Capacity Limits of LoRaWAN Technology for Smart Metering Applications

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***Abstract*— In this paper we analyze and discuss the capacity limits of LoRaWAN technology for smart metering applications using a real LoRa network simulator including uplink and downlink. First, we present the modeling of the network simulator. Then results for a critical case in the center of Paris show that, with meters all located deep indoor, the capacity of a network covering a dense urban area of 17 km^2 with 19 gateways distant from 1 km, considering only UL emissions, could be enough for an average targeted QoS of 98 % as soon as there is no other traffic in the considered band. But we also show that we could very quickly reach the limits when considering that meters will not be the only LoRa devices communicating and above all considering the important impact of DL emissions on capacity.**

Keywords—LPWAN; LoRa; smart metering; capacity.

I. INTRODUCTION

So-called Low Power Wide Area (LPWA) networks are one of the branches of Internet of Things (IoT) networks tree, designed to fulfill the need for long range, low power and low cost connectivity, when traditional wireless network technologies until now are not the best appropriate networks for low mobility devices emitting short messages once in a while.

Today different IoT connectivity technologies are or will soon co-exist. They are technologies leaning on Long Term Evolution (LTE) or Global System for Mobile Communications (GSM) heritage like Narrowband IoT (NB-IoT) or Extended Coverage GSM (EC-GSM) (Release 13). NB-IoT is a new radio added to the LTE platform optimized for the low end market when EC-GSM corresponds to Enhanced General packet Radio Service (EGPRS) enhancements which, in combination with Power Save Mode (PSM), makes GSM/ EDGE markets prepared for IoT. And they are technologies operating on license-free industrial, scientific and medical (ISM) radio bands. Among these technologies two are considered as leaders. The first one is the ultra-narrowband Sigfox technology [1]. The second one is the LoRaWAN technology, based on LoRa spread spectrum technique, which will be described in details in the next section.

All these technologies and some others present on the market are deemed to address a large panel of applications, from the smart city applications (smart lightning, smart parking, smart waste collection…) to e-health or smart home applications. One of the promising applications of such long range, low power technologies is the smart metering. In the next few years remote meter reading, whether for electricity, gas or water meters, will become automatic and intelligent everywhere. Intelligent consumption monitoring in particular will be of interest for both the user and the company. This kind of application, when thousands of meters per km^2 will have to be connected, with an important part sometimes localized deep indoor, raised de facto the question of capacity. Are we able to ensure for smart metering a 95 or 98 % of quality of service (QoS) in dense urban cities with LPWA technologies? In this paper we chose to focus on LoRaWAN technology and we aim to provide a comprehensive analysis of the limits of LoRaWAN for smart metering applications by using simulation. To the knowledge of the authors, only a few papers have been published analyzing LoRaWAN technology [3] [4] [5] [6] [7]. Only [5] and [6] brought up limits in the analysis and discussion. In [5] they carried out a performance analysis of a LoRa network in terms of maximum throughput and probability of successful transmission for different use cases but not simulating a whole network. They limited the study to one gateway and N nodes. In [6] a performance and a capacity studies were carried out for different use cases but still limiting the studies to one cell, N nodes and uplink transmissions. In this paper, for the first time, we propose a capacity study for a smart metering use case simulating a real LoRa network including both (up and down) link transmissions. In the next section we present a short technical overview of LoRaWAN technology. Section III introduces the LoRa network simulation model we built. Section IV aims to provide a comprehensive capacity study on a critical use case. Section V is discussing the impact of DL emissions on the capacity. And finally section VI concludes the article.

II. LORAWAN TECHNOLOGY

LoRa® designates the wireless modulation utilized to create the long range communication link. It is a proprietary radio technology owned by Semtech [2]. LoRaWAN™ defines the communication protocol and system architecture for the network. The LoRaWAN™ protocol specifies the PHY and MAC layers and is developed by the LoRa Alliance [8].

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A. LoRa modulation

LoRa spread spectrum modulation scheme is derived from Chirp Spread Spectrum modulation (CSS) which defines variable data rates by implementing 6 orthogonal spreading factors (SF) (from SF=7 to SF=12) within a fixed channel bandwidth. Signals with different SFs can therefore transmit at the same time on the same channel. The use of high bandwidth-time (BT) product and broadband chirp pulses makes the LoRa signals very resistant, first, to both in-band and out-of-band interference mechanisms and, second, to shadowing and fast fading phenomena. Consequently the technology is particularly adapted for use in urban environments. Finally the used modulation scheme allows high link budgets, enabling long range communications and reduced transmit powers.

