

Rate-Splitting Random Access Mechanism for Massive Machine Type Communications in 5G Cellular Internet-of-Things

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Abstract—The cellular Internet-of-Things has resulted in the deployment of millions of machine type communication (MTC) devices under the coverage of a single gNodeB (gNB). These massive number of devices should connect to the gNodeB (gNB) via the random access channel (RACH) mechanism. Moreover, the existing RACH mechanisms are inefficient when dealing with such large number of devices. To address this issue, we propose the rate-splitting random access (RSRA) mechanism, which uses rate splitting and decoding in rate-splitting multiple access (RSMA), to improve the RACH success rate. The proposed mechanism divides the message into common and private messages and enhances the decoding performance. We demonstrate, using extensive simulations, that the proposed RSRA mechanism significantly improves the success rate of MTC in cellular IoT networks. We also evaluate the performance of the proposed mechanism with increasing number of devices and received power difference.

Index Terms—5G Cellular Internet-of-Things, gNodeB, machine type communications (MTC), random access channel, rate-splitting multiple access, received power.

I. INTRODUCTION

The cellular Internet-of-Things (C-IoT) has transformed wireless communications from human-centric to human-independent. According to an IHS Markit report [1], this will result in the deployment of approximately 125 billion smart devices by 2030. Human-centric communication is also called as human-to-human communication, and it is primarily intended for voice or video calls, web browsing etc. [2]. Machine type communications (MTC), on the other hand, which is human independent communication, is designed to support millions of devices, energy efficiency, and so on [3].

Since the MTC devices have to be energy efficient, each device wakes up to transmit the collected data and then returns to sleep state. However, in order for information to be exchanged, the device must be connected to a gNodeB (gNB). A random access channel (RACH) mechanism is the mechanism by which a device transit from a radio resource control (RRC)-idle state to an RRC-connected state. 3rd generation partnership project (3GPP) has proposed a long-term evolution

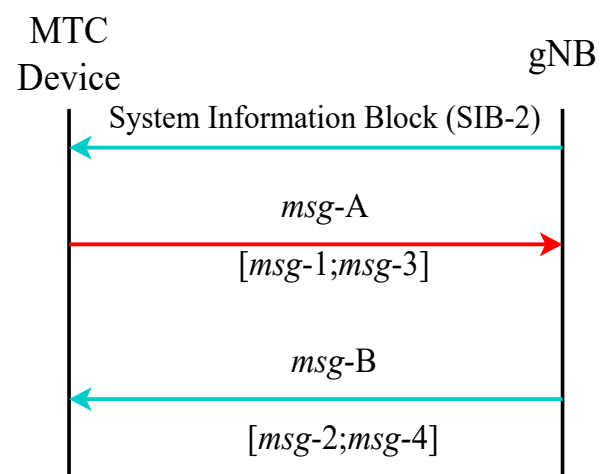


Fig. 1: RACH message exchange for 5G.

(LTE) random access channel (RACH) mechanism based on four message exchanges [4]. To reduce the latency and control-signaling overhead of LTE RACH, 3GPP has proposed a new RACH mechanism for 5G known as early data transmission (EDT), in which there is only two message exchange between each device and gNB, as shown in Fig. 1 [5].

In EDT, similar to the LTE RACH, the gNB broadcasts system information block (SIB)-2 message to all the devices under its coverage. All the devices with a packet to transmit reads the SIB-2. Here, SIB-2 indicates the preamble group to be used and configuration of preamble to resources for message (msg)-3, and the size of msg-3. After successful decoding of SIB-2, the device starts the RACH mechanism by transmitting msg-A, which is a combination of preamble msg-1 and RRC connection request msg-3 to the gNB. Here, msg-3 carries either collected data or the device identity. After successful reception of msg-A, gNB responds with msg-B, which is the combination of random access response (RAR) message

(*msg-2*) and RRC Contention resolution message (*msg-4*). The messages from *msg-1* to *msg-4* are same as defined for LTE RACH. There are three types of responses possible from the gNB to an MTC device based on the type of message received. The first one is no response due to the failure in receiving *msg-A*. In this case, the device takes a backoff and starts either two message exchange or falls back to four message exchange of LTE. The second one is the successful reception of *msg-1* but, failure to decode *msg-3*. In this case, the gNB responds with *msg-2* (RAR message) of four message exchange to indicate the PUSCH for retransmission of *msg-3* of *msg-A*. Then, the gNB responds with *msg-4* of *msg-B* after successful reception of *msg-3*. The third one is the successful reception of both the messages of *msg-A*. In this case, the gNB responds with *msg-B* (*msg-2+msg-4*) that indicates the contention resolution ID. Successful reception of *msg-B* indicates successful RACH [5].

