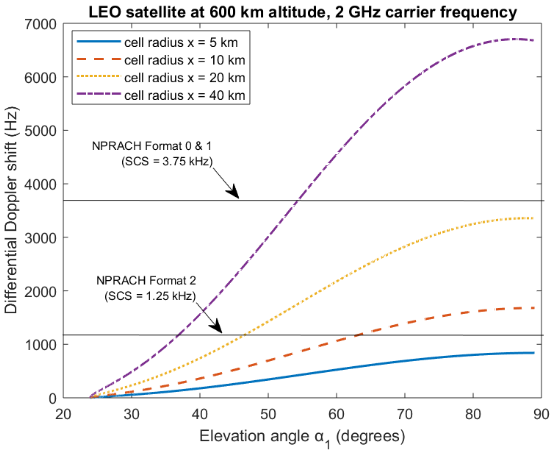

Fig. 11. Differential Doppler shift vs Elevation angle

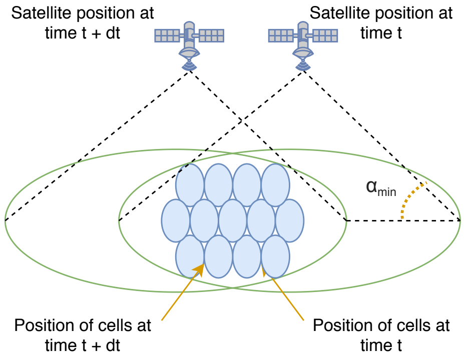

Fig. 12. Earth-fixed cells example

Fig. 13. Earth-moving cells example

a successful RA procedure. A straightforward solution would be to assign to each cell a separate NB-IoT carrier. Multi-carrier operation is supported by the standard and introduced in Release 15 [14]. However, this would lead to significant waste of spectrum, taking into account the large amount of cells, the low demand (especially in remote areas where the satellite would play a role), and the sporadic nature of the traffic coming from the UEs on ground. Alternative solutions should be proposed, with the aim to increase the cell size according to the UE demand, while minimizing the number of required NB-IoT carriers.

C. Differential Doppler shift

Doppler effects are quite a well-known problem in a LEO satellite-based communication system. While in a terrestrial network the Doppler shift is caused by the movement of the UEs, in a satellite communication system, an added factor is the high-speed movement of the satellite. A part of this Doppler shift will be common for all the users inside the same cell (for example the one in the center of the cell), and solutions exist in the literature on how to efficiently pre/post compensate it at the Gateway [16]–[18]. In addition, since the UEs on ground will have different locations, there will be a differential Doppler shift among them causing an overlap of their preambles. Obviously, the higher the overlap, the lower the probability of a successful RA procedure would be.

In our previous work [7], we propose a resource allocation strategy in order to limit the differential Doppler shift up to a level supported by the standard. Basically, the main concept behind is to schedule at the same radio frames only UEs which do not violate the differential Doppler limit. While this solution is well-suitable for message 3 transmission of the RA procedure (and all subsequent transmissions), it is not applicable to message 1. This is due to the fact that in message 1 the transmission is not controlled by the BS. The UEs compete for the same NPRACH channel and they randomly select the resources to use, subject to some pre-configured preamble formats.

As demonstrated in [7], the main contributor towards the differential Doppler shift is the change of position along x-axes (the direction of the satellite movement), whereas the y-axes (perpendicular to the direction of the satellite movement) differential Doppler is negligible. To calculate the maximum differential Doppler shift given the cell radius x, we use the following formula as derived in [7]:

$$\Delta f_d^{max} = \left| \frac{f_c w_s R_E}{c} \cdot (cos(\alpha_1) - cos(\alpha_2)) \right| \tag{9}$$

where w_s is the angular velocity of the satellite, which can be easily derived by knowing the satellite altitude, f_c is the NB-IoT carrier frequency, α_1 and α_2 are the elevation angles of the UEs experiencing the maximum differential Doppler shift (placed at a maximum distance of $2x$ along x-axes). As we can see from the plotted results in Fig. 11, the maximum differential Doppler shift increases proportionally with the increase of the elevation angle and cell radius, for a fixed carrier frequency $f_c = 2\ GHz$. For example, having a cell radius higher than 20 km, means that the preambles may totally overlap for NPRACH Format 0 and 1 at high elevation angles.

