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Massive Machine-Type Communications and Revival of ALOHA

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Abstract— **In this paper, we provide an overview of recent developments in the domain of Machine-Type Communications (MTC) for current and next-generation wireless cellular systems. We describe existing MTC standards and discuss in more detail the necessity of novel solutions for massive access of machine-type devices to the mobile cellular network. In particular, we focus on recent developments in the domain of ALOHA-based random access, known as Coded Slotted ALOHA (CSA). We review recent results that show CSA is capable of dramatically increasing the throughput of ALOHA-based schemes, both in single base-station and multi-base station scenarios, making CSA one of the suitable candidates for future MTC.**

Keywords-component; random access; ALOHA; mobile cellular networks; 5G

I. INTRODUCTION

The problem of sharing a common wireless communication channel is one of the classical problems in wireless communications and information theory. One of the first practical schemes that was proposed to address this problem is celebrated ALOHA protocol designed by Abramson that dates back to early 70s and targets multiple access channel in satellite communications [1]. Soon afterwards, and improvement in the form of Slotted ALOHA (SA) protocol was introduces by Roberts [2]. SA principle has been used afterwards in a number of wireless communication systems, and in fact represents an underlying principle for initial random access in the latest generation of mobile cellular systems, the fourth generation (4G) Long-Term Evolution (LTE) standard.

Random access protocols are surviving renewed interest due to emergence of Internet of Things (IoT) and necessity to connect a huge number of new machine-type devices to existing communication infrastructures. In terms of mobile cellular networks, a new service known as Machine-Type Communications (MTC), also known as Machine-to-Machine (M2M) communications, has been under intensive research and development in recent years. MTC services target connecting thousands of new low-power devices with low-rate service per base station to a mobile cellular network. Although attempts have been made to customize the existing technologies such as GSM/GPRS/UMTS to support MTC services, the first standards for MTC in cellular systems appeared only recently, as part of Release 13 of 3GPP LTE standardization [3].

Although new 3GPP standards for MTC, such as Narrow-band IoT (NB-IoT), have been introduced and are able to support massive number of connections per base station, novel and more efficient solutions for random access in MTC are still very much needed. In this paper, we review the line of research that suggests that SA-type protocols, that evolved significantly over the last decade, provide efficient solution to accommodate massive number of sporadic MTC users. The recent revival of ALOHA started with the Collision Resolution Diversity Slotted ALOHA (CR-DSA) [4]. CR-DSA builds upon previously considered Diversity Slotted ALOHA schemes, in which users repeat their packet transmission within several slots of a frame [5]. However, in CR-DSA, the key component of Successive Interference Cancellation (SIC) decoding is introduced at the base station, which is able to dramatically improve the system throughput. The full potential of SIC decoding is unleashed in [6] where it was recognized that the SIC decoding at the base station within CR-DSA scheme is equivalent to the iterative erasure decoding of Low-Density Parity-Check (LDPC) codes. The author of [6] proposed Irregular Repetition Slotted ALOHA (IRSA) scheme that, when carefully designed, is able to achieve close-to-optimal throughput. IRSA is later extended in different ways, for example, using rateless codes as a motivation into frameless ALOHA [7], or by allowing asynchronous packet reception but using SIC decoding [8], and also, by including precoding procedure into a more general form of Coded Slotted ALOHA (CSA) [9]. CSA is now commonly accepted term for all SA-based schemes in which iterative SIC decoding is applied. Finally, recent line of research investigated extensions of CSA to dense systems of base stations (such as small cell networks) where user transmissions are heard at many surrounding base stations which are in turn allowed to cooperate in order to decode user replicas [10]. These cooperative SA schemes for multi-base station systems provide a promising solution to achieve ever higher throughputs via exploiting unwanted inter-cell interference as useful in network-wide SIC decoding process.

The remainder of the paper is organized as follows. In Section 2, we provide an overview of developments of 3GPP MTC standards, both within the 4G LTE and as

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envisaged for 5G systems. In Section 3, we review CSA approach in single-base station systems. In Section 4, a review of cooperative CSA for multi-base station systems is provided. Finally, the paper is concluded in Section 5.

II. MACHINE-TYPE COMMUNICATIONS IN MOBILE CELLULAR SYSTEMS

In this section, we briefly review the evolution of MTC standards in 4G LTE system and the new standards proposed for the next 5G system.

