# A 5G Lightweight Connectionless Protocol for Massive Cellular Internet of Things

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***Abstract*—We present a novel protocol for massive cellular Internet of Things (IoT) based on the connectionless access approach. Our solution has very low signaling overhead and is thus very efficient for sporadic short burst traffic applications. Numerical analysis of the capacity achieved by our solution indicates that millions of (IoT) devices can be served with a 10 MHz system bandwidth. Furthermore, our proposal shows capacity gains of up to 260% when compared against state-of-the-art solutions such as legacy LTE, eMTC and NB-IoT.**

## I. INTRODUCTION

Advances in technology are constantly driving down the costs of devices and communications. Hence, communications systems - once designed to enable human-centric applications (e.g., voice, text, video) - are now being expanded to provide pervasive Internet connectivity to a massive number of monitoring and control devices, thereby unleashing the so-called *Internet of Things* (IoT).

Projections conducted by Bell Labs Consulting indicate that the number of IoT devices should explode to multiple tens of billions by 2025 [1]. In this context, several challenges are imposed on cellular networks in order to enable wireless connectivity for such a massive number of IoT devices per square kilometer. For instance, one important principle that guided the design of current 4G cellular networks is the provision of broadband communications to end users with guaranteed levels of *quality-of-service* (QoS) and varying degrees of mobility. As a consequence, sophisticated connection establishment and maintenance procedures involving user terminals and several other network entities are the norm in 4G networks. In contrast, the typical applications associated with massive cellular IoT (e.g., smart metering, smart cities, building automation, smart irrigation systems, etc.) are based on the exchange of short bursts of information (only a few hundreds of bytes) in a sporadic, low-mobility and delay-tolerant manner. Therefore, the architecture and the protocol stack of 4G networks are inherently inefficient to support massive *cellular IoT* (CIoT) traffic.

Recognizing the limitations of LTE prior to Release 12 [2], standardization groups within 3GPP [3] have been focusing on improving 4G in order to make cellular networks more efficient for CIoT service provision [4]. Two remarkable outcomes of those efforts are the technical specifications related to eMTC [5] and NB-IoT [6], which are being finalized for Release 13 [7]. For both eMTC and NB-IoT the goal is the satisfaction of the following requirements: longer battery life, lower device cost, low deployment cost, enhanced coverage and support for an increased number of devices.

While eMTC and NB-IoT are definitely more adequate than legacy LTE to support CIoT traffic, the improvements provided by those solutions may not be enough to handle the massive traffic growth and communication requirements generated by IoT devices that is predicted for the next decade. Therefore, we propose a novel lightweight, connectionless protocol for massive CIoT. Our proposal mainly focuses on the problem of enabling massive capacity in terms of the number devices per square kilometer. In order to achieve this objective, we parted ways with the 3GPP standardization trends and designed our CIoT protocol from scratch. This paper mainly focuses on the physical layer aspects of our proposed CIoT protocol and also displays the capacity gains it is able to achieve when compared against legacy LTE, eMTC and NB-IoT.

This paper is organized as follows. We first review the relevant aspects of the legacy LTE protocol with an eye to its applicability to short burst transmissions. Then, we describe the distinctive features of eMTC and NB-IoT. Subsequently, we present the main concepts associated with our 5G connectionless protocol for massive CIoT. The capabilities of all systems discussed in this paper of supporting large numbers of IoT devices are compared in a section devoted to numerical results. Finally, the paper is ended with a conclusion.

## II. PACKET TRANSMISSION IN LEGACY LTE

At a given moment, a *user equipment* (UE) in LTE can be in one of the two possible states of the *radio resource control* (RRC) protocol: RRC_IDLE or RRC_CONNECTED. The RRC protocol handles layer 3 signaling between UEs and the radio access network. The major procedures supported by the RRC protocol are: connection establishment/release, broadcast of system information, radio bearer establishment/reconfiguration/release, mobility functions, paging, and power control. In the RRC_IDLE state, the UE is able to receive broadcast or multi-cast data, which are generally associated with the acquisition of system information, monitoring of a paging channel to detect incoming calls, and measurement of neighboring cells to enable handovers. Furthermore, the UE in RRC_IDLE may be configured with a specific *discontinuous reception* (DRX) cycle that enables power savings. On the other hand, in the RRC_CONNECTED state, the UE must more closely monitor the control channels associated with shared data channels in order to determine whether data is scheduled for transmission and/or reception. Further activities of the UE in the RRC_CONNECTED state include reporting of channel quality feedback information and neighbor cell measurements.

