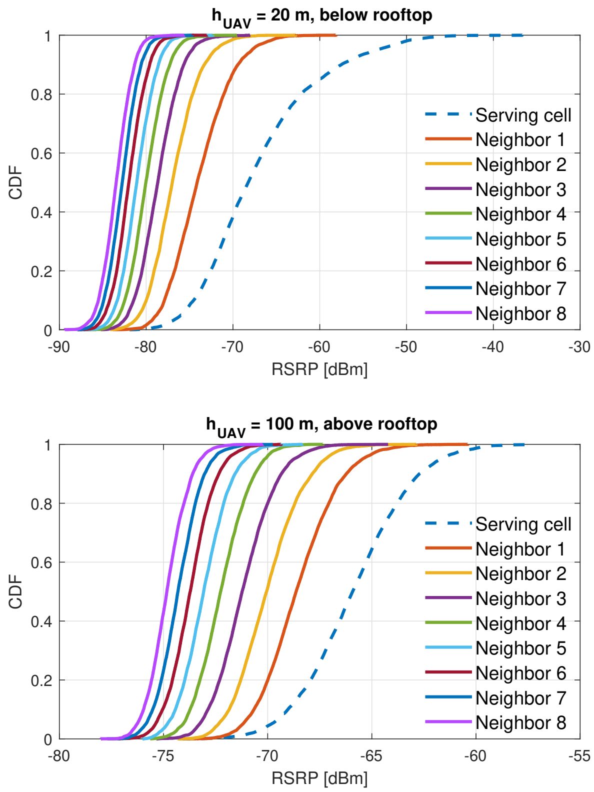

Figure 2: CDF of RSRP for 20 m vs 100 m height

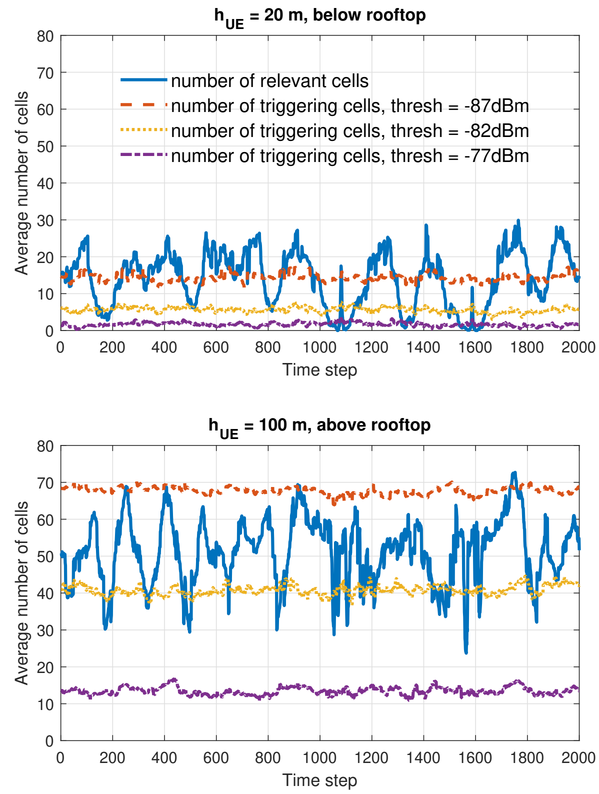

Figure 3: Number of triggering cells with time, for one circular path realization and 20 m vs 100 m height

height-dependent thresholds. The considered values are thus: $thresh = \{-87, -82, -77\}$ dBm.

We trace in Figure 3 the number of relevant cells, along with the number of triggering cells for the previously selected RSRP thresholds. We consider the circular path described in Section II that consists of 2000 steps ($\sim$ 12.5 km or $\sim$ 11 minutes).

We observe from Figure 3 that the number of relevant cells at 20 m is between 0 and 30, while it is between 22 and 72 at 100 m. In order to capture the majority of triggering cells at 20 m, a low *thresh* is required. Higher thresholds capture less cells, and most importantly less than 8 cells which are required for the report. At 100 m, due to the high number of triggering cells even for high thresholds (always above 8 cells), then any threshold can be considered.

We note here that the number of relevant cells is affected by the distance of the UAV to the serving cell because of the uplink power control, while the number of triggering cells follows the downlink RSRP and remains almost unchanged during the flight time.

We evaluate now the number of reports and the accuracy of the reporting schemes, for the considered circular path. We consider multiple UAV altitudes and RSRP thresholds: $h_{UAV} = \{20, 50, 100, 150\}$, $thresh = \{-87, -82, -77\}$ dBm. We run 10 simulations for each pair of height-*thresh*, while changing the shadow fading and LOS maps in every simulation, then average the results out to eliminate any abnormalities from the randomness of the maps.

