Unmanned Aerial Base Stations for NB-IoT: Trajectory Design and Performance Analysis

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***Abstract*—In this paper, we consider a NarrowBand-Internet of Things (NB-IoT) network where an Unmanned Aerial Vehicle (UAV) is employed to gather data from IoT devices deployed in a given area. It is well known that UAVs may fly over the terrestrial plane, where and when needed, acting as Unmanned Aerial Base Stations (UABs). In order to serve as many ground IoT devices as possible, a proper trajectory design is fundamental. As we show in the paper, the optimization of the UAV speed and the radio parameters are also essential. Specifically, this paper studies a cluster-based scenario, where IoT devices are deployed according to a Thomas process, and applies a Traveling Salesman Problem approach to design the UAB trajectory. Notably, our model considers the protocol constraints on the number of resource units available on the UAB's NPUSCH, and the data rate that it can provide to IoT devices. Our results reveal the impact of different design parameters, such as UAB speed and NPRACH periodicity on the network throughput and the number of requests served.**

***Index Terms*—NB-IoT, Unmanned Aerial Base Stations, Traveling Salesman Problem.**

I. Introduction

The statistical reports[1] demonstrate the steady increase of the number of the machine-type connectivity links happening every year, and predict the further increase of its pace. However, not only an increase of the Internet of Things (IoT) device numbers and their traffic represents a major challenge for the future. Another key challenge still to be addressed is the increase of the requirements for communication performance - the demand - imposed by the various applications and use cases (including, e.g., autonomous vehicles, Industry 4.0, and wearables).

Both these trends call for a new paradigm to networks design. One possibility will be to apply densification, that dramatically increases the number of Terrestrial Base Stations (TBSs) deployed. However, this will inquire substantial investments and will introduce extra energy consumption, which is already huge[2].

One possible alternative is to use mobile Base Stations (BSs), mounted on Unmanned Aerial Vehicles (UAVs, a.k.a. drones), providing service where and when needed to cope with peaks of traffic demand. Unmanned Aerial Base Stations (UABs) are particularly interesting since they are not tied to roads, not affected by traffic congestion and can feature good connectivity with both, on-ground users, and TBSs (i.e., backhaul), thanks to the large probability of being in line-of-sight (LOS).

Recent studies show that the UABs are an efficient complement to traditional TBSs, enabling service to ground human users, who cannot be served by the TBSs also due to the network congestion [1], [2]. However, this imposes the need to know in advance the positions of the users and the traffic demand to properly design the trajectory of the UAB. This information is not always available, neither is easy to be predicted. For this reason, in this paper we consider the use of a UAB for another purpose, i.e., to serve another type of users with specific traffic - the IoT machines.

Usually, the IoT devices, which are programmed to monitor or collect data, are static, and therefore their position does not change in time. Thus, their position is known (or can be made known through discovery). Moreover, the traffic they generate can also, often, be predicted (e.g, due to its periodic nature). The knowledge of these two basic inputs allows the UAB to make decisions in advance on the trajectory to follow to serve as many IoT devices as possible.

Therefore, a UAB that is able to go where the demand takes place and only when this is needed is a promising solution to address the IoT traffic for a mobile network operator. Specifically, a UAB providing service to ground nodes may efficiently offload traffic from the TBSs, such that they can retain more radio resources for mobile broadband users. This also allows to reduce the number of TBSs, thus reducing the operational and deployment costs and, importantly, consumption of energy.

One of the key mobile technologies that will be used in the coming years with the advent of 5G is Narrowband IoT (NB-IoT). NB-IoT takes the same numerology as 4G (and, possibly, 5G), and therefore perfectly fits with a UAB implementing Evolved/Next Generation Node B (eNB/gNB) functionalities. However, the NB-IoT technology, adapted specifically for the IoT requirements, substantially differs from conventional LTE.

