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LPWAN in the Context of 5G: Capability of LoRaWAN to Contribute to mMTC

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***Abstract*—A considerable amount of massive Internet-of-Things (IoT) applications that intend to connect a wide range of low-complexity IoT devices are pushing the digital revolution and making an interconnected daily life a reality. However, especially in the connectivity sector, a holistic technical solution seems unlikely. In this regard, future 5G networks aim at unified connectivity with an ambitious node density of 1,000,000 devices per square kilometer in the area of 5G *massive Machine Type Communication* (mMTC). In this regard, this work aims at analyzing the capability of LoRaWAN as a complementary solution in unlicensed frequency bands to contribute to given 5G requirements for specific mMTC applications in large-scale deployments. The performance evaluation indicates limited downlink capabilities due to regulatory requirements defined for the 868 MHz short-range device (SRD) frequency band, but at the same time depicts that the uplink can cover approximately 10% of the 5G mMTC connection density objective. Hence, LoRaWAN indicates a high potential to contribute to 5G mMTC application areas, especially for non-time-critical sensor use cases without or even with low Quality of Service (QoS) requirements.**

I. Introduction

Internet of Things (IoT) applications are enjoying increasing popularity and are being discussed in the context of a wide variety of private, industrial and commercial domains. As illustrated in Fig. 1, among others, application areas vary from sensor networks for Smart City Infrastructure, Smart Home or Building Management, Smart Environment, private and industrial transportation, as well as energy supply. Various technologies, specially tailored for these IoT areas, are not only discussed in research but increasingly implemented in real deployments. Concerning this, the future 5th mobile radio generation (5G) addresses the massive IoT area in particular and promises a very high subscriber density for the most diverse environmental scenarios. For this purpose, the ITU-R defines correlating requirements for massive IoT applications in the context of the *massive Machine Type Communication* (mMTC) [1]). Currently, two major technology groups providing functionalities to solve defined 5G mMTC requirements are discussed [2]. First, cellular IoT (cIoT) technologies standardized by 3GPP in licensed frequency bands can provide a nearby stable performance, due to full network

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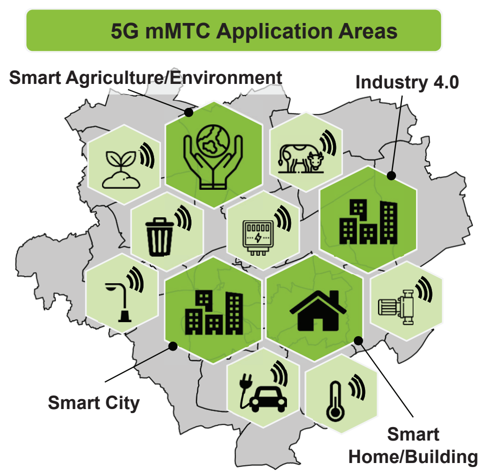

Fig. 1: 5G massive Machine Type Communication (mMTC) application areas and exemplary use cases

control of the responsible operator, exclusive utilization of underlying frequency spectrum, as well as limitable access based on contract arrangements. Moreover, IoT application users do not require any expertise to plan or operate the mobile radio network but are constrained by reasonable cost dimensioning. However, initial analysis of the LTE IoT extensions Narrowband IoT (NB-IoT), as well as enhanced Machine Type Communications (eMTC) show that the maximum scalability of these cIoT systems is limited for typical network configurations and cannot fully meet the 5G mMTC targets [3]. Of course, scalability can easily be increased by additional resources, but the frequency spectrum is limited and accordingly very costly. Alternatively or in addition to licensed technologies, Non-3GPP Low Power Wide Area Networks (LPWAN), operated in unlicensed frequency bands enable a simple, cost-effective network operation independent of commercial network operators. However, IoT service providers are in charge of network planning and operation. Due to a high degree of interaction with an unknown number of operators and subscribers in the unlicensed bands, the performance of LPWAN technologies can only be controlled to a limited extent. Besides, regulated congestion control and avoidance techniques can lead to increasing interference and bottlenecks, which cause lower available data rates and high latencies. In this context, this paper presents a model for determining the capacity limits of LPWAN networks with a focus on the well-known and widely used LoRaWAN technology. First, related 5G mMTC challenges are discussed in Section II. Section III introduces underlying related work that has been discussed and considered while developing methods for our presented LoRaWAN performance analysis (Section V). The evaluation of the capability of LoRaWAN to contribute to 5G mMTC challenges is given in Section VI. Concluding, major findings are summarized including an outlook on further work.