In order to initiate the transmission and/or reception of data packets from the RRC_IDLE state, the UE needs to transition to the RRC_CONNECTED state. Fig. 1 shows the messages exchanged between a UE and an eNodeB for a normal mobile-originated call setup as the UE transitions to RRC_CONNECTED and eventually is able to send and receive data packets. Also included in Fig. 1 is the size of the messages in bytes, where $L$ is the size of the data packets to

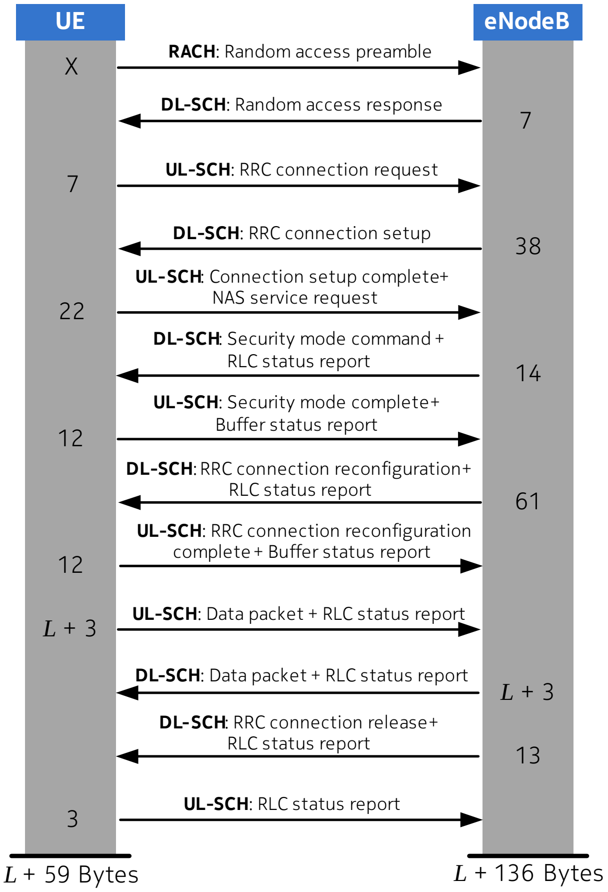


Fig. 1: Mobile-originated call setup from RRC_IDLE in an LTE system.

be sent and/or received. Note that the summation of the sizes of the messages in Fig. 1 reveals the LTE protocol overhead to be 59 bytes in the downlink and 136 bytes in the uplink, which is quite substantial for short packets transmissions (i.e., $L \leq 500$ bytes).

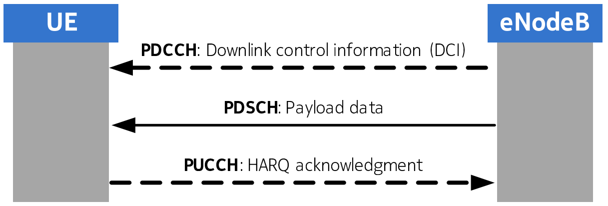
Below we discuss relevant details of the legacy LTE air interface and protocol that are going to be used later on to establish system limitations in the context of massive CIoT applications.

### A. *Random Access Procedure*

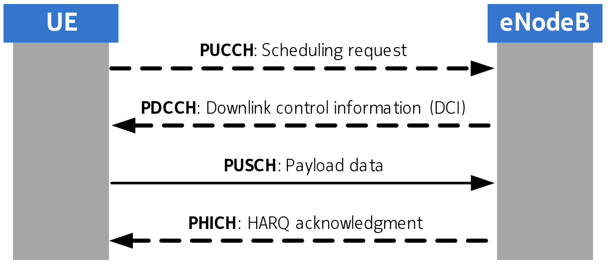
In order to initiate the transition of a UE from the RRC_IDLE state into the RRC_CONNECTED state, the random access procedure is used. This procedure encompasses the first 4 messages in Fig. 1, where the first message uses the *random access channel* (RACH) for the transmission of a random access preamble in a slotted ALOHA [9] fashion.