A. Machine-Type Communications in 4G LTE/LTE-A

Connecting machine-type devices to mobile cellular systems, as part of the so called Machine-Type Communications (MTC) is a topic of intensive research and development. Although MTC solutions exploiting GSM/GPRS connectivity have been in use in previous years, the first 3GPP standards for cellular IoT came only recently as part of the 3GPP Release 13 standards (LTE Advance Pro). Three solutions are introduced for mobile operators to enter the IoT market: enhanced Machine-Type Communications (eMTC), Narrow-Band Internet of Things (NB-IoT), and Extended Coverage GSM Internet of Things (EC-GSM-IoT) [4]. eMTC reuses most of the features of the LTE standard, while introducing low-cost user equipment (Category 0 UE) operating in a 1.08 MHz band (6 LTE Resource Blocks) with physical layer (PHY) enhancements for extended coverage. NB-IoT makes a step further in reducing the end device costs by introducing a new LTE signal that fits into a 180 kHz band (1 LTE Resource block). NB-IoT targets up to 50K devices per macro-cell with extended coverage and is an ideal solution for static and low-rate devices such as smart meters. Similar features as the ones offered by NB-IoT are also available by replacing legacy 200 kHz GSM channels with EC-GSM-IoT. At the present state, cellular IoT is capable of providing a solution for massive access of low-rate low-priority devices such as smart meters (NB-IoT), while for the more demanding devices, the solution for remote measurement systems with higher data rates is also available (eMTC), although with the same reliability and delay guarantees as provided by the standard LTE PHY. The solutions are standardized during final quarter of 2016, but commercial deployment and vendor offering NB-IoT and eMTC devices are expected to appear during 2017.

B. Machine-Type Communications in 5G New Radio

3GPP standardization of the so called New Radio for 5G (NR) interface is initiated in Rel. 13 with requirements and architecture study. 3GPP targets two-phase evolution where the initial system will be laid out in Rel. 15 by late 2018, making 5G ready for the first phase deployment in 2020, while the second phase of standardization will be completed in Rel. 16 by 2020. 5G will make a step forward in cellular IoT evolution, following the ITU 5G requirements to offer two main IoT services: massive Machine-Type Communications (mMTC) and Ultra-Reliable Low-Latency Communications (URLLC) [11]. The former is motivated by connectivity provision with extended range support for tens of billions of low-rate low-cost devices, while the latter targets mission-critical services such as vehicular connectivity (V2X) and industrial control. 3GPP formulated explicit requirements for mMTC connection density in urban dense scenario of 10^6 devices/km^2 satisfying packet drop rates of less than 1%. For URLLC, the generic target for both UL/DL latency is 0.5ms, while reliability targets packet loss rate of 10^{-5} for 32 byte packets and 1ms latency. However, note that for satisfaction of URLLC requirements, not only radio interface, but mobile core network architecture will play a significant role. Overall, it is clear that already with NB-IoT, and even more with the evolution to mMTC, the cellular IoT infrastructure will be ready to accommodate massive-scale data acquisition from ultra-dense low-rate deployment of devices such as smart meters. For more demanding and real-time remote measurements or applications that call for higher data rates, reliability and very low latency, URLLC service will be ideal solution. Thus initiated by 4G and further evolved in 5G, cellular IoT will offer service s for wireless large-scale distributed information acquisition suitable for future connected industry, connected vehicles, remote mission-critical and smart grid applications.

III. CODED SLOTTED ALOHA

In this section, we review recent development in the domain of Slotted ALOHA (SA) protocols. Although SA is classical protocol dating back to early 70s, several recent papers revived the interest in SA if additional processing in the form of Successive Interference Cancellation (SIC) is employed at the access point. If properly designed, SIC decoding may dramatically improve the throughput of SA protocol, which is the topic we describe next in more detail.

Slotted Aloha has been proposed in the 70s, and is one of the main random access protocols still in use in wireless communication systems [2]. With (framed) slotted Aloha, at each frame, each user transmits a data packet in one randomly selected slot. If the slot contains only a single user transmission, the access point is able to receive a clean signal and decode a packet, and we call such slots as singleton slots. Apart from singleton slots, other slots in framed SA system may be idle, and thus useless in case no users transmitted in these slots, and collision slots, in case two or more users transmitted their packet in the same slot. Thus the throughput of framed SA system is equal to the fraction of singleton slots which turns out to achieve a maximum value of 1/e ~ 0.37 in case the system load is equal to one, i.e., the number of active users matches the number of available slots in the frame.