For this reason, in this paper (the key contribution) we thoroughly study the network performance of a UAB flying over groups of NB-IoT nodes, taking into account the access mechanism, the time frame structure and the resource allocation mechanisms as they are specified by 3GPP. In particular, we test through simulation the impact that the following parameters

[1]See, e.g., https://www.statista.com/statistics/802690/worldwide-connected-devices-by-access-technology/ or https://www.ericsson.com/en/mobility-report/reports/november-2019/iot-connections-outlook .

[2]https://www.gsma.com/futurenetworks/wiki/energy-efficiency-2/, https://www.ericsson.com/en/blog/2019/9/energy-consumption-5g-nr, https://www.mdpi.com/2071-1050/10/7/2494/pdf.

have on network performance:

- NB-IoT frame structure in the uplink (UL)
- Transmitted packet size
- NB-IoT nodes density and distribution
- UAB speed while completing its trajectory

The paper is organized as follows. In Section II, we give an overview of the literature about UAV-aided networks. NB-IoT and its UL features are presented in III. Section IV describes the scenario and the network model. Final simulation results are reported in Section V.

II. Related Works

The previous studies relative to UAV-aided networks focused on the key link-level considerations, and specifically on the characterization of path loss, and on its impact on the air-to-ground channel. For instance, in [3] the effect of the user-UAV angle w.r.t. the ground plane as a function of drone height is studied. Further works on UABs focused on finding an acceptable trade-off between coverage, capacity and connectivity, as in [4]. In [5] a 3D-scenario is considered where multiple UAVs act as relays in a Device to Device-like communication. In the paper the Authors optimize the length of the links user-UAV-TBS through particle swarm optimization. UAVs as relays were studied also in [6], where one is used as a mule in a delay tolerant network for smart cities application. The initial works dealing with UAV-aided cellular networks addressed the optimal placement of UABs. Among many, [7] optimizes UAVs positions based on the trade-off between the probability of being in line-of-sight with UEs and the reliability of the backhaul, [8] minimizes the number of flying base stations needed to provide coverage to a group of UEs, and [9] deals with cell partitioning among UABs.

More recent activities deal with the definition of an optimal trajectory for UABs. In [10] and [11] the trajectory is optimized with the aim of maximizing the minimum user rate. However, they do not consider specific protocol constraints or overhead as it is in 3GPP standards.

In contrast with these works, we aim at analysing the behaviour of the NB-IoT network, taking into consideration the protocol mechanisms and practicalities. Furthermore, we consider the impact of nodes having a given activation time (randomly distributed) and a given expiration time, that imposes a maximum delay with which they have to be served. On the contrary, the above cited works assume users are active for the entire flight and no activation and expiration times are addressed. Moreover, we consider much larger and realistic scenarios with hundreds of nodes, while only 6 or 4 users are considered in [10] and [11].

To the best of Authors knowledge, literature still lacks the analysis of comparable scenarios and similar setups. Therefore, the focus of this paper is to discuss and understand the dynamics of our proposed model, rather than compare our approach with existing research activities. This study helps us to extract the major impacts of the NB-IoT protocol on UAV-aided networks to build a solid analytical model in further works.

III. Narrowband IoT technology and implications

A. NB-IoT overview

The initial version of NB-IoT technology addressing the needs of the massive machine-type communication (mMTC) applications has been standardized by 3GPP as a part of release 13 in 2016 with new functionalities introduced in the subsequent releases. The NB-IoT technical solution originates from the LTE technology, which has been substantially simplified and re-worked to reduce the overheads, minimize complexity, cost and consumption, and maximize the possible communication link length. The NB-IoT technology features substantial flexibility allowing to deploy the NB-IoT cell by rolling a software update on top of an already existing LTE cell. An NB-IoT cell may be deployed standalone in a dedicated frequency band, use the LTE guard bands or even operate in-band with LTE or LTE-M.

