Enhancing Mobile Networks for Urban Air Mobility Connectivity

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***Abstract*—Aerial technologies represent a fundamental part of transport systems, and the overload of terrestrial transportation as well as the high demand in urban scenarios are forcing for new solutions. From this perspective, Urban Air Mobility (UAM) is emerging as an outperforming solution to guarantee high-speed vertical transportation taking advantage of low altitudes. Connectivity is a key factor for UAM vehicles, and mobile networks represent the best solution to provide immediate connectivity with high-performance and low expenses. This calls for the development of enhancement strategies for terrestrial radio access networks. This letter aims to investigate a strategy to provide connectivity for UAM vehicles while minimizing the number of base stations required to provide UAM connectivity. Insights on the impact of different design parameters on the number of enhanced BSs required to guarantee average and minimum throughput requirements for UAM users are provided.**

***Index Terms*—Urban air mobility (UAM), advanced air mobility (AAM), mobile networks, RAN, 5G, 6G.**

I. Introduction

FUTURE evolution of urban mobility will include novel aerial transport systems, and Urban Air Mobility (UAM) represents an interesting solution that can offer high-speed passengers or cargo transportation based on electric Vertical Take-Off and Landing (eVTOL) vehicles, with the control of pilots in the first stage that will be gradually substituted by autonomous driving systems. Despite the definition of Unmanned Aircraft System (UAS) [1] and U-Space regulations [2] from the European Union and other agencies around the world, efforts are still ongoing in UAM development with an expected impact in traffic scenarios and communication aspects.

In fact, besides mobility connectivity represents a key factor, especially for the driverless scenario, the high mobility provided by UAM vehicles and the expected high density in vertiports (i.e., dedicated areas for take-off and landing) force to abandon classic aviation systems for connectivity and surveillance in favor of modern technologies. In general, UAM connectivity is classified into Communication and Control (C2) for the transmissions of flight control data (i.e., telemetry, diagnostic, etc.), and Payload communication (non-C2) for non-priority data transmissions [3], [4]. The different connectivity requirements between C2 and non-C2 communications as well as the flight altitudes represent major issues in developing a seamless and reliable UAM communication system. Considering that the typical altitude values will be above hundreds of meters, Terrestrial Networks (TNs) cannot guarantee UAM connectivity as for terrestrial User Equipment (UE). Non-Terrestrial Networks (NTNs) represent a feasible solution considering the increasing interest since the first 5G standard releases [5]. NTNs provide high coverage for potential users of different environments, but the satellite elevations and the propagation channel affect the latency and the reliability of the communication, highlighting the impossibility of adopting this solution for C2 communications at its actual level of development [6].

Many research efforts [7], [8] are ongoing in the development of Aerial Networks (ANs) to support vehicles flying at altitudes in the order of kilometers, e.g., Aerial Vehicles (AVs) and High-Altitude Platforms (HAPs) [9], [10], [11]. However, such networks require the development of ad-hoc technologies and focus on altitudes that are not compatible with UAM vehicles which are supposed to flight at $\leq$ 1km altitude.

Considering the high coverage offered by modern mobile systems (5G and forthcoming 6G) and the capability to connect a wide population of users, TNs have become a robust technology suitable to provide connectivity for UAM vehicles flying at altitudes below the kilometer. Leveraging on its readiness from industrial and commercial points of view, TN represents the best solution to immediately integrate connectivity in UAM scenarios. However, this requires novel methodological approaches in the design of Radio Access Network (RAN) elements as well as in the overall mobile network design and planning.

In particular, starting from current network scenarios, the estimation and selection of terrestrial Base Stations (BSs) to provide UAM coverage may represent a critical decision for mobile operators in terms of CAPital EXpediture (CAPEX) and Total Cost of Ownership (TCO) [12]. Thus, this letter aims to investigate the connectivity demand for emerging UAM transportation systems exploiting the potential and reliability of TNs. Our main contribution regards the design of RAN enhancement strategies to guarantee coverage for higher altitudes, providing connectivity to UAM vehicles. This approach will be captivating for mobile operators to exploit the