The limit that the standard can support is not known for the RA procedure. However, we might need to keep it as low as possible in order to minimize the overlap among preambles, hence increasing the chances of a successful RA procedure. The only way to decrease the differential Doppler shift, without modifying the existing standard, is to tighten the cells. Of course, to what extent, will depend on the probability of detection target of the RA procedure. Since the main contributor towards the differential Doppler shift is the change of position along x-axes, we obtain smaller ellipsoid cells as illustrated in Fig. 12 and Fig. 13. Again, for the Earth-fixed cells we have to take into account the worst-case scenario, whereas for the Earth-moving cell, depending on the elevation angle, the cells will have different x-axes sizes.

Compared to the analysis done in Section IV-B, the number of created cells which take into account both, the differential RTD and differential Doppler shift, would be considerably higher. As a consequence, the problem we already stated in Section IV-B would be reinforced.

D. Frequent Outdate of the TA value

As we previously emphasized, one of the reasons for the RA procedure is to ensure the time synchronization among UEs, through the TA value reported in message 2. It is evident that in our NB-IoT NTN scenarios with LEO orbit, due to the high-speed movement of the satellite, the relation of users inside a cell (either Earth-fixed or Earth-moving) will change quickly over time. This will cause the UEs to loose the time-synchronization, and repeat the RA procedure in order to get an updated TA value. A frequent RA procedure will lead to a RA congestion, and directly impact the overall throughput and the capacity of the NB-IoT network. Solutions should be found to keep the caused RA congestion under control.

V. Proposed solutions and research directions

In this section, we will outline some solutions and research directions, in order to overcome the challenges investigated in Section IV. Part of the proposals have already been discussed in the context of 5G NTN systems [6], [16], [17], and their feasibility for the NB-IoT NTN case will be analyzed.

A. New NPRACH configurations with extended RAR window sizes and CP length

The new RAR window sizes should be able to cope with the increased RTD of communication over the satellite channel. For the worst-case scenario of a GEO satellite with transparent payload, the RAR window size should be greater than 540 ms. This value is much higher than the maximum window size of 41 ms in case of a terrestrial NB-IoT network. Of course, other values should be included for all the possible scenarios and orbit altitudes.

To increase the coverage of the cells, new preambles with longer CP lengths are needed. This will allow the BS to have more degrees of freedom in selecting the size of the cells, and adapt them subject to the required traffic and number of UEs at a specific region on Earth.

B. Extended downlink control information (DCI) field

The additional NPRACH configurations, bring up the need of extra information to be reported to the UEs by the BS. In a terrestrial network, to select an appropriate NPRACH configuration, the UEs rely on the estimate of the received signal power by the BS. This is not enough in an NTN scenario because the estimated received signal power cannot indicate the orbit/type of the satellite, under which the UEs are covered with service.

Therefore, new fields should be included in the DCI containing information regarding the satellite altitude and payload type. This would greatly help the UEs to take proper decisions regarding the NPRACH configuration (having various RAR window sizes or CP lengths as previously explained). For example, for the six scenario options identified in our paper, at least 3 extra bits are needed in the DCI field, to indicate to the UEs under which scenario are being covered.

In addition, other fields can be included in the DCI to continuously update the UEs with the new TA value. Obviously, the estimation of the TA has to be done at the BS, by using the ToA of distinct signals coming from many UEs. By doing so, the UEs in an RRC connected mode, will be able to keep the time-synchronization and avoid multiple RA procedures.