The conventional media access procedure of a NB-IoT User Equipment (UE) operation is composed of a number of steps. First, a UE scans the channels for the synchronization signals. Once synchronized to the cell base station (i.e., the eNB), the UE obtains first the Master and then a set of Secondary Information Blocks (MIB and SIBs, respectively), containing all the relevant information about the network, the cell, and its resource allocations. To connect to the cell, the UE has to go through the procedure of random access (RA), the initial phase of which is transmission of an access preamble during one of the periodic random access windows. The preamble to be used is selected by a UE randomly (if connection is initiated by UE) or can be allocated to the UE (the so-called contention-free access, in case if connection establishment is driven by the network). Following the transmission of the random access preamble, the resources for the UL and downlink (DL) transmissions are scheduled by the cell eNB with data integrity insured through the Hybrid Automatic Repeat Request (HARQ) processes.

Before Rel. 15 introducing time division duplex (TDD) operation mode, the frequency division duplex (FDD) mode was the only option for NB-IoT. In this paper we consider the latter, since it is the primary mode used in most commercial networks and enables the maximum performance. The FDD mode implies different frequency bands to be used for UL and DL transmissions. In UL resource grid the subcarrier spacing of either 15 or 3.75 kHz are possible, providing either 12 or 48 possible subcarriers within a 180 kHz resource block. The 15 kHz spacing allows transmission of either single and multicarrier (over up to 12 carriers) signals, while only single-carrier transmissions are possible for 3.75 kHz grid. In DL the 15 kHz resource grid is used. Importantly, to increase the maximum communication range, the eNB may configure several coverage extension classes featuring different number of packet/symbols repetitions, and may even specify the number of repetitions to be used in UL and DL (can reach 2048 in DL and 128 in UL) by a specific UE in the respective Downlink Control Indicator (DCI) packet.

B. Uplink channels, parameters, and implications

Only two channels are defined in the UL, the narrowband physical random access channel (NPRACH) and the narrowband physical uplink shared channel (NPUSCH). The NPRACH is used to trigger the RA procedure. It is composed of a contiguous set of either 12, 24, 36, or 48 subcarriers with 3.75 kHz spacing, which are repeated with a predefined periodicity, that may take several discrete values between 40 ms and 2560 ms. The RA procedure starts with the transmission of a preamble, with a duration of either 5.6 ms or 6.4 ms (Format 0 and 1, respectively) depending on the size of the cell, and can be repeated up to 128 times to improve coverage. A preamble is composed of four symbol groups, each transmitted on a different subcarrier. The initial subcarrier is chosen randomly, while the following ones are determined according to a specific sequence depending on the first one. Two UEs selecting the same initial subcarrier will thus collide for the entire sequence. A special mechanism can help resolving the collisions and thus the access probability of a node u can be approximated as Eq. (1):

$$P_{acc,u} = e^{-\frac{U}{N_{RU}}} \quad (1)$$

where U is the number of nodes entering RA and N_{RU} are the total available subcarriers.

In case of standalone deployment the NPUSCH occupies all the UL resources left available after the allocation of the NPRACH. NPUSCH is used for UL data and UL control information. Only Binary or Quadrature Phase-Shift Keying (BPSK or QPSK) modulations are used, and the code rate is 1/3 for data transmission and 1/16 for HARQ Acknowledgement (ACK). The eNB decides how many resources to allocate to the UEs depending on the amount of data to be sent, the modulation-coding scheme (MCS) used and the number of repetitions needed to correctly receive the data. The minimum resource block which can be allocated, referred to as a resource unit (RU), depends on the UE capabilities and the configured numerology. Specifically, in the case of 3.75 kHz subcarrier spacing and single-tone operation, the RU is 32 ms long. In the case of multi-tone-enabled UE and 15 kHz spacing, an RU can be composed of 12 subcarriers and 2 time slots featuring QPSK modulation and have the total cumulative duration of 1 ms. The number of the RUs (ranging from one to ten) to be allocated depends on the size of the transport block size (up to 1000 bits in Rel. 13) and the MCS chosen to meet the required success probability. In addition, the eNB specifies the desired number of repetitions.