### B. *Downlink Shared Channel (DL-SCH) Transmissions*

In the physical layer, the *physical downlink shared channel* (PDSCH) is used to accomplish DL-SCH data transfer. The PDSCH usage happens in a dynamic scheduled fashion, with support of a *physical downlink control channel* (PDCCH) or *enhanced PDCCH* (ePDDCH) for grant notifications, and the *physical uplink control channel* (PUCCH) for hybrid-ARQ acknowledgments [8]. Fig. 2a shows in detail the message exchange between UE and eNodeB for one DL-SCH use. In a first step, a (e)PDCCH delivers a *downlink control information* (DCI) to the UE with the necessary information for the reception of the payload data, which is carried on the PDSCH. After the payload data is received, a HARQ acknowledgment is sent on the PUCCH in an asynchronous fashion.



(a) Downlink shared channel (DL-SCH) transmission procedure.



(b) Uplink shared channel (UL-SCH) transmission procedure.

Fig. 2: Shared channels transmission procedures in LTE.

### C. *Uplink Shared Channel (UL-SCH) Transmissions*

The payload data in UL-SCH transmissions is carried by the *physical uplink shared channel* (PUSCH), as shown in Fig. 2b. In a first step, the UE issues a *scheduling request* (SR) through the PUCCH. Then, the eNodeB grants PUSCH resources, which are communicated to the UE by means of a DCI on an (e)PDCCH. In accordance with the received DCI, the UE sends the payload data on the PUSCH. Finally, the eNodeB sends an HARQ acknowledgment on the *physical hybrid-ARQ indicator channel* (PHICH). In contrast to DL-SCH transmissions, note that the process for UL-SCH transmissions is synchronous.

## III. ENHANCED MTC (*e*MTC)

With the objectives previously mentioned – such as providing longer battery life, lower device cost, low deployment costs and enhanced coverage – the technical specifications for eMTC [5] have been developed. Some relevant eMTC features include: 1.4 MHz receiver bandwidth, reduced maximum transmission power (20 dBm), flexible in-band deployment in any group of 6 PRBs, 15 dB coverage enhancements over standard LTE (through, e.g., power spectral density boosting, TTI bundling/repetition), and extended discontinuous reception (eDRX) modes.

Except from the features mentioned above, the legacy procedures from LTE were largely carried over into the eMTC specifications. As an example, the exchange of messages between an eMTC UE and an eNodeB in order to transmit data from RRC_IDLE follows Fig. 1. In this context, the shared channels transmission procedures from Fig. 2 are also employed in eMTC, with the difference that there is no PHICH in eMTC and the HARQ acknowledgments for the eMTC PUSCH (M-PUSCH) transmissions are sent on the eMTC PDCCH (M-PDCCH), which is very similar to the ePDCCH.

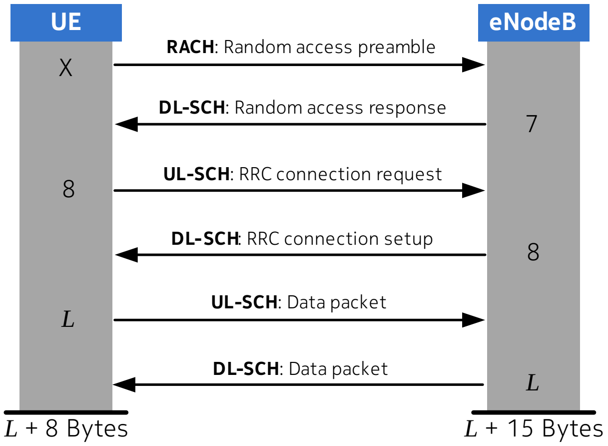


Fig. 3: Mobile-originated call setup from RRC_IDLE in a NB-IoT system employing control plane data transmissions.

## IV. NARROWBAND IOT (NB-IOT)

The NB-IoT specifications [6] further pursue the goals of providing a cost-effective solution for CIoT. However, in contrast to eMTC, the differences between the air-interfaces of NB-IoT and legacy LTE are larger. Some relevant NB-IoT features include: 200 kHz receiver bandwidth, half-duplex operation, 23 dB coverage enhancements over standard LTE (using similar techniques as in eMTC), new narrowband (NB) physical channels for downlink and uplink, power saving modes similar to eMTC, and control plane data transmission (piggybacking on RRC/NAS messages).