In RACH, congestion is a major limiting factor due to the large number of connection requests. Extended access barring (EAB) has been proposed as a connection control mechanism in 3GPP specifications [5]. Further, the EAB has been studied in [6] and two improved EAB schemes have been proposed. Similarly, [7] has proposed a distribution method based on non-orthogonal multiple access (NOMA) and Q-learning to dynamically allocate random access slots and handle massive MTC networks. The two-phase cluster-based group paging scheme was proposed in [8] to handle massive MTCs simultaneous channel access and overcome the limitations of the 3GPP. The orthogonal sequences generated from both Gaussian distribution and the Zadoff-Chu (ZC) have been studied and analyzed for asymptotic behavior for success probabilities using NOMA, and the closed-form expression has been derived in [9]. A Markov chain-based access barring (M-ACB) to reduce congestion of both delay-tolerant devices and delay-sensitive devices to properly utilize network resources has been studied in [10]. A distributive approach has been proposed in [11] to estimate the optimal back-off parameters according to precise interpretations of the observed statistics. With such a large number of MTC devices, resource allocation complicates the concern even more. To manage resources among MTC devices, a scheme has been proposed in [12] to dynamically prioritise the MTC devices.

In [13], the authors have proposed a non-orthogonal random access (NORA) mechanism that utilizes intra-slot successive interference cancellation (SIC) to decode the *msg-3* of collided devices. In this mechanism, the gNB can successfully decode the *msg-3* of two collided devices if the time in their *msg-3* arrival is greater than the root mean square of the delay spread. A SIC-based RACH mechanism has been proposed in [14], [15] that utilizes repetition at the device side and inter-slot SIC at the gNB. Moreover, a SIC-NORA mechanism has been proposed in [16] that utilizes both intra-slot and inter-slot SIC at gNB to further enhance the number of successful devices. However, the mechanisms in [14]–[16] increases the network congestion and energy consumption due to the repetitions of *msg-3*.

Recently, RSMA has gained a lot of attention due to its robust transmission and general framework in comparison to NOMA and space division multiple access (SDMA). It has been shown in [17] that RSMA significantly improves the achievable data rate in comparison to NOMA and SDMA. Several existing works focus on downlink and uplink transmission using RSMA [17]–[22]. Moreover, RSMA can improve the quality of service and spectral efficiency for downlink transmission under the perfect channel state information of transmitter (CSIT) or imperfect CSIT [21], [23]. In RSMA, each user's message to be transmitted is split into two sub-messages such as the common and private message. The sub-messages of different users are then super positioned and transmitted to the receiver. Further, the receiver decodes the respective sub-messages by applying SIC. However, RSMA faces few challenges during implementation [23]. Firstly, the decoding order of sub-messages needs to be carefully designed. Secondly, resource management for transmission of messages. Several works study the downlink RSMA. However, only a few existing works concentrate on uplink RSMA for performance improvement [22]. Further, the RACH mechanism has not been studied with RSMA. Motivated by this, we propose rate-splitting random access (RSRA) mechanism in this work. In the proposed mechanism, we consider *msg-1* as the common message and *msg-3* as the private message. The MTC devices with the same preamble use the same resource for *msg-3* transmission. On the other hand, the gNB decodes the preamble (common message) first, and then it applies SIC to decode the private messages (*msg-3*) of each device based on the received power. This will enhance the number of devices that are getting success in each time slot. The key contributions of this work are as follows:

- We propose a novel RSMA based RACH mechanism named as the RSRA mechanism for MTC in 5G. Wherein, we consider *msg-1* as the common message and *msg-3* as the private message.
- We present numerical results to obtain the number of contending devices and the corresponding successful devices in each time slot.
- We discuss the effect of increasing number of MTC devices on the performance of the proposed mechanism.
- We present simulation results that demonstrate the impact of the received power difference between the *msg-3* of collided devices on the performance of the proposed RSRA mechanism.
- We present numerical results comparing the proposed mechanism's performance to that of state-of-the-art RACH mechanisms.