First ideas with sending more than one replica of a data packet by each user appeared as so called Diversity SA (DSA) scheme, where in [5], authors propose a protocol where each user transmits in two randomly selected slots per frame. However, the major game-changer comes in [4] with so called Collision-Resolution Diversity Slotted ALOHA (CR-DSA) that significantly increases the achievable throughput with respect to standard SA. CR-DSA attains this major throughput increase by incorporating the SIC mechanism into the protocol at the decoding side. In CR-DSA, users contend by transmitting replicas of their packets sent in randomly selected slots, where multiple replica of each packet is sent, similarly as in DSA scheme. In contrast to DSA, each packet replica contains a header where pointers to all other replicas of the same packet (sent by the same user) are placed. During the SIC decoding process, once any replica is decoded from a singleton slot, the SIC is applied to remove the other replicas, from the information contained in the header of the decoded replica. The removal of all replicas may initiate new iterations of decoding and further replica removal [4]. Experimenting with CR-DSA, authors suggested usage of two replicas per user as in that case, the system throughput reached T ~ 0.55.

Next crucial development came in [6], where it was demonstrated that the SIC decoding protocol in [4] is equivalent to the graph-peeling decoding of LDPC (low density parity check) codes over erasure channel and exploits this analogy to improve the throughput. More precisely, the author introduced so called Irregular Repetition Slotted ALOHA (IRSA) scheme in which each user is allowed to send different number of replicas, motivated by irregular degree-distributions of LDPC codes. Equipped with the asymptotic analysis tools coming from modern coding theory, authors were able to design the degree distribution that governs the process of replica repetitions that considerably improve the asymptotic throughput. In fact, optimized degree distributions achieving asymptotic throughput of T~0.97 are designed.

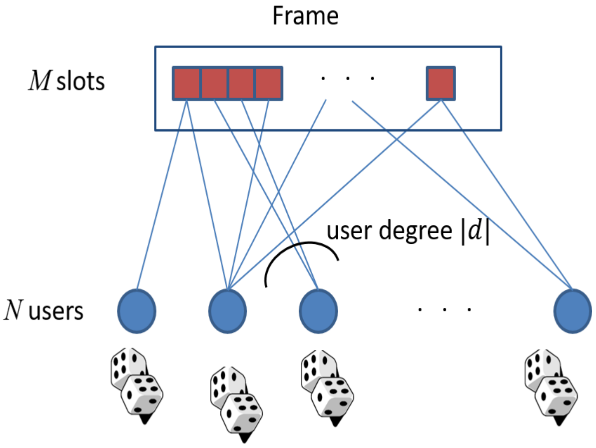

Figure 1. Graph-representation of IRSA scheme.

For the design of IRSA protocol, it is useful to represent the iterative SIC decoding process via a bipartite graph, similar to graphs describing LDPC codes. As in LDPC code graphs, this graph is describing packet replica recovery graph that contains K user nodes and M slot nodes, as shown in Fig. 1. Edges connecting user nodes to slot nodes correspond to transmissions, thus the graph provides full information about user activity within the frame. The number of replicas is governed by a user degree distribution $\Lambda(x) = \Sigma\, \Lambda_i\, x^i$, where Λ_i represents the probability a user will send i replicas. The iterative SIC decoder that ``peels off" the graph represents the process of transmission detection and decoding.

Similar to IRSA scheme, in [7], frameless ALOHA is introduced which achieves high throughputs by exploiting the analogy with rateless codes. As an example performance of SIC-based slotted ALOHA schemes, we reproduce the results from [7] and present it below. From the graph, one can easily note that the asymptotic throughput for frameless ALOHA design can reach T~0.87.

The author in [8] proposes and analyzes an un-slotted ALOHA protocol with SIC and show its high performance in terms of packet loss ratio (PLR) and throughput. Reference [8] further enhances the same scheme by incorporating a FEC coding mechanism to resolve partial packet collisions. Further, the work in [12] analyzes frameless Aloha with capture effect, while [13] further enhances the protocol in [4] by utilizing 3-5 packet replica transmissions, and by exploiting power unbalance and capture.

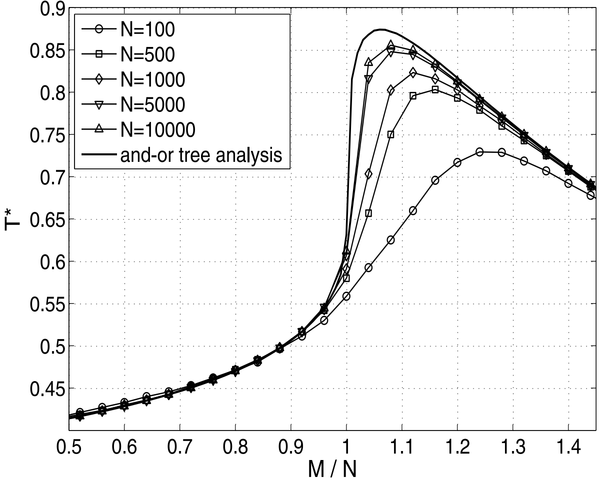

Figure 2. Frameless ALOHA throughput performance [7]

IV. CODED SLOTTED ALOHA IN MULTI-BS MODELS

In many wireless communication scenarios of interest, a user transmission can be detected at multiple base stations. For example, this include satellite communication systems, networks of Wi-Fi access points, or dense deployment of small cellular base stations in urban areas. An example of such a scenario is presented in Figure 3, where a large number of sensors are connected to a network of small cells.