As mentioned above, NB-IoT exploits control plane data transmissions that follow the CIoT EPS optimization principles described in [10][1]. Fig. 3 shows the messages exchange between an NB-IoT UE and a eNodeB that results in uplink and downlink data transmissions. Note that DL-SCH and UL-SCH usages in NB-IoT are similar to the ones presented in Fig. 2. However, in contrast to legacy LTE, the major differences are: HARQ acknowledgments for NB-PUSCH transmissions are carried on the NB-PDCCH, and there is no dedicated PUCCH. In this case, all uplink control information (e.g., HARQ acknowledgments for NB-PDSCH transmissions) is carried on the NB-PUSCH.

## V. 5G LIGHTWEIGHT CONNECTIONLESS PROTOCOL FOR MASSIVE CIOT

In contrast to the eMTC and NB-IoT initiatives, which primarily aimed at adapting legacy LTE to better fit the needs of machine-to-machine communications in a cellular environment, our efforts were focused on designing a novel, flexible, scalable, future-proof protocol that is primarily tailored to suit the requirements of massive CIoT communications. In this sense, one of the major targets of the novel protocol being proposed relates to its ability to cope with sporadic transmissions of short data packets on a massive scale.

As shown in Fig. 1, the signaling overhead associated with the sporadic transmission of short packets (e.g., $L \leq 500$ bytes) is quite substantial in legacy LTE and eMTC. For NB-IoT, there is some reduction of overhead due to the control plane transmission scheme shown in Fig. 3. In this context, the 5G CIoT protocol proposed in this paper aims at reducing the signaling activity both in the radio access and in the core network to a minimum in order to enable the support of a massive number of IoT devices per square kilometer. Motivated by the sporadic nature of the CIoT traffic to be supported, a *connectionless access* approach to protocol design has been proposed in [11]. The connectionless access approach can be described by the following ideas: design of very efficient layer 1 and layer 2, usage of a default CIoT RRC configuration, introduction of a layer 2 context header with UE identification and security token, forwarding of packets on common tunnels connecting a 5G eNodeB and the connectionless access gateway, and moving security from 5G eNodeBs to connectionless access gateways to avoid frequent security state updates. In other words, our objective is to provide a CIoT protocol solution that is very *lightweight* in terms of signaling overhead and breaks away from the connection-oriented approach implemented in legacy LTE.

Following the connectionless access approach for protocol design, below we describe the major components of the proposed 5G lightweight protocol for massive CIoT.

### A. Physical Layer

Research activities around 5G have suggested improvements in system performance and flexibility by the proper selection of the waveforms that carry data on the physical layer. A survey on the waveform contenders for 5G with focus on short packet applications can be found in [12]. Among the waveform options, *universal filtered OFDM* (UF-OFDM) has shown to be an attractive alternative for CIoT systems because it allows the relaxation of synchronization and power control requirements. Thus, UF-OFDM enables the elimination of the closed-loop synchronization signaling overhead and complex power control algorithms. Furthermore, the low out-of-band interference properties associated with UF-OFDM increase system flexibility by enabling multiple symbol periods (i.e., multiple services with different requirements on latency) to coexist in the same radio carrier. However, despite of the benefits described above, the adoption of new waveforms for 5G has been treated as optional and can be decoupled from the proposal of layer 2 and above protocols.

### B. Radio Access

The radio access procedure has a significant role in the determination of metrics such as successful accesses per time unit, latency and reliability achieved by a CIoT network. Thus, in order to cope with the diverse requirements that stem from different applications to be supported by a CIoT network, two basic approaches for the radio access procedure emerge as main options, namely, the 1-stage and 2-stage protocols. Below, we describe these two basic radio access approaches and propose a third one, which aims at combining the advantages of the 1-stage and 2-stage radio access protocols in a seamless fashion.