The remainder of the paper is framed as follows: In Section II, we discuss the system model and the proposed RSRA mechanism. Through extensive simulation results, the performance of the proposed mechanism is evaluated in Section III. Finally, Section IV provides the conclusion along with possible future work.

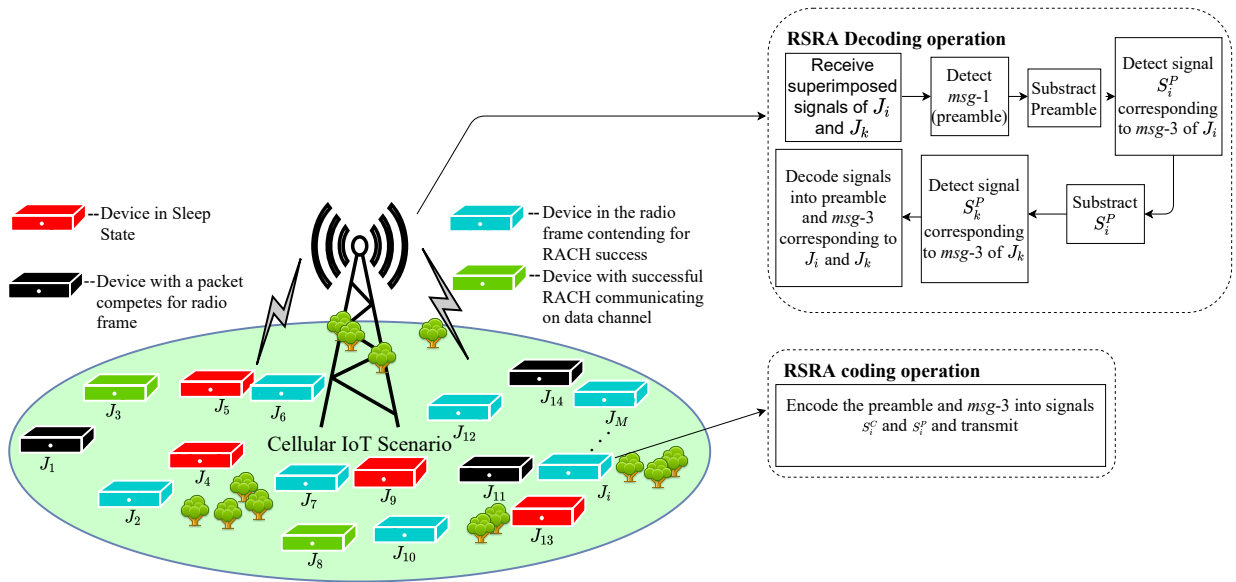


Fig. 2: System model.

II. SYSTEM MODEL

We consider a C-IoT scenario wherein, M devices namely $J_i \forall i \in \{1, 2, \dots, M\}$ deployed randomly under the coverage of a single gNB. These MTC devices are in either of the four states as shown in Fig. 2 [15]. Devices with no data to transmit remain in the sleep state. The device with a packet to transmit wake up and competes for radio frame for the initiation of RACH mechanism. The device in the radio frame competes for RACH success. All MTC devices that have successfully completed RACH, transmit data using a hybrid automatic repeat request (HARQ).