II. Challenges of 5G massive Machine Type Communication

Many communication technologies already exist today that meet the requirements of current IoT systems and today's applications. However, the introduction of the next 5G mobile radio generation specifically addresses machine-to-machine (M2M) applications and paves the way to fully digital life to interconnect a massive amount of various devices. According to this development, ITU and 3GPP define extended MTC requirement profiles, that can be distinguished in two main categories – critical MTC and massive MTC. Critical MTC address applications that rely on very high availability, low latency and ultra reliability. This application area, also known as *Ultra Reliable Low Latency Communication* (URLLC), extensively includes applications for critical infrastructures such as Vehicle-to-Everything (V2X) and Smart Grid applications in the high voltage domain. In contrast, this paper is focusing on challenges defined for mMTC, which refer to application areas that typically rely on a considerable number of devices in small areas. Underlying applications usually do not have high performance requirements. To cover and quantify all mMTC challenges, ITU-R and 3GPP standardization groups identified 5G mMTC Key Performance Indicators (KPI), that are listed in Table I.

TABLE I: 5G mMTC Key Performance Indicators (KPI)

KPI	**Value**
Conn. density	1.000.000 devices per km^2
Latency	≤ 10 *seconds*
Coverage	Maximum Coupling Loss of up to 164 dB
UE battery life	+10 years

First off, massive IoT sensors should consume very low amounts of energy to sustain a battery lifetime of at least 10 years [4] [5]. 15 years would be desirable. The desired communication range, respectively coverage, is expressed by the Maximum Coupling Loss (MCL) parameter of at least 164 dB. Modeling and results presented in this contribution are focused on the connection density KPI of one million devices per square kilometer [1] [5], but at the same time investigate how the mMTC latency requirement of worse than 10 s [4] [5] is affecting the maximum scalability. To perform the connection density evaluation, a traffic model needs to be agreed on. The model which was proposed to model future massive MTC traffic patterns in [6] contains two type of message transfer configuration that both rely on a Poisson arrival process for non-full buffer systems for a message size of 32 bytes, but differ in the frequency of one message per day per device up to one message every two hours per device. To cover the worse case, in the following this paper is focusing on the transmission interval of 2 hours.

III. Related Work

Several evaluations about performance and scalability of LoRaWAN networks have been discussed in ongoing research. Authors in [7] focus on the performance analysis of limited LoRaWAN downlink characteristics. In contrast, an analytical model for uplink capabilities is examined in [8]. Based on the consideration of the system throughput, the maximum number of subscribers for different traffic levels is derived. Based on this maximum number of subscribers, the point of maximum throughput for the Aloha channel access was determined. Another analytical model considering the Aloha channel access mechanism illustrates a weak performance for high traffic classes [9]. However, limited but still suitable scalability of multiple hundreds of devices per network cell has been indicated. Authors in [10] have demonstrated an optimization of reliability through the deployment of additional gateways and dynamic parameter variations by means of simulation. A further, extended analysis of reliability distinguishes between two traffic classes and constitute that acknowledged traffic limits maximum scalability significantly, due to weak downlink capabilities [11]. In contrast to presented ongoing research activities, the performance analysis approach depicted in this work is discussed with close reference to future 5G mMTC requirements. Besides, an essential contribution is the consideration of the 5G mMTC latency requirement and the evaluation of its impact on maximum scalability. In the following, the necessary basics of the LoRaWAN technology are introduced.

IV. LoRaWAN Fundamentals

LoRaWAN is a freely available Medium Access Protocol for IoT Applications defined by the LoRa Alliance. It is based on the LoRa Modulation technique specified by Semtech and mainly operated in the short-range device (SRD) band at around 868 MHz (Europe) and 915 MHz (US) respectively. LoRa uses a chirp spread spectrum (CSS) modulation scheme which uses signals with a linear increase (up-chirps) or decrease (down-chirps) of the frequency. It enables communication ranges of up to 11 km and good basement penetration depending on the deployment scenario [12] [13]. The spreading factor (SF) defines the duration of the chirps and therefore allows a trade-off between a more robust communication (higher SF) and a higher data rate (lower SF). Mandatory data rate classes use SF=7 to SF=12 with a channel bandwidth (BW) of 125 kHz and achieve data rates from 0.25 to 5.5 kbps which can be calculated using equation 1 distinguishing coding rates of 4/5 (CR=1) and 4/8 (CR=4).