*1) 1-Stage Approach:* According to this procedure, the UEs transmit their payload data on randomly selected radio resources, without previously sending a scheduling request. Fig. 4a shows the messages exchanged between a UE and an eNodeB for data transmission using the 1-stage approach. Note that a random access preamble is sent with the payload data. The use of a random access preamble has as main

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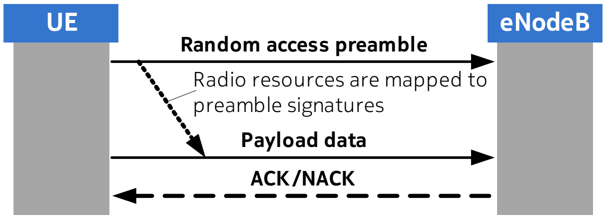
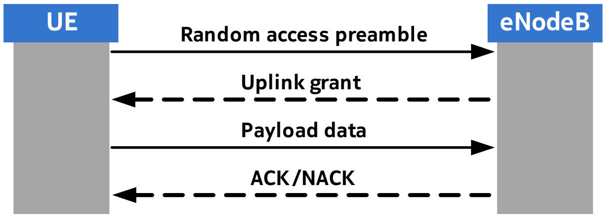
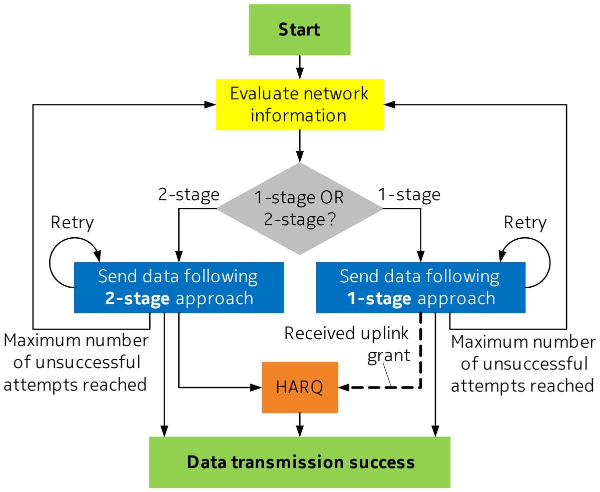
[1] Note that the class of UEs supporting control plane CIoT EPS optimizations [10] is not limited to NB-IoT UEs.



(a) 1-stage approach.



(b) 2-stage approach.



(c) Hybrid 1-stage/2-stage approach [13].

Fig. 4: 1-stage, 2-stage and hybrid approaches for the radio access procedure.

purposes the simplification of UE activity detection by the eNodeB and also the indication of the radio resources used for payload data transmission, which may be implemented by mapping specific radio resources to preamble signatures (e.g., Zadoff-Chu sequences). A clear benefit enabled by the 1-stage approach is that low latencies can be achieved for data transmissions. However, because of its contention-based nature, collisions limit the number of successful accesses per time unit. In summary, the 1-stage approach has its best use in situations where low transmission latencies are required, the CIoT network is only lightly loaded and the payload data packets are small.

*2) 2-Stage Approach:* This procedure relies on explicit scheduling grants from the eNodeBs that contain information about the radio resources to be used by the UEs for payload data transmission. Fig. 4b shows the exchange of messages between a UE and an eNodeB that results in the transmission of data according to the 2-stage approach. Note that LTE's shared channel transmission procedure presented in Fig. 2b has large resemblance with the 2-stage approach of Fig. 4b. In this context, the benefits of having scheduling grants explicitly indicating the resources to be used for data transmission lie in the reduction of the collisions that are expected in the 1-stage approach. As a consequence, the 2-stage approach enables better utilization of the radio resources, which is reflected on the higher number of successful accesses per time unit. A clear disadvantage of the 2-stage approach in comparison with the 1-stage approach is the higher transmission latency due to the increased number of signaling messages.

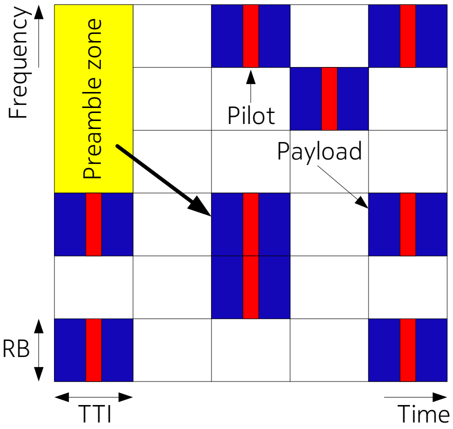


Fig. 5: Realization of the hybrid 1-stage/2-stage random access protocol on the physical layer [13].