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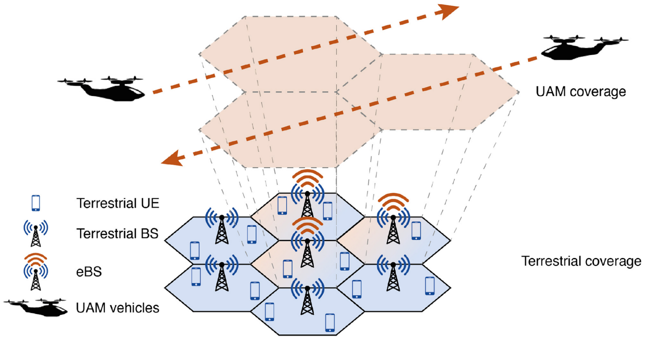

Fig. 1. Simplified representation of the considered scenario.

actual coverage offered to terrestrial users and save resources in terms of CAPEX and TCO.

The rest of this letter is organized as follows: Section II presents the system model and the proposed improvement strategy, Section III illustrates the optimization problem to adapt the terrestrial BSs for UAM connectivity while Section IV shows the simulation results; finally, conclusions are provided in Section V.

II. System Model

We consider a generic scenario where an urban area with terrestrial UEs is covered by a TN and a subset of terrestrial BSs has to be modified to guarantee coverage to higher altitudes providing connectivity to UAM vehicles. In the following, we refer to the BSs equipped with purposely designed antennas [12] and configured with proper power levels as to enhanced-BS (eBS). Here, we compare enhancement strategies to improve a TN and its BSs to provide connectivity to UAM vehicles while maintaining the same terrestrial coverage and performance, as shown in Fig. 1.

Regarding the power modeling, no regulations have been defined for UAM connectivity despite the TN limitations in the emitted power. For the downlink, the only aspect to take into consideration is the presence of vehicles and devices above the UAM altitude that can suffer interference in the same or adjacent frequency channels, which however are limited by path loss. On the contrary, specific regulations are required for the uplink, since UAM vehicle communications can interfere with terrestrial UE.

The scenario is assumed to be a square of length L; u_i is the generic UAM vehicle considered as a single UAM user, with $u_i \in \mathcal{U} = \{u_1, \dots, u_U\}$ and $i = 1, \dots, U$ where U is the total number of UAM users; b_j is the j-th BS, with $b_j \in \mathcal{B} = \{b_1, \dots, b_B\}$, $j = 1, \dots, B$ where B is the total number of BS of the TN in the considered scenario. Both UAM users and eBSs are deployed into the scenario according to a Poisson Point Process (PPP) while we consider a uniform random distribution for the altitudes. The UAM users connect to an eBS using the Orthogonal Frequency-Division Multiple Access (OFDMA) and a set of Resource Blocks (RBs) are assigned to each user following the bestCQI scheduling algorithm [13], prioritizing the UAM users with the higher MCSs.

III. Optimization Problem

In the aforementioned scenario, let us define the binary variable β_j as follows,

$$\beta_j = \begin{cases} 1 \text{ if } \; b_j \; \text{ is an eBS} \\ 0 \text{ otherwise} \end{cases} \tag{1}$$

and

$$N_{eBS} = \sum_{j=1}^{B} \beta_j \tag{2}$$

where N_{eBS} is the number of BSs enhanced to guarantee connectivity to UAM users.

We define the binary variable α_{ij} that sets the association between the UAM user u_i with the eBS b_j:

$$\alpha_{ij} = \begin{cases} 1 \text{ if } \; u_i \; \text{ is connected to } b_j \\ 0 \text{ otherwise} \end{cases} \tag{3}$$

where

$$\alpha_{ij} \leq \beta_j \quad \forall i, j \tag{4}$$

The following condition has to be satisfied

$$\sum_{j=1}^{B} \alpha_{ij} \leq 1, \quad \forall \; i \tag{5}$$

meaning that a UAM user can be connected only to a single eBS. The association rule followed by the UAM users is based on the Signal-to-Noise Ratio (SNR) and each user is connected to the eBS guaranteeing the highest SNR. Each UAM user experiences a spectral efficiency ε_{ij} with

$$\varepsilon_{ij} = f\left(\text{MCS}_{ij}^{m}, \text{SNR}_{ij}, \text{BLER}_T\right) \quad [\text{bps/RB}] \tag{6}$$

