A Random Access Scheme for Large Scale 5G/IoT Applications

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Abstract—The integration of slotted Aloha with power domain non-orthogonal multiple access (NOMA), dubbed slotted Aloha-NOMA (SAN) can emerge as an appealing MAC protocol to be used for Internet-of-Things (IoT) applications over 5G networks. In this paper, SAN is discussed, and its performance is evaluated in detail. The simulation results demonstrate that the maximum normalized throughput can be increased from 0.37, which is the case for slotted Aloha, to 1 by means of SAN. Specifically, this full throughput efficiency can be obtained at all low, medium and high network traffics. Besides that, the average delay can be significantly reduced compared to the slotted Aloha.

Index Terms—IoT, 5G Networks, MAC protocol, slotted Aloha, NOMA.

I. Introduction

Ubiquitous communication among many heterogenous devices including various sensors, actuators, cameras, smart meters, autonomous vehicles makes channel access challenging for Internet-of-Things (IoT) applications over 5G networks such as smart cities. In this scenario, the main impediments for channel access come from the heterogeneity of devices and a very large number of nodes contending for the same channel, e.g., there can be many simple low data rate sensors and actuators as well as complex data consuming devices such as cameras, smart meters, autonomous vehicles. A medium access control (MAC) protocol addressing these issues for IoT can be useful, and remains open as stated in [1].

Support for heterogeneity requires a MAC protocol that enables high throughput for high data rate devices and energy efficiency for battery operated low data rate devices. However, the existing methods primarily address either high throughput energy inefficient protocols such as IEEE 802.11, M2M-LTE or energy efficient low throughput protocols such as IEEE 802.15.4, Bluetooth, Z-Wave, EPC global [2]. Additionally, a very large number of nodes implies a MAC protocol that should be dynamic, i.e., robust to changing network conditions, scalable, and easy to setup. A promising approach that embraces all these features can emerge if the throughput bottleneck of Aloha can be boosted.

With this motivation, a novel MAC protocol is proposed in this paper with the promising combination of slotted Aloha and power domain non-orthogonal access (NOMA). The former addresses a dynamic network with easy setup for a very large number of nodes, and the latter ensures high throughput, and

energy efficient protocol that does not necessitate channel listening as well as reducing collisions and retransmission attempts. Note that slotted Aloha is more appropriate to NOMA compared to pure Aloha, because it is more practical to prevent new incoming packets once decoding starts at successive interference cancellation (SIC) . Furthermore, slotted Aloha has better throughput than pure Aloha.

Increasing the throughput efficiency of Aloha based protocols has been recently studied. Accordingly, each node sends two replicas of one packet and the packets that do not collide with others are decoded first and then subtracted from the packets that interfere with these detected packets [3]-[7]. It is shown that the maximum normalized throughout can be increased to 0.55 compared to 0.37 for conventional slotted Aloha in [3] and its energy efficiency is depicted in [4]. Optimization of this method with the bipartite graphs shows that the throughput can be further increased to 0.8 [5]. Further optimizations of this method are discussed in [6], [7]. However, these improvements are valid only for low network traffic. The proposed schemes become worse than the conventional slotted Aloha for high traffic. Furthermore, transmitting duplicate packets at the beginning, even if there is no collision, may not be the best approach for large scale networks regarding network traffic.

In this paper, it is shown that the maximum normalized throughput of slotted Aloha can be increased to 1 irrespective of the network traffic with the proposed protocol dubbed slotted Aloha NOMA (SAN) by adjusting the power levels at the transmitter and the number of detectable signals for one slot using a SIC receiver that has the capability to cancel the interference. This result is quite important, since all transmitted packets become throughput for the random channel access. Moreover, it is demonstrated that the average delay can be greatly reduced with SAN. This paper also proposes a transmitter and a receiver architecture for the corresponding SAN protocol with simple or no modifications at all for the state of art IoT transmitters, which makes it a promising candidate for future IoT applications.

The paper is organized as follows. The proposed MAC protocol is discussed in Section II. A generic transmitter and receiver implementation corresponding to the proposed protocol are given in Section III, and the simulation results

are given in Section IV. The paper ends with the concluding remarks in Section V.