B. LoRaWAN protocol

LoRaWAN networks use a star topology in which gateways forward messages between nodes and applications in the backend. Nodes use a single-hop wireless connection to one or more gateways. Communication between nodes and gateways is spread out on different frequency channels (433 or 780/868/915 MHz) depending on the country frequency regulations and data rates. Selection of the data rate is a trade-off between communication range and message duration. Rules for uplink communication are as follows. Devices may transmit on any channel available at any time (pure aloha). They change their transmission frequency in a pseudo-random fashion for every transmission and they shall be compliant with the maximum transmit duty cycle related to the used sub band.

C. Device classes

LoRaWAN specifies 3 classes of devices [8], depending on how the downlink is managed (tradeoff between downlink latency and battery lifetime). Class A devices are in received mode only after having transmitted (for optimized power consumption). They open 2 reception windows after each emission. For class B devices, gateways broadcast a synchronized beacon providing a timing reference. Based on this timing, the end-devices open periodically reception windows. Network may send downlink packets to class B devices at any receive slot. Finally class C devices are in continuously listening mode (devices that are mainly powered). It is important to specify that the three classes are defined in the specifications but it is only mandatory to implement class A in the end-devices.

III. MODELING OF A LORA NETWORK BEHAVIOR

MATLAB was used in order to simulate a realistic LoRa network, considering both uplink (UL) and downlink (DL) emissions.

A. Network Structure

We modelled a hexagonal distribution of LoRa gateways with an omnidirectional layout (Figure 1). Gateways and node heights are configurable. Number of gateways and number of nodes per gateway are also configurable, the nodes being uniformly distributed in the cell coverage. One can choose the inter-site distance, depending on the simulated environment.

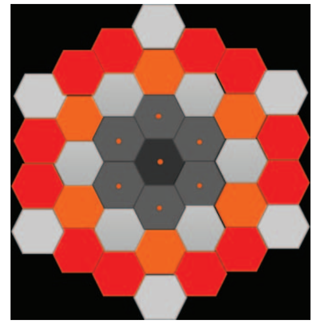

Figure 1 Hexagonal distribution of LoRa gateways with an omnidirectional cell layout

Antenna sensitivities for each SF are given in Table I.

Table I LORA GATEWAY ANTENNA SENSITIVITIES PER SF

SF	LoRa gateway antenna sensitivity (in dBm)
7	- 124
8	- 127
9	- 130
10	- 133
11	- 135
12	- 137

B. Network Operation

Node emissions are following a pure aloha protocol, each node emitting one frame randomly during a fixed time slot. All the nodes are emitting on one unique channel. A 1 % duty cycle is respected, which means, for example, that a node emitting one frame per hour will have to wait a certain time between two frames, depending on the frame time-on-air duration. No retransmissions are considered. Macro-diversity is modelled, i.e. one frame can be received by several gateways.

1) Adaptive Data Rate algorithm

An algorithm of Adaptive Data Rate (ADR) is modelled, which determine, considering the Signal to Interference and Noise Ratio (SINR), a distribution of SFs among nodes.
For each node, the last 10 Signal-to-Noise Ratio (SNR) values are taken into account to calculate the median SNR and then the SF distribution is refined by taking into account the last 10 SINR values (see Table II for threshold values). Median SNR and SINR values are taken referring to the gateway receiving the frame with the highest Received Signal strength Indication (RSSI). A margin is taken into account (10 or 12 dB).

Table II ADR ALGORITHM THRESHOLDS FOR EACH SF

SF	**Min SINR required to demodulate (dB)**	**ADR threshold with 10 dB margin**
7	-7	3
8	-9	1
9	-11.5	-1.5
10	-14	-4

11	-16.5	-6.5
12	-19	

2) Collision rules

On the same channel two LoRa frames can collide in time (see Figure 2). Both intra-SF and inter-SF collisions are modelled.