$$R_b = SF \cdot \frac{\frac{4}{4+CR}}{\frac{2^{SF}}{BW}} [bps] \quad (1)$$

Due to regulatory duty cycle limitations of 1% for uplink channels described in section IV-A, the peak data rates are significantly decreased to an average throughput of 1.5 to 48 bps, as it is shown in Fig. 2.

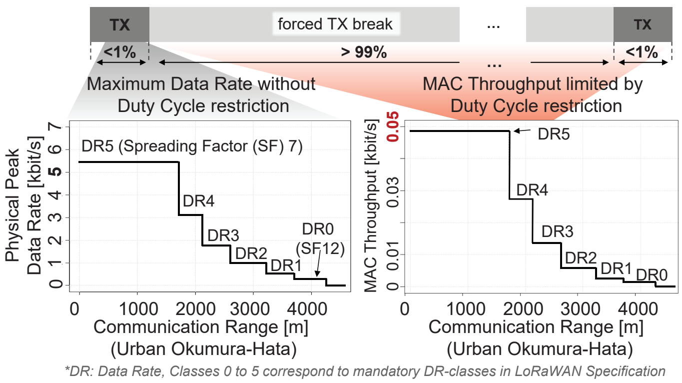

Fig. 2: Impact of regulatory duty cycle restrictions on LoRaWAN data rates

It can be seen that the throughput reduction is mainly caused by the inactivity time (time off) subsequent to the transmission time per packet (time on air), which is needed to comply with duty cycle limitations [8]. Three frequency channels at 868.1 MHz, 868.3 MHz and 868.5 MHz are mandatory, more resources can be used optionally. Channels are switched in a pseudo-random manner to reduce interference. LoRaWAN uses a pure Aloha channel access approach to limit system complexity. This mechanism is used for the analytical scalability model in Sec. V.

A. Regulatory Limitations

As LoRaWAN operates in unlicensed frequency bands, it must comply to regulatory frequency band conditions, which provide fair channel access of various participants. Regulations defined by the European Commission in cooperation with ETSI allow mitigation techniques like listen before talk (LBT) or detect and avoid (DAA) [14]; alternatively a duty cycle limit has to be met. Due to the simple Aloha channel access used by LoRaWAN, duty cycle limitations apply. As shown in Fig. 3, duty cycle limitations are applied per SRD subband.

Typical LoRaWAN channels are implemented within subbands which have a duty cycle restriction of 1%. However, a dedicated channel for downlink communication is used at 869.525 MHz which allows 10% duty cycle. Duty cycle limitations apply for the whole subband ,i.e. after a transmission the whole subband has to remain unused for a subsequent time off. This can be achieved either by enforcing the time off for a whole subband, or by treating each channel within a subband individually.

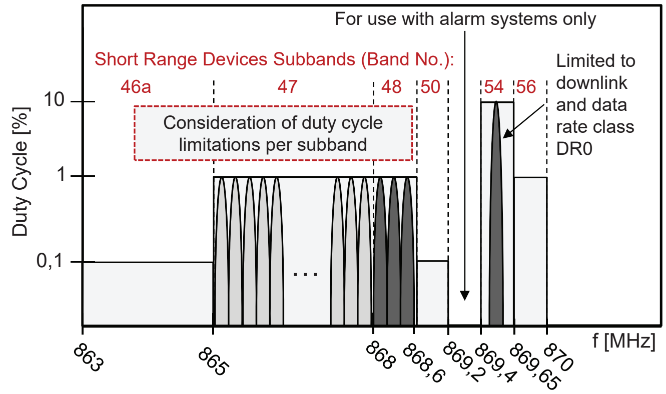

Fig. 3: European LoRaWAN channel frequencies in the ISM Band (EU863-870) [15] [16]

For example, using the three mandatory channels within subband 48 would result in a duty cycle of 0.33% per channel accordingly to 1% duty cycle limitation for the whole subband.