The results are organized in Table II, comparing LTE, 5G NR, and our proposed scheme based on *NumberOfChangedTriggeredCells*. We fix the parameter *NumberOfTriggeringCells* = 4 for LTE and 5G NR, and *NumberOfChangedTriggeredCells* = 4 for our proposal. We highlight in Table II, the maximum achieved accuracy with the lowest number of reports for each scheme. We discard accuracy values below 87.5%, as discussed earlier.

From Table II, we observe that below rooftop, h_{UAV} = 20 m, the only acceptable accuracy is achieved for the lowest considered threshold $thresh = -87$ dBm, in both LTE and Change schemes. This is also observed from Figure 3, when this threshold is sufficient to capture the 8-best RSRP cells. For h_{UAV} = 20 m and $thresh = -87$ dBm, Changed scheme requires 20% less reports to achieve 97% accuracy, almost the same accuracy as LTE. However, 5G NR scheme performs poorly in terms of accuracy, since it reduces the number of reports by 80%.

For the cases above rooftop, we notice that all thresholds provide an acceptable accuracy in LTE and Changed

Table II: Evaluation of the number of reports and accuracy for LTE, 5G NR, and our proposed scheme, for a configured parameter = 4.

thresh	-87 dBm		-82 dBm		-77 dBm	
scheme	**# Rep**	**Acc.**	**# Rep**	**Acc.**	**# Rep**	**Acc.**
h_{UAV} = 20 m						
LTE	414	98%	353	74%	185	22%
5G NR	54	57%	78	52%	23	16%
Proposal	332	97%	241	74%	113	26%
h_{UAV} = 50 m						
LTE	397	98%	391	98%	308	95%
5G NR	20	66%	20	65%	19	65%
Proposal	307	98%	311	98%	223	93%
h_{UAV} = 100 m						
LTE	372	97%	415	98%	336	96%
5G NR	29	68%	27	69%	28	69%
Proposal	266	95%	317	98%	240	94%
h_{UAV} = 150 m						
LTE	335	95%	406	97%	347	96%
5G NR	27	69%	28	69%	28	69%
Proposal	219	92%	302	97%	244	94%

schemes, and it is maximized at *thresh* = −82 dBm. Changed scheme always provides a 20% to 25% reduction in reports, without losing any accuracy. Our proposal eliminates most of the redundant reports generated from *ReportOnLeave* of cells that are not included in reports.

We recall here that the agreed scheme for 5G NR does not verify the minimum accuracy of 87.5% for any *thresh*.

In Table II, we only show the results for one parameter configuration for each scheme. However, we evaluated the schemes for different parameters and concluded that the parameter *NumberOfTriggeringCells* for LTE and 5G NR has a very limited effect on the accuracy and number of reports, because most reports are generated from *ReportOnLeave*, while reports due to multi-cell trigger are sent once after each handover. On the other hand, the parameter *NumberOfChangedTriggeredCells* plays an important role in our scheme. For example, at h_{UAV} = 150 m and *NumberOfChangedTriggeredCells* = 6, we can obtain 96% accuracy for 284 reports, which means that our scheme can still achieve ±2% the accuracy achieved by LTE with 30% reduction in number of reports.

Different circular path diameters were also simulated to verify the results and we had the same conclusions above. By that, we demonstrate the advantage of our scheme over the existing LTE and 5G NR ones, regarding the accuracy, number of reports, and the flexibility in setting the parameter to the desired performance.

We also advocate for height-dependent threshold configuration, mainly for below and above rooftop ∼ 40 m. In fact, the different LOS/NLOS conditions in the two cases strongly impact the accuracy of reporting as shown in Table II. To indicate which parameters are configured at any time during the flight, the UAV can use events H1 and H2 where event H1 is triggered when the aerial UE's height becomes above a certain threshold, and event H2 is triggered when it drops below a certain threshold. These events were specifically defined for LTE-supported aerial UEs [4], and the network can configure multiple thresholds for the same event.

V. Conclusion

We studied in this paper measurement reporting for UAVs in cellular networks. We reviewed the main problems in LTE and 5G NR to support measurement reporting for UAVs and proposed a new substitute reporting scheme. We evaluated the performance of our proposed scheme against LTE and 5G NR, in a simulated rural environment, and one UAV flying in a circular path with different fixed heights. We modeled spatially-correlated LOS/NLOS below rooftop heights based on 3GPP models. The results demonstrated a superior performance of our scheme compared to LTE, with a 30% reduction in number of reports, without degrading the reporting accuracy. We also showed the dowsides of 5G NR scheme and its inability to achieve a target accuracy. We further studied height-dependent parameter configuration, to increase the reporting accuracy.

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