- For intra-SF collisions: if two LoRa frames are received simultaneously with the same SF on the same frequency, the frame with the highest power will be decoded if it is at least 6 dB higher than the other LoRa frame.
- For inter-SF collisions: if two LoRa frames are received simultaneously on the same frequency but with different SF (SFn to SFm) : n≠m , packet is demodulated if power difference is > SINR(n) (see Table II)

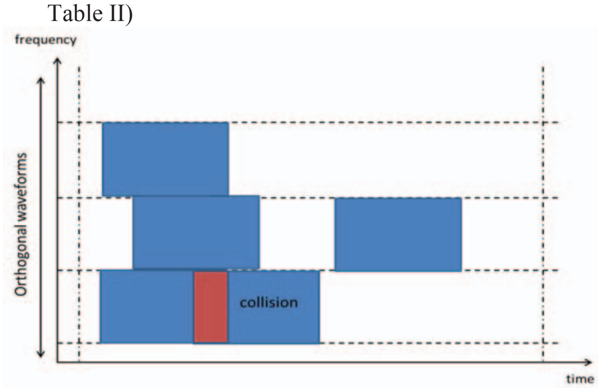

Figure 2 Illustration of two LoRa frames collision

3) DL emissions

Only devices of class A are considered in our study. And DL emissions can happen only during the first opened window (RX1 in Figure 3), 1s after the end of the UL emission, on the same channel and with the exact same SF as the UL emission.

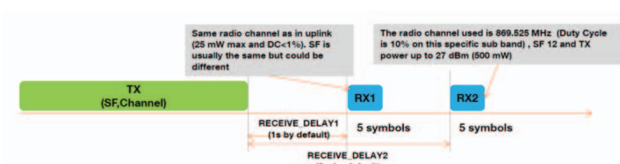

Figure 3 Illustration of used window for DL emissions

In the network simulator impossibility of a gateway to receive messages when emitting DL is up to now modeled in the algorithm. In the future we intend to model also interferences between gateways.

C. Propagation Model

For propagation, we use the Okumura-Hata model for urban areas and adaptations for suburban and rural areas as recommended by ETSI for GSM 900MHz [9]. We consider typical indoor penetration losses (see TABLE III) and an additional 6 dB loss for deep indoor environments [10] [11].

TABLE III TYPICAL CONSIDERED INDOOR LOSSES

Area type	typical indoor penetration loss (dB)
Urban	15
Suburban	12
rural	10

D. Shadowing and Fast fading modelisation

Shadowing represents the fact that the received signal power fluctuates due to objects obstructing the propagation path between transmitter and receiver when Rayleigh fading is the variation of the signal power due to multipath propagation. In the LoRa network simulator Shadowing effect was modelled as a log-normal distribution with a 12 dB standard deviation outdoor and 13.4 dB standard deviation for indoor applications (supposing 12 dB for the standard deviation outdoor and 6 dB indoor). Fast fading effect was modelled by a Rayleigh distribution.

IV. CAPACITY STUDY FOR ELECTRICITY SMART METERING IN THE CENTER OF PARIS

We decided to conduct a capacity study for the electricity meter reading use case in the center of Paris (France) as if one may reach the capacity limits of LoRaWAN it would be in such a big city where the electricity meter density can be roughly evaluated to 18 000 meters/km^2 (which corresponds in fact to the number of households + the number of companies or offices divided by the total area: 1 358 884 households in Paris in 2013 and 551 952 companies or offices for an area of 105 km^2 [12]). The considered network works in the LoRa European band 863-870 MHz. Our simulations were conducted at the 868 MHz channel frequency. Table IV summarizes the network configuration and input parameters.

Table IV LoRa NETWORK CONFIGURATION AND MAIN INPUT PARAMETERS

Channel frequency	868 MHz
Bandwidth	125 kHz
Number of gateways	19
Gateway noise figure	3 dB
Gateway antenna gain	5 dBi
Gateway height	30 m
Inter-site distance	1 km
End-device height	1.5 m
End-device antenna gain	0 dBi / -5 dBi
Targeted C/N after despreading	6 dB
Input power	14 dBm
ADR algorithm margin	10 dB

The considered time period was 24h. 19 gateways with an inter-site distance of 1 km allow covering an area of around 17 km^2, which corresponds to the surface occupied by the height first Paris districts. Each device emitted one frame per hour. The frame size is 11 bytes (4 bytes of payload for the consumption index + 7 bytes Zigbee Cluster Library application protocol overhead [13]). Times on air for each SF were calculated using Semtech LoRaWAN specifications [8] and are summarized in Table V. In order to consider the worst case devices were supposed to be located deep indoor.