V. LoRaWAN Scalability Analysis

A. Analytic Modeling Approach

The performance evaluation itself is performed by two independent modeling approaches. First, an analytical model based on current state-of-the-art [8] is evolved to analyze the key performance indicators such as range, latency and data rate. Major enhancements are detailed latency evaluations even for large-scale scenarios, which improve scalability results utilizing the prediction of service qualities. In terms of downlink communication, the maximum capacity can easily be derived from the capabilities of a single LoRaWAN node, as it is not interfered by the uplink communication. The LoRaWAN gateway also has to comply to the duty cycle requirements described in section IV-A, which leads to minimal downlink capacity of LoRaWAN networks, as illustrated in Fig. 4. Class A LoRaWAN nodes make use of two consecutive receive windows following an uplink message. In the first receive window (RX1), opened one second after the uplink transmission a node can receive a downlink message on the same frequency channel that is used for the precedent uplink transmission. For the second receive window (RX2) two seconds after the uplink transmission, a dedicated channel at 869.525 MHz is used, which alllows a duty cycle of 10% but only uses data rate class DR0.

It is shown that the average downlink data rate of the whole LoRaWAN cell is approximately 31.16 bps. Thus, LoRaWAN is not suited for downlink heavy use cases such as update/upgrade functions for security-related applications. In the uplink direction, multiple nodes attempt to access the channel using a pure ALOHA approach. Due to the spreading factors being orthogonal to one another, every data rate class is modeled as an independent ALOHA channel access scheme. The throughput of every data rate class depending on the number of nodes can subsequently be determined using the well known ALOHA

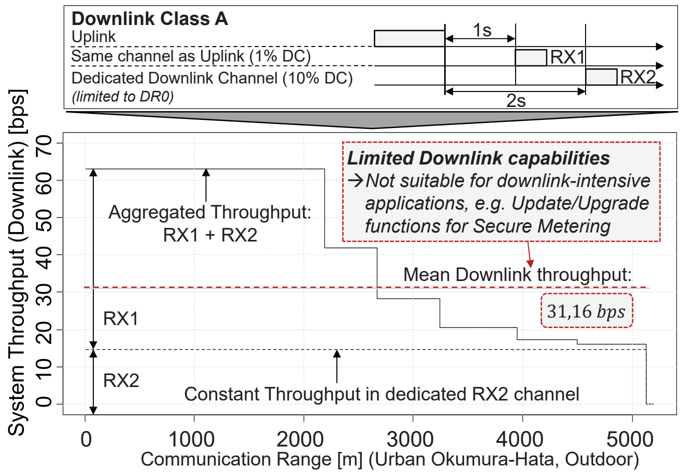

Fig. 4: System Throughput (Downlink) utilizing maximum duty cycle capabilities

throughput equation $S = G \cdot e^{-2G}$ with the normalized channel throughput S and the channel traffic G [17].

This pessimistic approach assumes that all packets involved in collisions will be lost. However, considering the capture effect, which allows one packet to be decoded even when another transmission occurs in parallel with a minimum RSSI delta of 6 dB for co-channel rejection [18]. Considering this threshold, a network constellation is assumed whereby two groups of devices are located with a corresponding pathloss delta of 6 dB. In case of packet collisions between these two groups, the packet with the higher received power is assumed to always be decoded correctly. Aloha equations can be adapted to $S = \frac{G \cdot e^{-2G}}{2} \cdot (1 + e^{G})$ [19]. To allow a prediction of service quality beyond the throughput calculation this work examines the latency of packets in the uplink direction. The latency is composed of the time on air (ToA) and the subsequent time off (T_{off}) that is needed to meet duty cycle regulations. For each unsuccessful transmission attempt, $ToA + T_{off}$ is added to the usual transmission time ToA. Therefore, to make a statement about the mean latency, the mean number of attempts per packet $\frac{G}{S}$ is used. Equation 2 determines the mean latency $\overline{\tau_{DR}}$.

$$\begin{aligned} \overline{\tau_{DR}} &= \frac{G}{S} \cdot (ToA + T_{off}) - T_{off} \\ &= (e^{2G} - 1) \cdot (ToA + T_{off}) + ToA \end{aligned} \tag{2}$$

To consider the 5G mMTC latency requirement for the 99%-Quantile of the latency the number of collisions occurring at a probability of 1% is determined. Equation 3 determines the 99%-Quantile of the latency $\tau_{99\%}$.