where MCS_{ij}^{m} and SNR_{ij} are the m-th Modulation and Coding Scheme (MCS) among the ones defined in [14] assigned to the user u_i and its SNR, respectively, and BLER_T the target BLock Error Rate (BLER). In fact, the MCS assignment derives from the set of BLER values depending on the adopted modulations and coding rates [15]. Among the possible sets of MCSs provided by 3GPP, we consider the ones in [14] which account for lower MCSs that are suitable for longer distances as in our scenario. Thus, given BLER_T and SNR_{ij}, we define BLER_{ij} as the corresponding BLER resulting from SNR_{ij}. MCS_{ij}^{m} is assigned selecting the maximum m such that BLER_{ij} is lower than BLER_T. Once the MCS is identified, the corresponding spectral efficiency per RB ε_{ij} is obtained through [14] with the function f describing the above procedure.

Defining $w_{ij} \in [0, 1] \subset \mathbb{Q}^+$ as the portion of RBs of eBS b_j assigned to the user u_i and assuming that each eBS assigns all the available RBs, the following condition can be stated:

$$\sum_{i=1}^{U} \alpha_{ij} \cdot w_{ij} = 1 \quad \forall \; j \tag{7}$$

The available data rate of the user u_i connected to the eBS b_j can be defined as

$$R_{ij} = w_{ij} \cdot K \cdot \varepsilon_{ij} \quad [\text{bps}] \tag{8}$$

where K is the overall number of available RBs per eBS and $K \cdot w_{ij}$ is the number of RBs of b_j assigned to the user u_i. Therefore, the throughput of the generic UAM user u_i is:

$$\mathrm{THR}_{ij} = R_{ij}\left(1 - \mathrm{BLER}_{ij}\right) \quad [\mathrm{bps}] \tag{9}$$

We aim to minimize the amount of BSs N_{eBS} that should be enhanced to guarantee connectivity to UAM users. In the following, we provide a formal definition of two optimization problems aiming at offering a target average throughput and minimum throughput per UAM user, respectively.

A. Average Throughput per UAM User

The first optimization problem $\mathcal{OP}1$ is based on the average throughput per UAM user, aiming to guarantee a certain performance on average. The average throughput per UAM user can be defined as:

$$\overline{\mathrm{THR}} = \frac{\sum_{j=1}^{B}\sum_{i=1}^{U}\alpha_{ij}\cdot \mathrm{THR}_{ij}}{U} \quad [\mathrm{bps}] \tag{10}$$

where THR_{ij} is calculated according to (9). Then, $\mathcal{OP}1$ can described as follows:

$$\mathcal{OP}1 : min\{N_{eBS}\} \tag{11}$$

$$s.t. \quad N_{eBS} = \sum_{j=1}^{B}\beta_j \tag{C1.1}$$

$$\alpha_{ij} \le \beta_j \quad \forall i,j \tag{C1.2}$$

$$\sum_{i=1}^{U}\alpha_{ij}\cdot w_{ij} = 1 \quad \forall\, j \tag{C1.3}$$

$$R_{ij} = w_{ij}\cdot K \cdot \varepsilon_{ij} \tag{C1.4}$$

$$\mathrm{THR}_{ij} = R_{ij}\left(1 - \mathrm{BLER}_{ij}\right) \tag{C1.5}$$

$$\overline{\mathrm{THR}} \ge Th_{avg} \tag{C1.6}$$

where Th_{avg} is the average throughput threshold.

B. Guaranteed Throughput per UAM User

Note that $\mathcal{OP}1$ targets an average throughput level. As a consequence, single users may experience a very low throughput or stay disconnected as long as the average throughput condition is fulfilled. Since C2 communications in UAM may require high levels of reliability, here we provide an alternative formulation $\mathcal{OP}2$ of the optimization problem targeting a minimum throughput per user.

$$\mathcal{OP}2\text{:} \quad min\{N_{eBS}\} \tag{12}$$

$$s.t. \quad (C1.1), (C1.2), (C1.3), (C1.4), (C1.5)$$

$$\mathrm{THR}_{ij} \ge Th_{min} \quad \forall\; i,j \tag{C2.1}$$

where Th_{min} is the minimum throughput threshold. This enforces that all the UAM users experience a minimum throughput level, and consequently no UAM users can remain unconnected.