II. Slotted Aloha NOMA

Inspired from the intriguing throughput enhancement of NOMA [8], we propose a novel MAC protocol that combines the appealing features of slotted Aloha such as robustness to dynamic network conditions, easy implementation, low overhead signaling with the throughput enhancement of NOMA. Accordingly, many heterogenous devices from autonomous vehicles to simple IoT sensors can send data to the IoT gateway at any time slot without any control signaling or listening to the channel. Here, the IoT gateway resembles the machine type communication gateway (MTCG) defined in LTE-A [9]. An illustrative example is depicted in Fig. 1, where many different types of devices such as autonomous vehicles, temperature sensors, smart meters, music players and cameras strive to send their packets to the IoT gateway through the SAN network. Assuming sufficient SIC capability (as we do throughout this paper), any type and any number of devices can send packets to the IoT gateway in whichever slot they want according to the proposed SAN protocol.
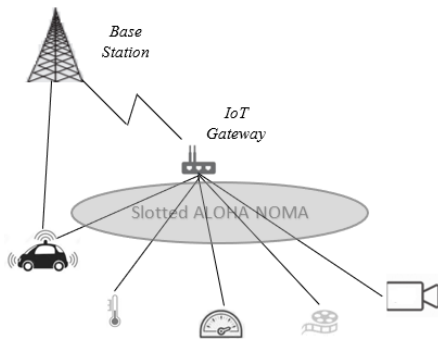

Fig. 1. An IoT Application over 5G Networks

Basically, there are 3 types of frames in SAN: beacon frames, data frames and acknowledgment (ACK) frames similar to [10]. More precisely, at the beginning of each slot the IoT gateway sends a beacon signal to synchronize the nodes. It follows that any number of nodes can transmit their packets to the gateway with proper power levels through data frames. Notice that if one node's channel is sufficiently different than the others, then it can transmit without making any power control[1]. At the end of each slot, the IoT gateway sends an ACK signal to indicate the successfully detected packets and ensures reliable communication. The nodes that do not find their packets within the ACK frame retransmit the same packet after waiting, or backing off, for a random number of slots.

One of the key points of the proposed protocol depends on the SIC receiver being configured so that it can detect multiple user packets in a slot. Here, the challenge is to determine the number of detected signals with SIC for each slot, which can be dynamically changing. Although the maximum number

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[1]For example, with a centralized power allocation policy.

of detected signals that maximizes the throughput will be found in Section IV, it is straightforward to express that there may be fewer packets than the maximum number of detectable packets at some instances. To address this challenge, a multi-hypothesis testing approach [11] is proposed that works collaboratively with the SIC detector, which can prevent unnecessary processing at the IoT gateway. This will be further elaborated in the next section in the context of proposing a simple receiver architecture.

The primary features of the proposed SAN protocol are given below with details.

- Dynamic: The changing number of nodes can be managed by multi-hypothesis testing and a SIC receiver, and thus there is no need to know the numbers of nodes as *a priori* information. This makes the proposed protocol dynamic and flexible against a changing number of users. Furthermore, the SAN does not require any setup or additional control overhead so that any number of nodes can join, leave or go to sleep mode whenever they want.
- Reliable: At the end of each slot, the IoT gateway sends an ACK signal to indicate the successful transmissions that provides quality of service to the users.
- Low control overhead: There is no control overhead other than the beacon signal. This makes SAN appealing in particular for short length packets. Furthermore, newly participating IoT devices to the network do not have to register to the gateway.
- Throughput efficient: Adapting power control at the transmitting nodes and using a SIC receiver at the gateway with multi-hypothesis testing can boost the throughput compared to the conventional slotted Aloha.
- Energy efficient: Relying on throughput improvement by mitigating the effect of collisions using a SIC receiver and multi-hypothesis testing, retransmissions attempts are reduced that can lead to an energy efficient protocol. Also, avoiding the need for channel listening (sensing) before transmitting further enhances the energy efficiency of the SAN protocol.
- Delay efficient: In parallel with the throughput increase, the probability of collisions becomes smaller and more packets can be successfully transmitted without waiting for back-off times.
- Scalable: The integration of slotted Aloha and throughput efficient NOMA constitutes the scalability feature of the SAN so that it can serve large scale networks as in the case of IoT.
- Complexity: The proposed method brings a little complexity increase to the transmitting nodes due to power control or no burden at all provided that the node's channel is sufficiently different than the others. On the other hand, there is a complexity increase at the IoT gateway stemming from the SIC receiver, however, this complexity increase can be more easily tolerated with respect to the IoT devices.

Although the IoT gateway has to implement the 5G wave-

form to communicate with the base station, IoT devices are not obliged to have this waveform that can be quite complex for some low complexity sensors. Accordingly, many different waveforms can collide with each other at the gateway. The question of whether this may ease or complicate the receiver design in the physical layer will be discussed as a future research, which is out of scope for this paper which deals only with the channel access in MAC layer.