$$\tau_{99\%} = \log_{1-e^{-2G}}(0.01) \cdot (ToA + T_{off}) + ToA \tag{3}$$

Results of throughput and latency calculations for an exemplary parameter set of 32 byte payload, 3 channels and the maximum duty cycle are given in Fig. 5. It is shown that the maximum throughput for this configuration of approx. 3.3 kbps is achieved with 900 nodes which are equally distributed over the six data rate classes. Taking the capture effect into consideration, this capacity can be increased by about 50 %. However, considering DR0, as latency bottleneck, this leads to a higher mean delay of about 400 s compared to 350 s without capture effect, both considering maximum system throughput.

B. Simulative Validation

The valdiation of the presented analytical model is based on a LoRaWAN framework implemented for OMNeT++, covering LoRaWAN channel access. This simulation framework, detailed in [20], is enhanced by necessary functionalities to cover previous introduced latency and throughput results for large-scale deployments. The reliability of both models is verified within a cross-validation process, whereby both models enable sensitivity analysis for traffic amount, duty cycle, as well as resource utilization. To guarantee a feasible validation process of the proposed analytical model, the underlying network model within the simulation environment has been fitted to our analytical model assumptions. For this purpose, three different network models have been implemented. Within the first two models capture effect constellations (with and without) have been reproduced. Additionally, a random device distribution, which corresponds to more realistic network deployment, has been evaluated. 100 simulation runs have been performed for all three network models, covering all mandatory data rate classes considering a payload of 50 Byte and a maximum duty cycle of 1 % applied on one frequency channel. Both, analytical and simulation results, are illustrated in Fig. 6 with focus on data rate class DR0 to cover the highest transmission ranges. A good match between simulation and analytical results can be evaluated with a mean deviation of approx. 4 %. In case of the random device distribution, simulation results perform as expected and are located within the deployment margin, which leads to the conclusion that the proposed deployment gap provides a good idea of possible real deployment situations.

VI. LoRaWAN contribution to 5G mMTC

As indicated in Section IV LoRaWAN provides a very good coverage with an MCL of 151 dB resulting in a maximum communication range of up to 5 km even in urban Smart City environments [13]. Thus, 5G mMTC coverage target of 164 dB cannot be fulfilled, however, even in urban environments, LoRaWAN is capable of covering the desired coverage area of 1 km² which is defined for the 5G mMTC connection density target. Evaluating the proposed 5G mMTC traffic model of 32 byte payload every two hours (see Sec. II), Fig. 7 illustrates the impact of varying, available frequency resources on the maximum scalability within the desired coverage area of 1 km². It can be shown that the underlying limited traffic model results in a significant contribution of LoRaWAN to 5G mMTC targets of 10% (for 3 x 125 kHz channels) up to 25% (for 8 x 125 kHz channels) of the overall 5G mMTC