Without the loss of generality, in what follows we imply 3.75 kHz subcarrier spacing with 48 carriers allocated for RACH. Furthermore, since the UAB is expected to be close and in, primarily, line-of-sight conditions, only single coverage class with one repetition is implied. This implication also allows to minimize the potential interference experienced by the TBS, and to simplify the design and reduce the consumption of the eNB on the UAV. Furthermore, we imply that the NPUSCH setting for MCS is defined by $I_{TBS} = I_{MCS} = 6$ and the size of the sensor data is either 500 or 1000 bits. Table I shows the packet size (or Transport Block Size as for NB-IoT terminology) in bits for the selected scheme for the different possible number of RUs (for clarity, only the selected cases are reported). Note that, in this paper, we do not consider contention-free channel access being available.

Table I
NB-IoT UL transport Block Size (TBS) in bits

RUs number	2	4	5	6	8	10
Max. packet size for $I_{MCS} = 6$ [bits]	176	392	504	600	808	1000

IV. Network Model

A. Reference Scenario

We consider an urban environment, where IoT devices are deployed at smart traffic junctions, in city parks, at waste collection points, in the parking lots, or into buildings, to name just a few examples. Thus, in our real scenario we have clusters of IoT devices, characterized by close vicinity, distributed in different areas of a city.

We model this real scenario using a Poisson Cluster Process, namely the Thomas cluster process (TCP) [12], as conventionally done in the literature (see, e.g., [13]). The TCP is a stationary and isotropic Poisson cluster process generated by a set of offspring points independently and identically distributed (i.i.d.) around each point of a parent Poisson Point Process (PPP) [12]. In particular, the locations of parent points are modeled as a homogenous PPP, with intensity λ_{p}, around which offspring points are distributed according to a symmetric normal distribution with variance σ^2 and mean value n. therefore, the intensity of the offspring points is $\lambda = \lambda_{\text{p}} \cdot n$. In our scenario, both parent and offspring points represent the IoT nodes, without any difference in the type and role of the physical device. However, as it will be clarified later, parent points will be used to define the UAB trajectory.

We simulate a square area of size L x L m^2, where parent points and offspring points are deployed according to the description above. A snapshot of the simulated scenario is depicted in Fig. 1. A single UAB is considered to save in costs. We assume it starts its flight from a fixed position, denoted as Home and coincident with one of the parent points, where it has to come back at the end of the trajectory. In this way, it can recharge or change its battery for the next flight. Note that, in this study, the processes of take-off and landing are not simulated. Moreover, we do not model the consumption of the UAB and imply that the capacity of its battery is sufficient to

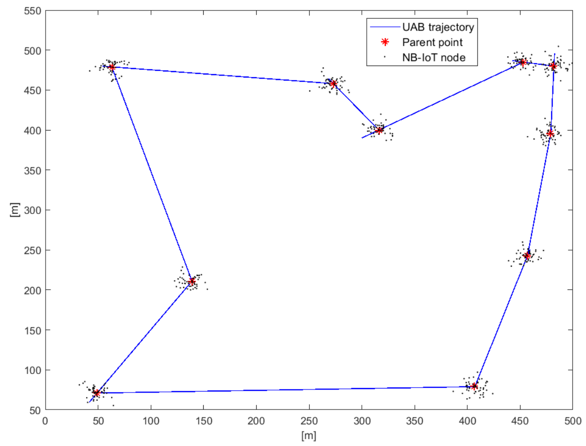

Figure 1. Node deployment illustration and TSP example.

enable a full round trip over any trajectory. This is reasonable [14], [15], since the total flight times considered do not exceed half an hour. The UAB is assumed to fly at a constant altitude from the ground of 100 m (not violating the regulations in EU - [16]).

B. Traffic Model

Each user u is characterized by three parameters related to traffic demand: i) the size of data demand, d_u, that is the number of bits the user wants to send in uplink, ii) the activation time, a_u, that is the instant in which the demand is generated; iii) the expiration time, e_u, that is the maximum amount of time user u can wait before the service is satisfied completely. So, the deadline for completion of data download is at instant $a_u + e_u$ for user u. We assume each node generates only one packet to transmit in a time period T and a_u is assumed to be randomly and uniformly distributed in T.