For each node, each emission time slot (1h) and each gateway there were 20 random selections of Shadowing and Rayleigh fading effects. 20 was enough to obtain a good estimation of the average quality of service (QoS) in terms of total number of demodulated frames compared to total number of emitted frames over the considered time period (24h).

Table V TIME ON AIR FOR EACH SF FOR A PAYLOAD FRAME OF 11 BYTES

SF	Time on air (s)
12	1.48
11	0.823
10	0.371
9	0.206
8	0.113
7	0.0617

Two simulations were performed at 868 MHz frequency. One simulation considering end-devices with 0 dBi antenna gain and 1500 devices per gateway and another considering end-devices with -5 dBi antenna gain, which corresponds more to the reality of LoRa devices on the market, and 1000 devices per gateway.

SF distributions for both simulations are given in Table VI and Figure **4** illustrates the distribution for the simulation with -5 dBi gain end-devices.

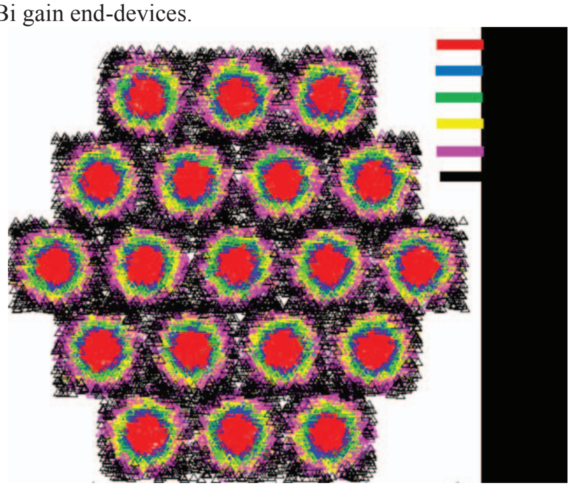

Figure 4 SF distribution for -5 dBi gain end-devices

Table VI SF DISTRIBUTIONS FOR BOTH SIMULATIONS

SF	0 dBi gain end-devices/1500 nodes per gateway	-5 dBi gain end-devices/1000 nodes per gateway
SF 7	50 %	29.4 %
SF 8	14.7 %	9.9 %
SF 9	15.1 %	12.1 %
SF 10	11.7 %	14 %
SF 11	6.1 %	13.6 %
SF 12	2.3 %	21 %

As the ADR algorithm is designed, the SF distribution tends to be organized in circles, nodes close to a gateway emitting in SF 7 and the furthest nodes emitting in SF 12 (as observed in Figure 4).

Results are presented in terms of average QoS and distribution of Packet Error Rate (PER). The QoS value is an average value over the considered period and corresponds to the total number of demodulated frames compared to the total number of emitted frames. The PER over the considered time period (24h) is evaluated per node. It corresponds to the percentage of lost frames over 24h.

Table VII RESULTS IN TERMS OF QOS AND PER FOR ELECTRICITY SMART METERING SIMULATIONS IN PARIS FOR 0 DBI AND -5 DBI GAIN END-DEVICES

End-devices gain	0 dBi	-5 dBi
Number of nodes per gateway	1500	1000
Average QoS	98.5 %	95.8 %
% of nodes with a PER<5 %	96.6 %	68 %
% of nodes with a PER between 5% and 25%	3.4 %	32 %