C. Disabled HARQ protocol

Disabling the HARQ protocol would significantly reduce the message exchange between the UEs and the BS. This is highly desirable for the RA procedure over a satellite, first because it would enable a faster uplink data transmission, and second more UEs would be able to access the network.

However, it is worth highlighting here that to keep the same link reliability as in the case of HARQ operation, the block error rate (BLER) target should be properly adjusted.

D. GNSS solutions for differential RTD/Doppler estimation

This technique is also proposed by the authors in [6], [16], [17] for the 5G NTN. It is based on the capability of the UEs to estimate their location and the position of the satellite. An ideal estimation, would lead to a perfect pre-compensation of the differential Doppler shift and RTD at the user side. Thereby, the frames from various UEs will be aligned both, in time and frequency, regardless of the cell size. In such a case, even a cell as large as the satellite coverage, would be able to operate without facing the time-frequency misalignment problem.

The applicability of GNSS solutions for NB-IoT NTN is questionable. Although in the next NB-IoT releases, the UEs will have the GNSS positioning capability, frequent estimation of the differential Doppler/RTD to be compensated (typical for NB-IoT over LEO) means extra processing, diminishing the device battery lifetime. A straightforward solution to this, as also used in other practical systems, would be to periodically disable the GNSS and use the latest position information for differential Doppler/RTD estimation. While this decreases the required processing, it impacts the accuracy of the estimation.

E. Group-based RA

An alternative solution to the one proposed in Section V-D is the group-based RA. The main concept behind is to use the same NB-IoT carrier for more than one cell, but at different times. This means that only the UEs inside a certain cell are allowed to start the RA procedure for a period of time. For another period, the BS will allow users of another cell to access the same NB-IoT carrier. Following this approach, it is also possible to adapt to different demands coming from various cells. The higher the demand, the longer the NB-IoT carrier will be available for the UEs to perform the RA procedure. If only one NB-IoT carrier is not enough to support all the cells, secondary ones may be added. No complexity is added at the user side, but only at the BS, being the responsible entity for resource allocation.

Another advantage of this access mechanism is that it reduces the RA congestion, which is also a well-known problem in a terrestrial network. Since fewer devices will be granted to access the network at the same time, the RA detection probability can be increased.

The only drawback of this approach is that the access will be always initiated by the BS and not by the UEs. After achieving downlink synchronization, the device needs to first check whether its access class (different classes for different cells) is allowed to access the network. In case the device is barred (belongs to another class), it should back off and then reattempt access at a later point in time. The information regarding the UE class is reported in the system information block (SIB) in the downlink transmission, as specified in the standard.

F. Early data transmission (EDT)

As previously explained, in an Earth-fixed cell scenario, the movement of the satellite causes the related parameters among users and the satellite to constantly change over time. On the other hand, for an Earth-moving cell scenario, the UEs will be constantly moving in and out a certain cell. Such a dynamic system brings up the need for transmitting the uplink data as soon as possible in the RA procedure, thus avoiding extra message exchange between the BS and the UEs. In fact, the NB-IoT Release 15 has already introduced the concept of early data transmission in message 3 of the RA procedure. This technique would be very suitable for an NB-IoT NTN. The difference is that while in a terrestrial NB-IoT the EDT is projected to be used in certain scenarios (reduce the delay or increase the battery life), for an NB-IoT NTN this would be the default solution for data transmission.

The disadvantage of this approach is that the BS will be unable to assign the resources for uplink data transmission according to the UE demand, because the data volume that the UEs has to send to the BS is reported in message 3.