*3) Hybrid 1-Stage/2-Stage Approach:* In the hybrid approach, the UEs evaluate network information sent on the downlink before deciding whether to start the data transmission using the 1-stage or 2-stage protocol. In this context, relevant network information to be used by the UEs may include: direct commands on whether to use the 1-stage or 2-stage protocols, network load indicators, and even statistics on ACKs/NACKs that were sent to other UEs. The hybrid approach discussed here has been proposed in [13] and Fig. 4c shows a simplified schematic representation of it. Note that once the 1-stage or 2-stage procedure is initiated, the UE remains on it until the payload data is successfully transmitted, an HARQ process is started, or a maximum number of unsuccessful transmission attempts has been reached. In this framework, for each new attempt, the UE may decide to increase the transmission power and/or apply a back-off time until the next attempt. A further feature of the hybrid approach is that transmissions initiated according to the 1-stage approach can be resumed through an HARQ process. In this case, the eNodeB may allocate resources for further transmission and informs the UE using uplink grants.

A possible realization of the hybrid radio access approach on the physical layer is shown in Fig. 5. Within the preamble zone, the preamble sequences from different UEs are superimposed. However, the correlation properties of the different preamble sequences allow the eNodeB to detect each sequence. Furthermore, from all possible preamble sequences that may be transmitted by the UEs, a subset may be reserved for the 1-stage procedure, i.e., for those UEs configured to send payload data in an unscheduled fashion. In this case, each 1-stage preamble sequence uniquely points to a group of uplink radio resources for payload transmission, as shown in Fig. 5. The pilot sequences to be used in conjunction with the payload transmissions are also connected with the preamble sequence

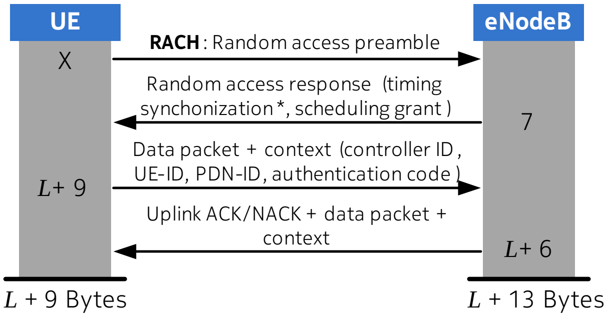


Fig. 6: 5G lightweight, connectionless, 2-stage packet transmission procedure.

chosen by the UE. It is possible that more than one preamble sequence point to the same uplink resources and collisions on the payload data may occur. Here, *multi user detection* (MUD) techniques can be used to detect the colliding payloads as long as the preambles pointing to the same uplink resources can be detected and are different – i.e., they define different pilots to be used with the colliding payload transmissions.

For the UEs configured to send payload data in a scheduled fashion, preamble sequences may also be reserved for the 2-stage protocol. In this case, after sending a 2-stage protocol preamble sequence, the UE waits for the resource allocation to be communicated by the eNodeB in order to proceed with the payload transmission.

Note that beyond grouping the preamble sequences according to their association with the 1-stage and 2-stage protocols, it is also possible to further split the preambles based on the amount of radio resources needed for payload transmission.

### *C. Connectionless Packet Transmission Procedure*

As mentioned above, our 5G protocol solution for massive CIoT does not require RRC configuration and the establishment of radio bearers. Therefore, as shown in Fig. 6, the 2-stage procedure[2] for connectionless packet transmission results in very few messages being exchanged and, consequently, very low overhead and reduced protocol latency. In this framework, note that all necessary information related to the UE identity, network addresses and security is included as a *context header* with the data packets in the messages 3 and 4 of Fig. 6. Thus, after receiving a message 3 packet from a UE, the eNodeB forwards it to a *connectionless access gateway*, which inspects the context header, verifies integrity, performs decryption, and, based on stored state information, forwards the packet to the expected network entity. Furthermore, the timing synchronization advance included in message 2 can be eliminated if waveforms tolerating synchronization errors, such as UF-OFDM, are employed in the physical layer. Finally, in terms of control information, the messages 2 and 4 have their resource allocations communicated to the UEs via a downlink control channel, and message 4 is acknowledged by using spectral efficient techniques such as the code multiplexing employed by the legacy PUCCH.