C. Channel Model

In this paper, the propagation model affects the UAB-ground node link. We compute the received power, P_{rx} as a function of the transmit power, P_{tx}, as: $P_{rx}[dBm] = P_{tx}[dBm] - A_L[dBi] - L(d)[dB]$. We consider the probabilistic model for drones in urban environment provided in [3], [17]. According to this model, connections between drone and nodes can either be LoS or Non-Line-Of-Sight (NLoS). For NLoS links, the signals travel in LoS before interacting with objects located close to the ground which result in shadowing effect. We denote as p_{LOS} the probability of connection being LoS. The LoS path loss model is given by:

$$L_{LoS}(d)[dB] = 20 \log \left(\frac{4\pi f_c d}{c} \right) + \xi_{LoS} + \eta \qquad (2)$$

while $L_{NLoS}[dB]$ for the NLoS case is given by eq. (2) by substituting ξ_{LoS} with ξ_{NLoS}. ξ is the shadowing coefficient which is set as described in [3], c is the speed of light, f_c is the center frequency, and d is the transmitter-receiver distance in meters. An additional penetration loss, η, as for in indoor monitoring or basement applications is considered. The probability p_{LoS} at a given elevation angle, θ, is computed according to the following equation

$$p_{LoS} = \frac{1}{1 + \alpha \exp(-\beta[\frac{180}{\pi}\theta - \alpha])} \qquad (3)$$

with α and β being environment-dependent constants, i.e. rural, urban, etc, and adopted as given in [3]. Eq. 3 determines for every link if it is in LoS or NLoS condition, impacting then the value of ξ_{LoS} in Eq. 2.

If the received power is above the receiver sensitivity $P_{rx,min}$, then we consider the node be in connectivity range of UAB. At this moment, it can attempt to access the channel through the NB-IoT NPRACH (see Sec. III-B), so that, if succeeded, it may be given resources to transmit its data. The number of resources assigned determines the packet size that the device is able to transmit in the assigned time slot (see Sec. III-B and Table I for scheduling details). Note that, since the IoT nodes are the devices more limited in their available resources (especially including the maximum transmit power), we consider that:

- the connectivity range is defined by the uplink,
- the downlink control communication is error-less.

D. UAB Trajectory Design

In this paper, we consider one UAB flying over clusters of ground nodes following a predefined path. In this way, we can avoid static positioning of multiple drones, that would require increasing capital expenses. Moreover, a static deployment still has energy consumption issues due to the hovering of the aerial platforms. Given the cluster-based nature of devices distribution, a simple approach for the UAB trajectory design has been used. Since the UAB has to serve clusters of fixed nodes, we may consider the locations of the parent points as reference points to model it as a Traveling Salesman Problem (TSP) [18]. The TSP addresses the task to find, for a finite set of points whose pairwise distances are known, the shortest route connecting all points. Therefore, to reduce both energy consumption and service delays, we consider the UAB trajectory to follow TSP solution for cluster reference points. Despite the fact users have activation and expiration times, their high number in the area allows the TSP to be an effective method (see Sec. V). An example is depicted in Fig. 1.

As one can easily see, the performance of the considered network depends both on the UAB mobility pattern and the UAB NB-IoT cell configuration. In the following section we consider how the respective parameters (e.g., UAB speed and NPRACH periodicity or NPUSCH duration) affect the performance.

V. Results

In the simulations performed, the radio and network parameters are set as summarized in Table II. The simulations

Table II
RADIO AND NETWORK PARAMETERS

Parameter	Value
UL transmit power, P_{tx}	14 dBm
Antennas loss, A_L	2.5 dBi
Penetration loss, η	40 dB
Noise power, P_N	30 10^{-17} W
Receiver sensitivity, $P_{rx,min}$	-121 dBm
β	9.6117
α	0.1581
Channel bandwidth, B_c	180 KHz
Subcarrier spacing	3.75 kHz
Available subcarriers, N_{RU}	48
Carrier frequency, f_c	1747.5 MHz
RU duration	32 ms
MCS index, I_{MCS}	6
Activation Time, a_u	Uniform[0; 120] s
Expiration Time	10 s for all u

are performed for a UAB altitude of 100 m in an area with side $L = 500$ m. Therefore, due to the finite area size, a number N_u of IoT devices is present in each simulation. In our simulations, all presented results are obtained by averaging over 1000 iterations, characterised by different nodes distributions and values of N_u. The simulations were carried in a MATLAB environment using a specifically-developed script for nodes deployment. Then, a NB-IoT simulator was developed in a Java environment, including the IBM CPLEX v. 12.7.1 framework to solve the TSP.