VI. CONCLUSIONS

In this paper, we considered an NB-IoT system over satellite and identified six scenario options, based on the satellite orbit, payload and cell type. By referring to the latest 3GPP specifications, we addressed the impact of the typical channel impairments on the NB-IoT random access procedure. We proposed new NPRACH configurations with extended RAR window sizes and CP length, which take into account the increased RTD and differential RTD in the satellite channel. The additional NPRACH configurations, bring the need for extra information to be reported to the UEs by the BS, which can be included in the DCI. To increase the coverage of the cells, opposed to GNSS solutions, group-based RA can be a less complex one, which not only is able to adapt to different demands coming from various cells, but also helps to reduce the RA congestion. Last but not least, due to the dynamicity of our NB-IoT NTN system, we propose to deactivate the HARQ protocol and use EDT, in order to limit as much as possible the data exchange between the UEs and the BS.

REFERENCES

[1] 3GPP TR 38.811, "Technical Specification Group Radio Access Network; Study on New Radio (NR) to support non-terrestrial networks (Release 15) ," Tech. Rep., September 2019.

[2] 3GPP TR 38.821, "Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks (NTN) (Release 16) ," Tech. Rep., December 2019.

[3] 3GPP RP-193235, "Study on NB-Io/eMTC support for Non-Terrestrial Network ," Tech. Rep., December 2019.

[4] S. Cioni, R. De Gaudenzi, O. Del Rio Herrero, and N. Girault, "On the satellite role in the era of 5g massive machine type communications," *IEEE Network*, vol. 32, no. 5, pp. 54–61, Sep. 2018.

[5] N. Alagha, "Satellite air interface evolutions in the 5g and iot era," *SIGMETRICS Perform. Eval. Rev.*, vol. 46, no. 3, p. 93–95, Jan. 2019. [Online]. Available: https://doi.org/10.1145/3308897.3308941

[6] A. Guidotti *et al.*, "Architectures and key technical challenges for 5g systems incorporating satellites," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 3, pp. 2624–2639, March 2019.

[7] O. Kodheli, S. Andrenacci, N. Maturo, S. Chatzinotas, and F. Zimmer, "Resource allocation approach for differential doppler reduction in nb-iot over leo satellite," in *2018 9th Advanced Satellite Multimedia Systems Conference and the 15th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, Sep. 2018, pp. 1–8.

[8] J. Doré and V. Berg, "Turbo-fsk: A 5g nb-iot evolution for leo satellite networks," in *2018 IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Nov 2018, pp. 1040–1044.

[9] S. Cluzel *et al.*, "3gpp nb-iot coverage extension using leo satellites," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, June 2018, pp. 1–5.

[10] H. Saarnisaari, A. O. Laiyemo, and C. H. M. de Lima, "Random access process analysis of 5g new radio based satellite links," in *2019 IEEE 2nd 5G World Forum (5GWF)*, Sep. 2019, pp. 654–658.

[11] 3GPP RP-180581, "Interim conclusions on IoT for Rel-16 ," Tech. Rep., March 2018.

[12] Olof Liberg Marten Sundberg Eric Wang Johan Bergman Joachim Sachs Gustav Wikstrom, *Cellular Internet of Things : From Massive Deployments to Critical 5G Applications, 2nd Edition*. Elsevier Science & Technology, 2020.

[13] TS 36.321, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification (Release 15) ," Tech. Rep., December 2019.

[14] 3GPP TS 36.213, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (version 15.7.0 Release 15) ," Tech. Rep., October 2019.

[15] A. Guidotti, "Beam size design for new radio satellite communications systems," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 11, pp. 11 379–11 383, 2019.

[16] A. Guidotti *et al.*, "Satellite-enabled lte systems in leo constellations," in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, May 2017, pp. 876–881.

[17] O. Kodheli, A. Guidotti, and A. Vanelli-Coralli, "Integration of satellites in 5g through leo constellations," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Dec 2017, pp. 1–6.

[18] Jionghui Li *et al.*, "Fast tracking doppler compensation for ofdm-based leo satellite data transmission," in *2016 2nd IEEE International Conference on Computer and Communications (ICCC)*, Oct 2016, pp. 1814–1817.