In terms of core network architecture, our 5G connectionless protocol is supported by a lean infrastructure that leverages *network functions virtualization* (NFV) and *software-defined networking* (SDN) in order to provide high degrees of efficiency, scalability and flexibility [11]. Thus, the proposed 5G core network is capable of adapting to different types of traffic (not only CIoT traffic) and varying traffic intensities in an efficient manner. Furthermore, beyond the low protocol overhead discussed previously, a very important benefit enabled by the proposed 5G core network is the capability of moving computing resources closer to the UEs, which is particularly critical in low latency applications.

## VI. NUMERICAL RESULTS

In this section, we compare all systems discussed in this paper with respect to their capabilities of supporting a massive number of devices generating sporadic short burst traffic. The calculation results shown hereafter were performed by taking into consideration the signaling overheads depicted by the Figs. 1, 2, 3 and 6 with the assumptions summarized in the table below.

| **Parameters** | **Value** |
|---|---|
| System bandwidth | 10 MHz (50 PRBs) |
| Control overhead UL/DL (including pilots) | 30% |
| Spectral efficiency of UL/DL data channels | 1.0 bits/s/Hz |
| Number of PDCCH symbols in legacy LTE | 3 |
| Number of (e)CCEs per (M)-(e)PDCCH signaling | 4 |
| Number of CCEs per NB-PDCCH | 2 |
| Number of resource elements per NB-IoT UL ACK/NACK | 4 |
| Packet sizes | {100; 1000} bytes |
| Interarrival times | {1; 600} seconds |

Note that the 1.0 bits/s/Hz spectral efficiency listed in the table above is an achievable target in current cellular systems. In this context, we expect that 5G UEs will have at least the same capabilities as todays UEs but at a much reduced cost, which would satisfy the requirements for low-cost IoT devices. Moreover, the 30% uplink/downlink control overhead is in line with current legacy LTE deployments. Here, we expect that the resources allocated for uplink control are also enough to provide the random access capacity needed, thus, avoiding a radio access bottleneck. Finally, the *(enhanced) control channel elements* ((e)CCEs) [8] allocations for downlink control signaling correspond to the average amounts observed in current deployments.

Fig. 7 presents the number of users supported in 10 MHz system bandwidth for each of the systems discussed in this paper. Note that the number of users supported by each system is defined by the lowest between its downlink and uplink capacities. A major assumption in the results shown below is that the eNodeBs are able to schedule the UEs perfectly, i.e., no radio resources are wasted, as long as there are users waiting to communicate. Each of the plots shown below depicts a particular configuration in terms of payload size and *interarrival time* (IAT) between transmitted packets. As it can be seen in Figs. 7a and 7b, our 5G CIoT protocol provides capacity gains between 60% and 260% with respect to the other systems. For longer packets, e.g., in Figs. 7c and 7d, the advantages of having a connectionless protocol become diminished, as the signaling overhead becomes only a fraction of the payload data. For longer interarrival times (Figs. 7b and 7d), note that legacy LTE starting from RRC_CONNECTED is not an option because the limited PUCCH resources only support some 3000 active users in typical situations.