We evaluate the performance in terms of number of served users, that are users to which the UAB has assigned enough radio resources for the transmission of their data; and network throughput, S_{N}, defined as the sum of the throughput of the different users, given by:

$$S_N = \sum_{u=1}^{N_u} S_u \tag{4}$$

where S_u is the user u throughput, given by: $S_u = d_u/T_u$, where T_u is the service delay.

To study the performance of the proposed UAV-aided NB-IoT network, we analyse the percentage of served NB-IoT nodes in different cases, by varying:

- the density of parent points, λ_p,
- the mean number of nodes in one cluster, n.

The value of σ^2 is fixed to 100 m. In addition, we show results by varying the NPRACH periodicity, which affects the number of occasions a node may try requesting access to the UAB. Note, that it affects also the NPUSCH duration, because frequent NPRACH occurrences lead to shorter NPUSCH thus reducing resources available for UL user data transfer.

Figure 2 reveals the effect of the nodes distribution on the cumulative throughput of the network. The demand of each node is either 500 or 1000 bit, and the UAB speed is fixed at 20 m/s. We can easily distinguish two sets of curves: 1) with dashed lines, and 2) without dashed lines. The former set is obtained with 1000 bit of node demand, and the latter

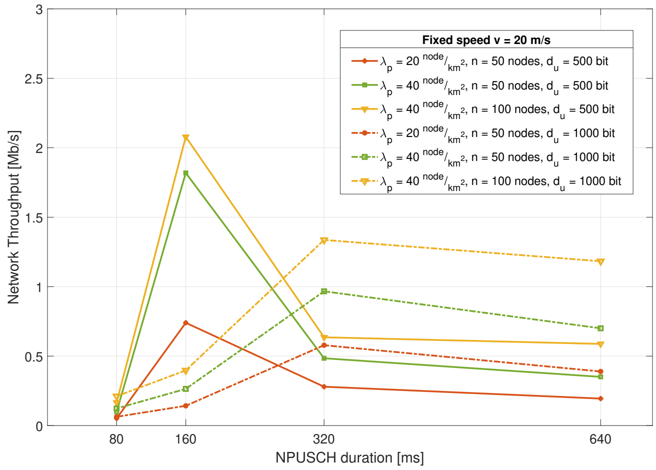

Figure 2. Effect of nodes distribution on network throughput.

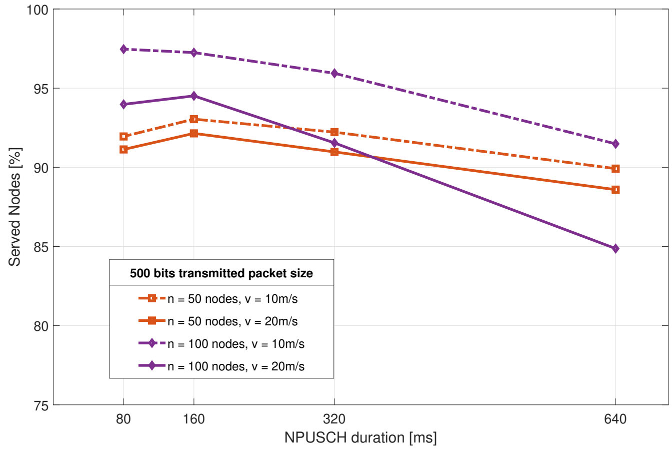

Figure 3. Variation of nodes distribution vs number of served nodes, with $\lambda_p = 20$.

with 500 bit. Interestingly, curves in the same set show a similar behaviour, that is an increased network throughput as the average number of nodes increases, and a maximum for the same value of NPUSCH duration (320 ms and 160 ms). We can deduce that, despite the diverse distribution of nodes, there is one value for the NPUSCH duration (or, equally, timing of NPRACH occurrences) that is optimal for the specific traffic demand of users. Moreover, it has to be noted that the position of the maximum differs from 500 to 1000 bit demand because the number of resources to be assigned changes.