TABLE I
SIMULATION PARAMETERS

Parameter	Description	Value
L	Scenario length	20 km
U	Number of UAM users	250
$BLER$	Block error rate	10^{-1}, 10^{-3}
P_{tx}	BS Tx power	$(30, 40, 50)$ dBm
Th_{avg}	Average throughput per UAM user threshold	$[5-30]$ Mbps
Th_{min}	Minimum throughput per UAM user threshold	$[0.1-5]$ Mbps
K	Number of RBs per BS	100
h_{UAM}	UAM altitude	$[150-200]$ m
h_{BS}	BS altitude	$[30-40]$ m
F_c	Carrier frequency	2 GHz
Bw	Bandwidth	20 MHz
K	Rice factor	5 dB
N_0	Noise spectral density	-174 dB/Hz

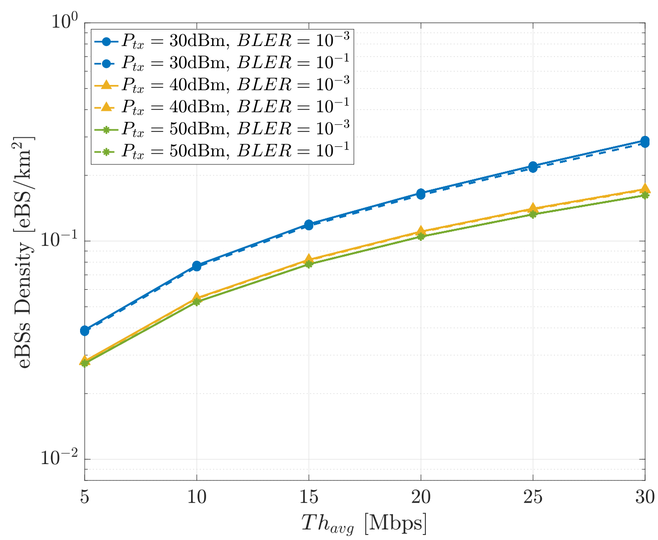

Fig. 2. Simulation results with the average throughput per UAM user constraint for different values of BLER and P_{tx}.

IV. SIMULATION RESULTS

The previously defined optimization problems for the UAM users scenario have been analyzed by implementing an exhaustive search algorithm and evaluated through a Monte Carlo approach across 10000 snapshots. The parameters adopted for the simulations are listed in Table I.

We assume the full buffered traffic model for the UAM users. The outcome of each simulation is thus the minimum number of eBSs over the simulated area able to fulfill the two performance requirements, Th_{avg} and Th_{min} where both are intended as downlink performance indicators. A LOS channel is assumed for each link between UAM users and eBSs [16], while the UAM user-eBS association is regulated through the maximum SNR.

In Fig. 2 we evaluate the density of eBSs vs the average throughput thresholds for different eBS transmitted powers (P_{tx}) and BLER values, considering $U = 250$ UAM users. Results show that the increase in the average throughput threshold corresponds to a higher demand for eBSs. For

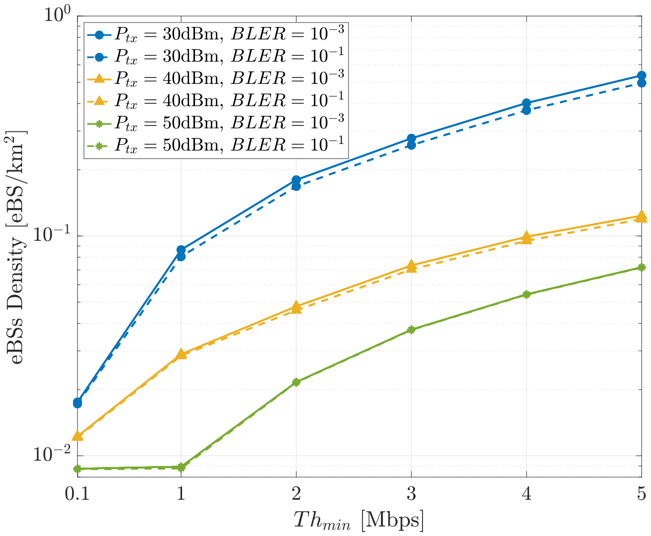

Fig. 3. Simulation results with the minimum throughput per UAM user constraint for different values of BLER and P_{tx}.