III. TRANSMITTER AND RECEIVER ARCHITECTURE FOR SLOTTED ALOHA NOMA

One of the fundamental questions about the proposed SAN protocol is how one can implement a proper transmitter and receiver architecture. In this regard, a generic transmitter structure is depicted in Fig. 2. There is not any restriction for encoder and modulator so that any encoder and modulator techniques can be used. The encoder block can have sub-blocks, e.g., it can involve an interleaver, scrambler, etc. Specifically, a power control block is needed for SAN protocol to allow the SIC receiver to resolve the signals. Notice that if a node's channel is sufficiently different than the other signals, power control will not be needed in this case. As a result, the proposed MAC protocol can be easily adapted to the currently used sensors, actuators, or IoT devices regarding transmitters by implementing power control.
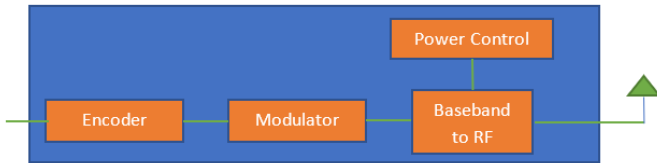

Fig. 2. A generic transmitter model for the proposed MAC protocol

A generic receiver structure for IoT gateway is given in Fig. 3. Here, the received signal is filtered by a low pass filter and properly sampled without any information loss. This means that sampling rate can be faster than symbol rate to ensure the Nyquist sampling theorem in case of excess bandwidth [12]. The underlying benefit of such kind of a structure is to become compatible with any type of transmitted waveforms or any transmitters implemented with different coding, modulation techniques. For instance, if there was a matched filter whose output is sampled by symbol rate sampling, this would be compatible with only one type of waveform to which matched filter is implemented.

Fig. 3. A generic receiver model for the proposed MAC protocol

The key elements of the proposed architecture in Fig. 3 are the multi-hypothesis testing and SIC detector. More precisely, the gateway can detect more than one packet in a slot relying on the power control at the transmitter, different channel conditions, multi-hypothesis testing and the SIC detector. That is, power control and different channels make the arrived packets powers different from each other and which are to be resolved by a SIC detector. The fundamental question here is to determine the number of incoming packets[2]. Since the number of nodes can dynamically change, and a control mechanism brings a significant overhead, a multi-hypothesis testing approach is employed. Accordingly, multi-hypothesis testing finds the number of incoming signals, however, there is a practical upper bound for the maximum number of detectable signals. This is not only for practical concerns but also to decrease the error probability of multi-hypothesis testing. Note that an upper value will be determined for the SIC detector by simulations considering the network traffic, performance and practical conditions in the next section. In short, if the number of incoming packets in a slot is lower than the upper bound, the SIC can detect this number of signals. On the other hand, if the number of incoming packets in a slot is higher than the upper bound, the number of detectable signals becomes equal to the upper bound. The advantages of this method are two-fold. First, it prevents unnecessary processing at the gateway. That is, it is a useless effort if the number of incoming packets are less than the upper bound and SIC detector strives to detect more than the incoming number of different signals. Second, it restricts the maximum detectable signal for multi-hypothesis testing so that it reduces the error probability. That is, if there are infinite number of hypothesis, the error grows significantly due to noise.

Notice that this paper solely focuses on channel access issues for large scale heterogeneous IoT applications, and the channel estimation at the receiver and the power control at the transmitter are out of scope for this paper. That is, it is assumed that channel is estimated perfectly, and power levels are adjusted properly before sending the data frames.

IV. SIMULATIONS

The biggest problem in slotted Aloha is the low throughput especially in case of high network traffic despite its desired features for large scale networks such as being dynamic, easy to implement, and minimizing control overhead. Notice that some IoT applications have been focused on low data rate applications, however the future applications of IoT such as smart city will bring heterogenous platforms including both low data rate and high data rate transmissions [13]. Hence, enhancing the throughput of slotted Aloha is important if it is to be employed in heterogenous IoT applications. Within this scope, the proposed SAN protocol whose aim is to boost the throughput of the slotted Aloha is directly compared with the conventional slotted Aloha in terms of throughput efficiency.

[2]The lack of ACKs can be a mechanism that limits the number of active transmission in each slot.

Furthermore, the decrease in the average delay by means of SAN is evaluated for low, medium and high network traffic.