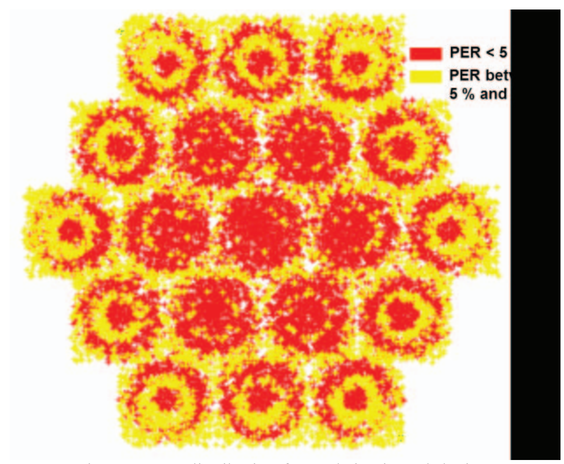

Figure 5 PER distribution for -5 dBi gain end-devices

It is interesting to look at both performance indicators, the average QoS over 24 h and the PER distribution. The average QoS obtained as well as the PER distribution for the simulation with 0 dBi gain end-devices indicate quite good performances. On one channel, for 1500 deep-indoor nodes per km^2 emitting one frame per hour, we can conclude that an average QoS over 24h of 98.5 % can be reached. Considering that the electricity meter density was evaluated to 18 000 meters per km^2, 12 channels would be at least needed to reach an average QoS superior to 98 %. But let's remind that, for the scope of the study, we have made the hypothesis that our electrical smart metering services based on Lora are the only users of the considered band. In the case of a shared or license free band, coexistence with other users will need to be taken into account.

In the case of end-devices with an antenna gain of -5 dBi, simulation results show a clear performance degradation. The average QoS of 95.8 % is still acceptable but we can also see in Table VII that only 68 % of the meters have a PER lower than 5 %. Figure 5 shows that meters having a PER above 5 %

are those using the highest spreading factor (SF12) , located at the cell border, because they are more sensitive to collisions, but also some meters with small SFs located in the external cells. This can be explained by the impact of macro-diversity we have not discussed yet. For -5 dBi gain end-devices simulation frames were received and demodulated by an average of 3 gateways. However, meters located in the external cells are unable to take benefit of such a diversity which can explain the obtained PER distribution.

V. IMPACT ON CAPACITY OF DL EMISSIONS

When raising the question of capacity limits of LPWA networks DL transmissions are often said to be the ones that will really limit the capacity of such networks and LoRa is not an exception.

A. One cell and N devices

In order to analyze the impact on capacity of DL emissions, a network with one cell and N devices was simulated, performing the exact same simulation with and without DL emissions. The input parameters and network configuration were exactly the same as for the electricity smart metering capacity study. We considered end-devices with a 0 dBi antenna gain. For DL emissions we considered one DL emission per device and per time slot (1h) in order to illustrate clearly the DL impact on capacity, even if the gateway duty cycle is not respected. Then we considered DL emissions for 25 % of nodes per time slot. The DL payload frame size was set at 4 bytes (acknowledgement message). We conducted simulations for different number of devices (1000 and 2000). Results in terms of QoS and PER distribution are summarized in Table VIII and Table IX.

Table VIII RESULTS IN TERMS OF QOS AND PER FOR 1000 NODES SIMULATION

	N=1000		
	with DL for each UL	with DL for 25 % of nodes	UL only
Average QoS	92.25 %	96.8 %	98 %
% of nodes with a PER<10 %	76 %	96 %	98.8 %
% of nodes with a PER between 10% and 50%	23.9 %	4 %	1.2 %
% of nodes with a PER>50 %	0.1 %	0 %	0 %

Table IX RESULTS IN TERMS OF QOS AND PER FOR 2000 NODES SIMULATION

	N=2000		
	with DL for each UL	with DL for 25 % of nodes	UL only
Average QoS	84.1 %	93 %	96.3 %
% of nodes with a PER<10 %	28.6 %	75.5 %	93.1 %
% of nodes with a PER between 10% and 50%	70 %	24.5 %	6.9 %
% of nodes with a PER>50 %	1.4 %	0 %	0 %

For 1000 devices the average QoS with 1 DL frame emitted per UL frame and per device was found to be 92.25 % and 96.8 % with DL frames emitted for 25 % of nodes. The average QoS without DL messages was found to be 98 %.

For 2000 devices the average QoS with 1 DL frame emitted per UL frame and per device was found to be 84.1 %. The average QoS without DL messages was found to be 96.3 %.

The more devices are considered highest is the impact on capacity of DL emissions. With 1000 devices distributed within a radius of 600 m around the gateway the QoS is already decreasing of almost 6 % when adding one DL emission for each UL frame and of 1.2 % when adding DL emissions for 25 % of nodes. It is even decreasing of respectively 12 % and 3.3 % with 2000 devices. Other numbers that quite speak for themselves are the percentages of nodes with a PER<10%. With 1000 devices, the percentage of nodes with a PER<10% drops from 99 % to 76 % without and with DL emissions. In the same situation with 2000 devices it drops from 93 % to 29 % (see Figure 6). For a use case such as smart metering, electricity or gas providers could barely imagine to satisfy themselves with 70 % of the meters having a PER superior to 10 % .