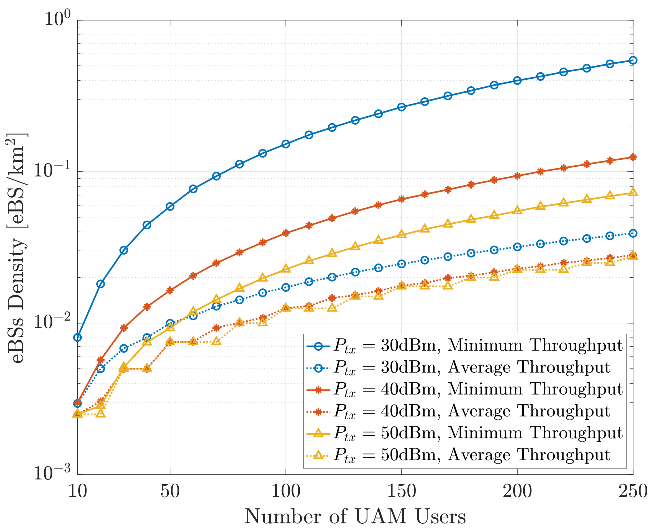

Fig. 4. Simulation results comparison between average and minimum throughput conditions for different values of UAM users and P_{tx}.

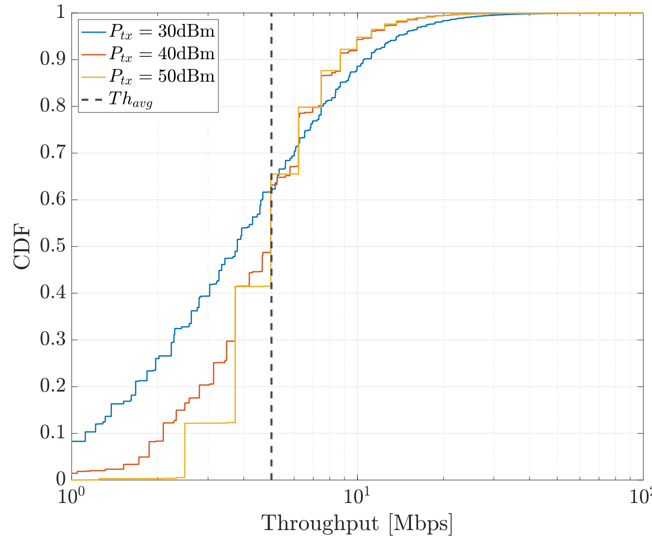

Fig. 5. Cumulative distribution functions of UAM user throughput for different values of P_{tx} in average throughput condition.

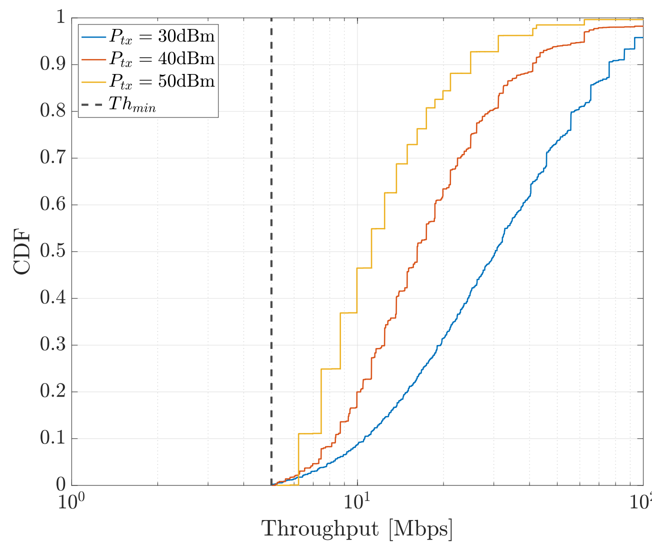

Fig. 6. Cumulative distribution functions of UAM user throughput for different values of P_{tx} in minimum throughput condition.

an increasing Th_{avg}, the eBS density increases linearly for higher P_{tx} values, i.e., $P_{tx} = \{40, 50\}$, while it grows more rapidly for low P_{tx} values ($P_{tx} = 30\,\text{dBm}$). Indeed, P_{tx} plays a critical role. Values like 40dBm and 50dBm result in better channel conditions between UAM users and eBSs and consequently in the utilization of higher MCSs. Instead, for 30dBm the low experienced SNR corresponds to the selection of low data rate MCSs which cannot guarantee high performance. This corresponds to a higher demand for eBSs to fulfill the performance requirements. This effect is also pointed out from the BLER. High P_{tx} values reflect the high quality links between UAM users and eBSs with almost equal results for different BLER values. Conversely, low P_{tx} highlights the higher demand for eBS to guarantee high quality links with low errors.