The simulation result of the conventional slotted Aloha is first checked with the theoretical analysis regarding the throughput, which is equal to Ge^{-G} where G is the transmission attempts per slot. As can be seen from Fig. 4, our simulation is perfectly matched with the analytical result. In what follows the proposed SAN protocol is compared with slotted Aloha. It is clear from Fig. 4 that SAN can lead to considerable improvement in throughput even if only two different signals or packets are distinguished for one slot at the IoT gateway. Of course, further increase in the number of detected signal at a slot brings additional enhancement.
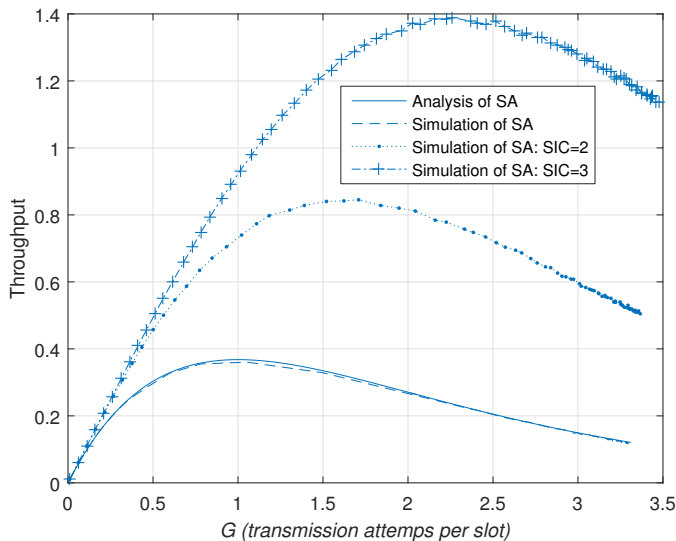

Fig. 4. Throughput advantage of the proposed SAN protocol depending on the number of detected signals due to SIC detector

To understand how SAN improves the throughput with the ascending number of detectable signals in one slot, the throughput percentage that is the ratio of the successfully transmitted packets per slot to the transmission attempts per slot is evaluated against low, medium and high traffic. Accordingly, the transmission probability p of each node in the network is selected as 0.0057, 0.057 and 0.57 corresponding to low, medium and high network traffic without any loss of generality. Observe that the probability of 0.0057 nearly offers single transmission attempt per slot providing the maximum normalized throughput of 0.37 for slotted Aloha. Hence, the curve in Fig.5 for low traffic starts at 0.37 and gradually increases depending on the number of detected signals per slot and finally reaches 1. This result is quite striking implying that each randomly transmitted packet can successfully access the channel. The same pattern is observed for medium and high network traffic as well so that a full throughput efficiency can be achieved by increasing the number of detected signals using SIC. In fact, the higher the number of detected signals the better the throughput is. Notice that the number of detected signals increases for higher network traffic for a given throughput percentage. These results are quite meaningful in

the design of a SAN receiver as stated in the previous section, which requires an upper bound for the SIC receiver to ease the function of multi-hypothesis testing.
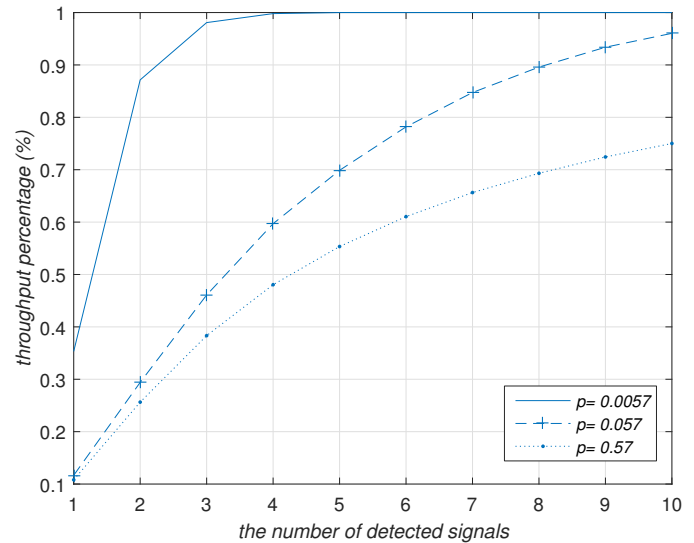

Fig. 5. SAN improvement in throughput percentage depending on the number of detected signals

Another important point for future IoT applications is the low-latency requirement for some devices. This emphasizes the importance of low latency in addition to high throughput. Considering the slotted Aloha protocol in which collided packets have to wait some back-off time increases the average delay. Hence, it is straightforward to express that increasing the throughput will also reduce the average delay. To quantify this benefit of SAN over the conventional slotted Aloha, a simulation is performed regarding the average delay in terms of the number of slots for different maximum back-off time and low, medium and high network traffic. The maximum back-off time in case of collisions is taken as 100 slots for Fig. 6. As can be seen from Fig. 6, the SAN protocol presents significant advantage compared to the slotted Aloha. Another important point that is worth to be mentioned is that the biggest improvement occurs when the SIC receiver can resolve two packets such that further increase in the number of detected signals brings less advantage.