Figure 3. Massive MTC scenario in multi-AP model

In multi-base station scenarios, each base station can exploit the temporal diversity of user's packet replicas via SIC decoding across the time slots. However, one can also exploit the spatial diversity, where SIC is done across multiple base stations in a single time slot. More precisely, due to limited range of user transmissions, a packet replica of a transmitting user may appear as a singleton slot at one of the surrounding base stations, while at the same time being a collision slot at other surrounding base stations. In that case, a base station, that decodes a clean packet replica in a singleton slot, can spatially cooperate with neighboring base stations by sharing the decoded packet replica, thus allowing them to use SIC to remove the replica from their collision slot [10].

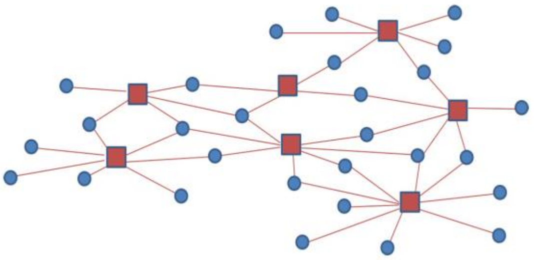

Figure 4. Graph representation of multi-base-station model

Figure 4 illustrates an example of a single-slot transmission where a subset of users transmitted their packets and each user is heard only at a set of neighboring base stations. The user transmission process generates a random geometric bipartite graph containing user nodes and slot nodes (overlaid on top of base station nodes) and the decoding process again proceeds equivalently to erasure decoding of LDPC codes. In case CSA is applied over slots in time domain, the graph in Figure 4 is extended by adding additional slot nodes at each base station, thus extending it in time domain. In [10], we provide detailed asymptotic analysis of different cooperative decoding algorithms. It was concluded that joint spatio-temporal decoding of CSA for multi-base station system can achieve the highest throughput, which considerably improves over the case when CSA is applied at single base station independently.

As an example, we provide a performance of four different decoding schemes from [10] for a small example scenario. In the simulation setup, we set the number of base stations M = 40, and the number of slots in the frame to $\tau = 40$. We simulate the recovery probability versus the system load $G = N/(M\tau)$ by varying N. We perform Monte Carlo simulations where for each N, we generate 30 random placements of users and base stations. For the cases with temporal SIC, we apply the temporal degree distribution $\Lambda(x) = x^2$ (i.e., each user generates two replicas per frame).

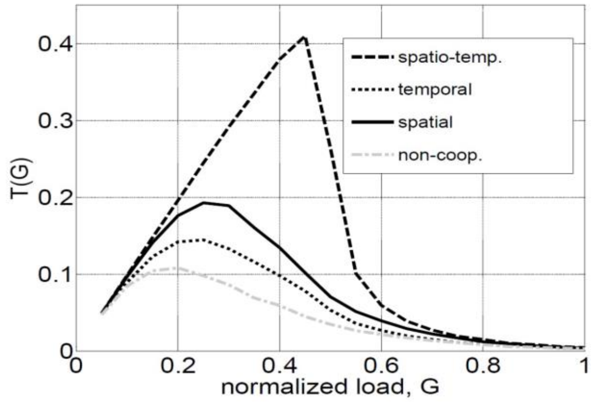

Figure 5. Performance example of CSA in multi-base station system [10]

Figure 5 plots the normalized throughput T(G) versus normalized load G for the four decoding cases: i) non-cooperative case where each base station applies SA independently, ii) temporal cooperation, where each base-station applies CSA independently, iii) spatial cooperation, where base stations apply SA and cooperate spatially, and iv) spatio-temporal, where base stations apply CSA and cooperate spatially. We can see that the Case 4 (spatio-temporal cooperation) achieves much higher peak normalized throughput than the remaining three schemes.

V. CONCLUSIONS

In this paper, we reviewed recent developments in Coded Slotted ALOHA random access solutions empowered with Successive Interference Cancellation decoding. CSA schemes are shown to approach asymptotically optimal throughput, while preserving flexibility of ALOHA random access. CSA in multi-base station models promises significant gains when joint cooperative decoding is applied among base stations.

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