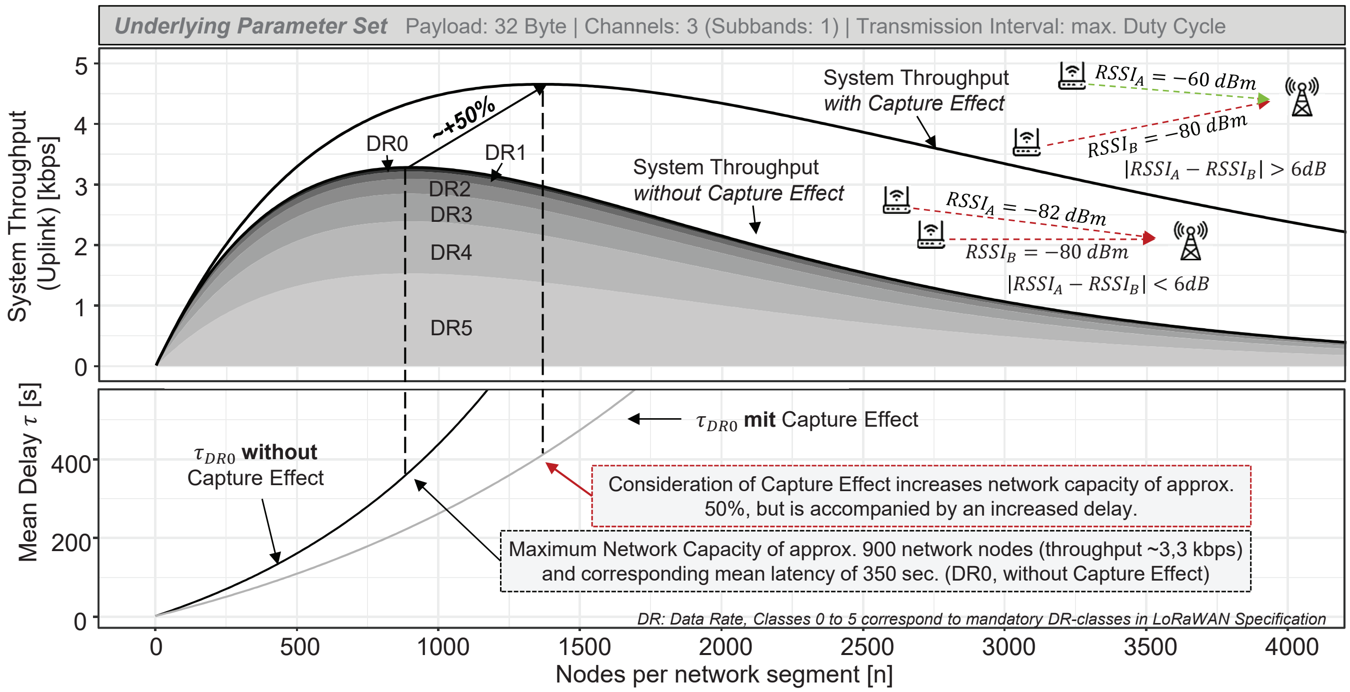

Fig. 5: System Throughput (Uplink) and Latency utilizing maximum duty cycle capabilities

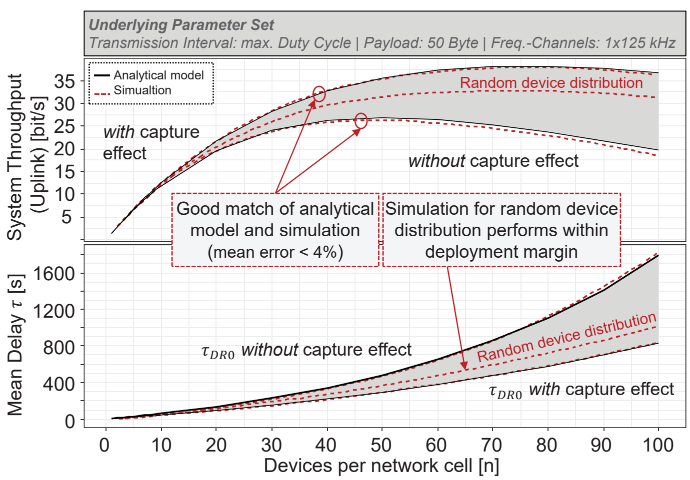

Fig. 6: Validation of analytical model through LoRaWAN network simulation using OMNeT++

target of one million devices per km². Based on the above introduced 5G parameter assumptions, the traffic parameters are varied for a constant capacity of three frequency channels and constitute a minor impact of IoT payload in uplink direction compared to significant transmission interval impact. In case of a fairly low transmission interval of 12 hours (32 bytes payload), a maximum connection density of over half a million devices per km² can be achieved. This results in increased scalability of about 600 % compared to the 5G mMTC target parameter assumption for a capacity of three frequency channels. If the 5G mMTC latency requirement of 10 s next to the desired connection density is additionally considered, it can be seen that the scalability is significantly reduced for all configurations. Hereby, the consideration of a mean latency of 10 s (50%-quantile) reduces scalability by 25 %, whereas consideration of 99 %-quantile reduces scalability up to 70 %. Results discussed so far focus on the evaluation of unacknowledged traffic in the uplink direction. If additionally ACK messages in downlink direction are considered, the downlink represents substantially limited scalability of the LoRaWAN network. The overall connection density is significantly decreased by 97 %, which results in a maximum number of 14,250 devices per km², even for a transmission interval of 12 hours (32 bytes payload). As introduced in Sec. V, this can be explained by the limited LoRaWAN downlink capabilities. However, due to centrally coordinated traffic originating from one gateway, related connection density stays stable even for the consideration of the mMTC latency requirement. All in all, scalability results verify that LoRaWAN is a feasible technology solution that can contribute to the future 5G IoT area, whereby the application field should be limited to non-time-critical sensor applications.