From Table I we can infer that 5 RUs are needed in the first case, and 10 in the second. Then, if one RU lasts 32 ms, 160 ms perfectly fit 500 bit, while 320 ms the case of 1000 bit. Then, for both sets, the maximum lays in the value of NPUSCH duration guaranteeing to each node no additional overhead (i.e., extra NPRACH occurrences) nor additional delays.

Figures 3 and 4 show the percentage of served nodes while varying their distribution and the UAB speed. Node's demand is fixed at 500 bit. Again in these plots, there is often a

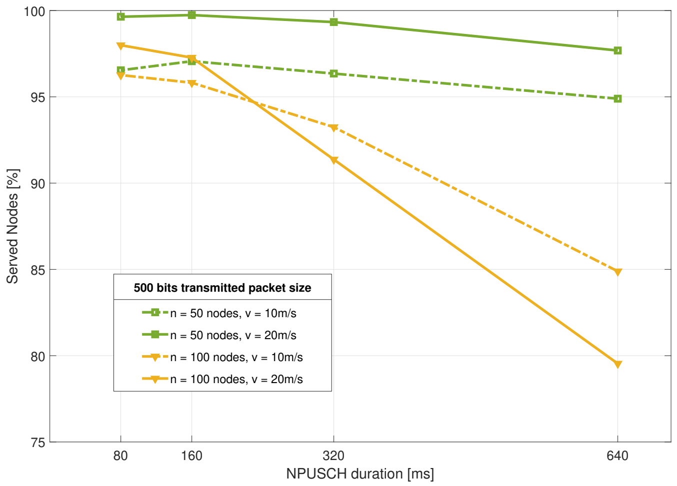

Figure 4. Variation of nodes distribution vs the number of nodes served, with $\lambda_p = 40$.

maximum at 160 ms. This shows that, given the number of nodes in the service area, an optimal choice on the timing of NPRACH occurrences has to be planned. When designing an NB-IoT network with UABs, a good trade-off between the access occasions, availability of RUs in the NPUSCH and the number of active devices is to be considered. Furthermore, these curves show that the UAB speed strongly impacts the system performance. If the average number of nodes is low, the trajectory is shorter and a lower speed (e.g. 10 m/s) increases the node's chance to connect to the UAB and transmit its packet. On the other hand, if the number of nodes increases, a higher speed (e.g. 20 m/s) allows to visit and serve more nodes in the given expiration time. Note that the percentage of served nodes is in almost all considered cases above 90%. To conclude this analysis, a TSP trajectory may be a good solution to achieve both an acceptable performance and algorithm simplicity.

In this activity, we assumed an urban scenario with stringent path loss characteristics and a fixed altitude of the UAB. Note that, another interesting investigation would be on the variation of the UAB height to observe the impacts on network behaviour. In fact, it has an impact on the UAB coverage area (and indirectly on the access probability) and channel quality.

VI. Conclusions

In this work we studied the impact of a UAB overlaid to a NB-IoT network. We have shown the performance considering the percentage of served NB-IoT nodes and network throughput through simulations when a TSP approach for trajectory design is used. Results show that UAB and network parameters should be properly tuned depending on the scenario, and that in the considered case this simple approach provides a good balance between achieved performance and algorithm simplicity.

Furthermore, the scope of this paper is to get an insight into the utility and feasibility of using NB-IoT base stations on UAVs, together with understanding the effects of the technology parameters on the performance and associated tradeoffs.

With these results, we can better steer further research activities targeting the development of analytical solutions of the problem. Moreover, in future works we intend to improve the precision of our results further by accounting the NB-IoT link layer procedures and accounting the respective numerology (for example, by focusing on the intended NPRACH period settings).

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