Similar results outcome by enforcing a Th_{min} throughput condition in the network design, as reported in Fig. 3. However, it can be noticed that for low P_{tx} values the increase in eBSs density is drastically higher compared to T_{avg} throughput condition. This arises from the requirement to guarantee a minimum performance level for all UAM users. In scenarios where the transmit power P_{tx} is low, this necessitates the addition of extra eBSs to ensure coverage for all users. Instead, higher values of P_{tx} such as 50dBm result in lower eBS demand, with an implication for network operators in terms of costs, since Th_{min} values up to 1Mbps can be guaranteed with the same amount of eBSs thus without cost variation.

Furthermore, in this scenario, the BLER has a more significant impact on the demand for eBSs. Specifically, reducing the BLER from 10^{-1} to 10^{-3} leads to an approximate 10% increase in the eBSs density for P_{tx} = 30dBm, compared to an approximate 4% difference when enforcing the average throughput requirement. Fig. 2 and Fig. 3 highlight that while low performance requirements imply lower costs to enhance the network, high requirements have an impact on costs but enable more throughput-demanding services.

The eBSs densities for the average and minimum throughput conditions have been compared in Fig. 4 varying the number of UAM users for $P_{tx} = \{30, 40, 50\}$dBm, BLER $= 10^{-3}$ and throughput thresholds $Th_{avg} = Th_{min} = 5\,\text{Mbps}$. The disparity among eBS demand is fairly consistent for $P_{tx} =$ 40dBm and $P_{tx} =$ 50dBm, with $P_{tx} = 50\,\text{dBm}$ exhibiting an eBS density in the Th_{min} condition up to 2.6 times higher than that of Th_{avg}, while for $P_{tx} = 40\,\text{dBm}$, the difference reaches up to 4.4. However, for $P_{tx} = 30\,\text{dBm}$ the minimum throughput condition shows a different order of magnitude, being up to 14 times greater than the Th_{avg} condition.

Fig. 5 and Fig. 6 exhibit the Cumulative Distribution Functions (CDFs) with the average and minimum throughput thresholds, respectively, for different P_{tx} values. Here we consider 250 UAM users, BLER $= 10^{-3}$, and throughput thresholds $Th_{avg} = Th_{min} =$ 5Mbps reported with the vertical dashed lines. CDFs for the average throughput condition highlight that high P_{tx} values not only reduce the number of eBSs but also increase the UAM user experienced throughput. In fact, despite the average throughput requirement is satisfied, a significant number of UAM users experience a throughput below the threshold for $P_{tx} =$ 30dBm. While for $P_{tx} =$ 30dBm approximately 60% of UAM users present a throughput below the Th_{avg} threshold, this quantity is reduced to nearly 40% for $P_{tx} =$ 50dBm. An analogous effect is shown in Fig. 6 for the different P_{tx} values. Here, all UAM users experience a throughput above the Th_{min} threshold as per the design requirement and the UAM user throughput is higher for higher P_{tx} values.

V. Conclusion

Sustaining the rising interest in UAM motivated by industrial and research communities, the purpose of this letter is to provide a novel strategy for the integration of commercial mobile networks to satisfy the connectivity necessity of UAM vehicles. The integration of mobile networks stands out as the easiest and fastest solution to provide seamless and reliable connectivity for critical transport services, requiring only an improvement strategy for the terrestrial BSs to guarantee connectivity toward higher altitudes. This strategy has been investigated defining two optimization problems, providing insights on the impact of different design parameters on the minimum number of enhanced BSs needed to guarantee average and minimum throughput requirements for UAM users. Further directions involve optimized handover procedure, which may be impacted by different mobility patterns of UAM compared to other vehicular technologies, and the development of integration strategies exploiting NTN to provide enhanced and reliable coverage while offering efficient radio resource utilization and cost optimization.

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