VII. Conclusion

In this work, a performance analysis approach to evaluate the suitability of LoRaWAN networks to contribute to the given 5G mMTC requirement of about 1.000.000 devices per square kilometer is presented. An essential contribution is the consideration of the 5G mMTC latency requirement, which reduces the scalability significantly, but at the same time improves the evaluation concerning reliability. Scalability results verify that LoRaWAN is a feasible technology solution that can contribute to the fu-

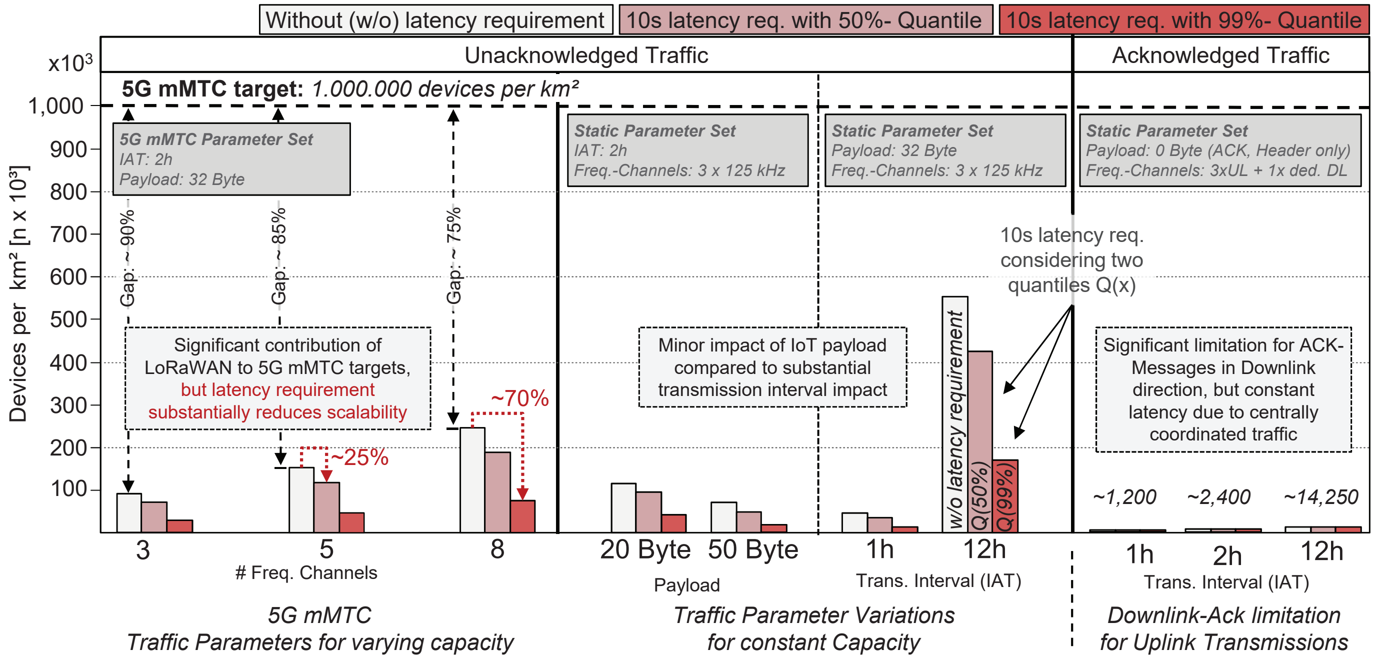

Fig. 7: Impact of various LoRaWAN parameter configurations on maximum scalability considering 5G mMTC connection density and latency requirements

ture 5G IoT area, whereby the application field should be limited to non-time-critical sensor applications. Currently, the LoRaWAN evaluation is limited to analytical methods cross-verified utilizing simulations. In future work, this can be enhanced by lab and field trials, to further validate and strengthen already achieved evaluation results. The LoRaWAN evaluation can be extended to LoRaWAN implementations at 2.4 GHz, which supports significantly larger bandwidths and thus promises increased scalability. Moreover, the downlink capability could be enhanced by means of lightweight application-aware scheduling to enable a broader applicability in the IoT sector.

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