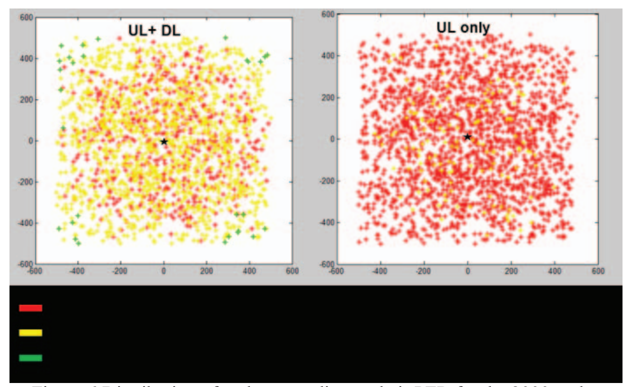

Figure 6 Distribution of nodes according to their PER for the 2000 nodes simulation

B. Impact of DL illustrated for electricity smart metering in Paris

We reproduced the exact same simulation as the -5 dBi gain end-devices simulation from section IV adding DL emissions for one third of devices. Results in terms of QoS and PER distribution are summarized in Table X. We can observe, when adding DL emissions for 33 % of devices, a decrease of the average QoS of 1.5 %. The degraded performances are particularly clear on the PER distribution: less nodes with a good PER (less than 5 %). One more time meters located in the external cells are not taking benefit from the macro-diversity and are the ones the most impacted by DL as illustrated in Figure 7. Our results have shown that DL emissions are very expensive in terms of capacity, as a gateway cannot receive messages when emitting. Some use cases such as smart metering may not bear this kind of price.

Table X RESULTS IN TERMS OF QOS AND PER FOR ELECTRICITY SMART METERING SIMULATIONS IN PARIS FOR -5 DBI GAIN END-DEVICES WITH AND WITHOUT DL EMISSIONS

	with DL for 33 % of nodes	UL only
Average QoS	94.2 %	95.8 %
% of nodes with a PER<5 %	54.7 %	68 %
% of nodes with a PER between 5% and 25%	44.6 %	32 %
% of nodes with a PER>25 %	0.7 %	0 %

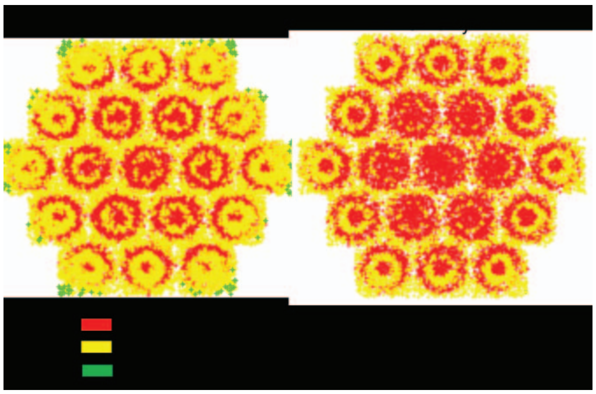

Figure 7 Distribution of nodes according to their PER for the -5 dBi gain end-devices simulation with and without DL emissions

VI. CONCLUSION

In the paper we analyzed the capacity limits of LoRaWAN technology for smart metering applications using a real Lora network simulator including both uplink and downlink. The presented results have shown that, for a critical case like the center of Paris, with meters all located deep indoor, the capacity of a network covering an area of 17 km^2 with 19 gateways distant from 1 km, considering only UL emissions could be enough for an average targeted QoS of 98 % as soon as there is no other traffic in the considered band. But we could very quickly reach the limits when considering that meters will not be the only LoRa devices communicating and above all considering the important impact of DL emissions on capacity. We could think to different solutions to overcome these limits: message repetitions, not considered in the work presented here, antenna densification or use of nanogateways. The perspectives of use of such a LoRa network simulator are extended, whether to analyze the impact of macro-diversity or analyze the impact of antenna densification.

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