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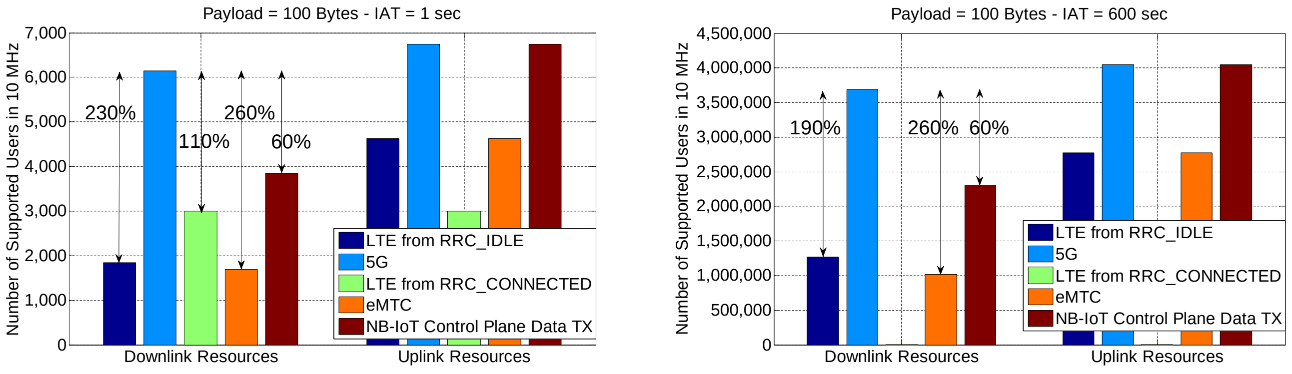
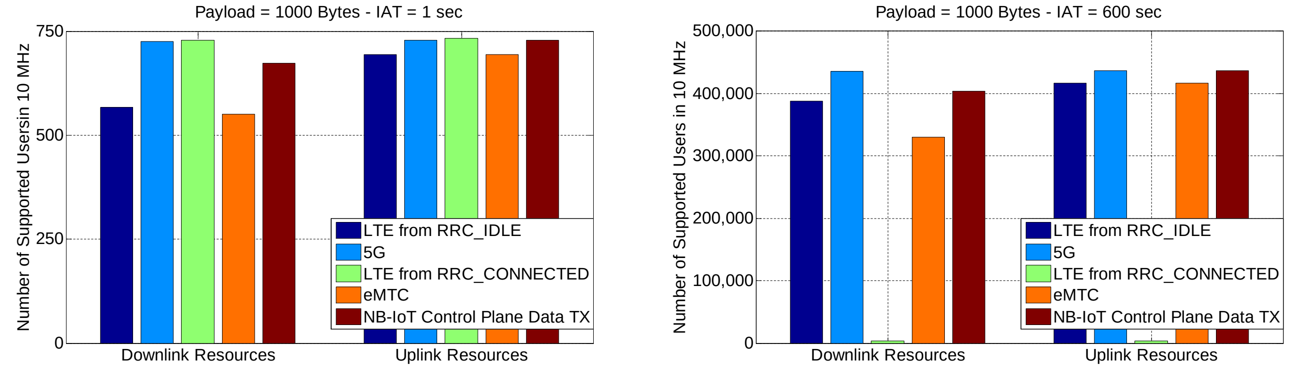
[2] 1-stage and hybrid procedures are also defined for the connectionless packet transmission approach. However, in terms of *massive* CIoT applications, the 2-stage procedure is more relevant due to its improved spectral efficiency.



(a) Number of supported users for 100-byte packets and IAT = 1s. (b) Number of supported users for 100-byte packets and IAT = 600s.



(c) Number of supported users for 1000-byte packets and IAT = 1s. (d) Number of supported users for 1000-byte packets and IAT = 600s.

Fig. 7: Number of supported users for different packet sizes and interarrival times (IATs).

An interesting fact that emerged from our numerical results is that NB-IoT – when using the control plane data transmission scheme from Fig. 3 – is able to offer system capacities relatively close to our 5G protocol proposal. However, NB-IoT is a lot less flexible in terms of supporting high data-rate transmission modes, frequency-selective scheduling and lower latencies than our 5G connectionless CIoT solution. Moreover, the CIoT EPS optimizations [10] used for data transmissions in NB-IoT prevent separate scalability of control plane signaling and user plane data transmissions. Consequently, if the communication requirements of the network devices become somewhat more heterogeneous and deviate from NB-IoT specifications, it is expected that the advantages of our 5G CIoT protocol will further increase over NB-IoT. Furthermore, one should remember that the core network supporting NB-IoT is ill-equipped to satisfy future needs related to scalability and flexibility that would allow the simultaneous support of different types of applications and provide low end-to-end latencies through the capability of moving computing resources closer to the UEs.

## VII. CONCLUSIONS

In this paper, we introduced the concept of a novel protocol for massive CIoT communications. Our proposal is based on the connectionless access approach and consists of a lightweight protocol with very low signaling overhead. In a 10 MHz system bandwidth, our 5G CIoT protocol is able to provide service to millions of IoT devices with gains of up to 260% over state-of-the-art technologies such as legacy LTE and eMTC. We believe that the capacity of our solution can be improved even further by incorporating advanced receiver algorithms based on multi-user detection.

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