The same simulation is performed with the same settings by only decreasing the maximum back-off time from 100 slots to 50 slots as depicted in Fig. 7 to emphasize the importance of SAN regarding the average delay. Notice that the average delay of SAN is not affected much from the maximum back-off time while the slotted Aloha is significantly affected. More precisely, the average delay increases when the maximum back-off time is decreased which can be explained by increased collisions. Furthermore, we observe the nearly same average delay for $p = 0.057$ and $p = 0.57$. As a result, the maximum back-off time is quite an important parameter in slotted Aloha, whereas it is not an issue for SAN.
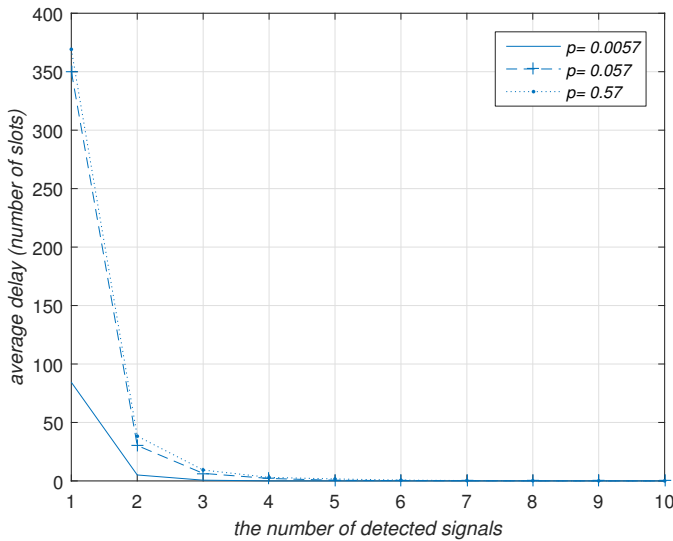
Fig. 6. The decrease in the average delay of a SAN receiver in terms of the number of detected signals when the maximum back-off time is 100 slots
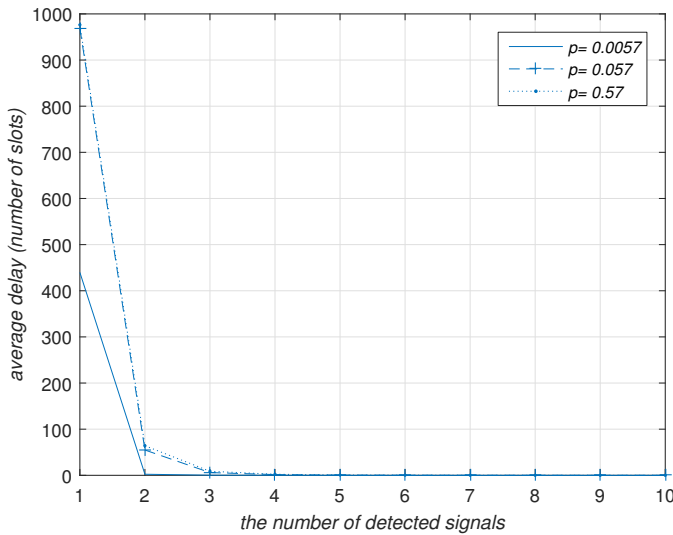

Fig. 7. The decrease in the average delay of a SAN receiver in terms of the number of detected signals when the maximum back-off time is 50 slots

V. CONCLUSIONS

This paper is directed towards an efficient MAC protocol for IoT applications by proposing a dynamic, reliable, high throughput, energy efficient, low delay, and scalable protocol. The proposed protocol called SAN has striking performance advantages compared to the conventional slotted Aloha. More precisely, SAN can increase the normalized throughput efficiency from 0:37 to 1 for low, medium and high network traffic. Additionally, SAN greatly decreases the average delay of packets irrespective of the maximum back-off time. Note that SAN can be implemented easily by the state of art IoT devices through a small modification at the transmitter or possibly no modification at all at the transmitter. These features make the SAN a promising MAC protocol for future

IoT applications over 5G networks.

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