A. RSRA coding and decoding operation

The proposed RSRA coding and decoding operation is described in Fig. 2. Each MTC device transmits the encoded $msg-A$ consisting of a preamble and an RRC connection request as signals s_k^c and s_k^p , respectively. In particular, preamble and RRC connection request represents the common message and private message, respectively. Thus, s_k^c and s_k^p represent the common signal and private signal of the k th device, respectively. On the other end, the gNB responds with $msg-B$, which is the random access response message followed by contention resolution message, after successfully decoding the $msg-A$. In case only one device selects a given preamble, the gNB can successfully decodes $msg-A$ and responds with $msg-B$ to all such devices. If more than one device select a given preamble, they use the same resource to transmit $msg-3$ that leads to collision in $msg-3$. To all such messages, the gNB applies the RSRA decoding mechanism to successfully decode $msg-3$. The decoding operation is performed in a series of steps. The RSRA decoding order for two users J_m and J_n is shown in Fig. 2. Because both devices have selected and transmitted the same preamble, first part of the $msg-A$ (s_k^c) can be decoded at gNB. Thereafter, gNB sequentially decodes the

second part of the $msg-A$ (s_K^p) based on their received powers for $k = m$ and $k = n$. This procedure is repeated until all collided devices' $msg-3$ have been successfully decoded.

B. Proposed RSRA Mechanism

Similar to 3GPP EAB mechanism, in the proposed mechanism, the gNB broadcasts SIB-2 message that indicates the configuration information of preamble and $msg-3$ and access barring parameter P as given in Algo. 1. Each MTC device generates n uniformly from $[0, 1]$ upon successful reception of SIB-2. An MTC device with $n < P$ enters into a radio frame by selecting a time slot uniformly from $\{1, 2, \dots, T\}$. A device that has selected a time slot t , waits for $t-1$ time slots and transmits its $msg-A$, which is concatenation of a preamble followed by $msg-3$ after a guard band. Here, preambles are chosen randomly from the set $\{1, 2, \dots, K\}$. As stated earlier, the preamble and the $msg-3$ are transmitted using signals s_k^c and s_k^p , respectively, each with a transmit power of P_T .

On the other end, gNB can decode the $msg-3$ of a device in case it alone chooses a given preamble. Since the resources for $msg-3$ transmission are configured to each preamble, the device alone transmits the $msg-3$. In case a given preamble is chosen by two or more devices, they get the same resource for $msg-3$ transmission. This leads to a collision. However, with RSRA mechanism, the gNB may decode the $msg-3$ of such collided devices using SIC as given in Algo. 1. The gNB starts the decoding of $msg-3$ based on their difference in the descending order received powers. In case the difference in the received powers of $msg-3$ of first device and second device in the descending order set is greater than ΔP , the gNB can successfully decode $msg-3$ of the first device [22]. This process repeats until either all devices are decoded or till the difference in power levels of two devices in the descending order set is greater than ΔP as given in Algo. 1. The derivation of the expression for P_R is discussed in the following section.

Algorithm 1: Proposed RSRA algorithm.

Input: P
Output: RACH success

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1 if There is data then
2   Uniformly generate a number  $n$  from  $[0, 1]$ ;
3   if  $n < P$  then
4     Select a time slot from the set  $\{1, 2, \dots, T\}$ 
       uniformly at random;
5     Wait for the transmission slot;
6     Select a preamble from the set  $\{0, 1, \dots, K\}$ 
       uniformly;
7     Start RACH mechanism by transmitting the
       preamble followed by  $msg-3$ ;
8     if RACH success then
9       Go to Step 1;
10    else if There is a collision in  $msg-3$  then
11      Sort the  $P_R$  of  $msg-3$  of all the collided
        devices in descending order;
12      while The difference in  $P_R$  of two devices
        in the descending order set is greater than
         $\Delta P$  do
13        RACH success with SIC;
14        Go to Step 1;
15      end
16    else
17      Wait for the current radio frame to finish
        and go to Step 2;
18    end
19  else
20    Wait for the current radio frame to finish and
    go to Step 2;
21  end
22 else
23   Wait for the current radio frame to finish and go to
    Step 1;
24 end

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C. Received Power Calculation

The expression of received power, P_R , (in dB) is given as [24]

$$P_R = P_T - PL, \quad (1)$$

where, P_T (in dB) denotes the transmit power at device and PL (in dB) denotes the propagation/path loss. Propagation loss is defined as the amount of power loss in the channel for transmission. For the calculation of pathloss, we consider Okumura-Hata model in this paper [25]. The expression for pathloss in an urban environment is obtained as

$$PL(dB) = A_1 + A_2 \log_{10}(r), \quad (2)$$

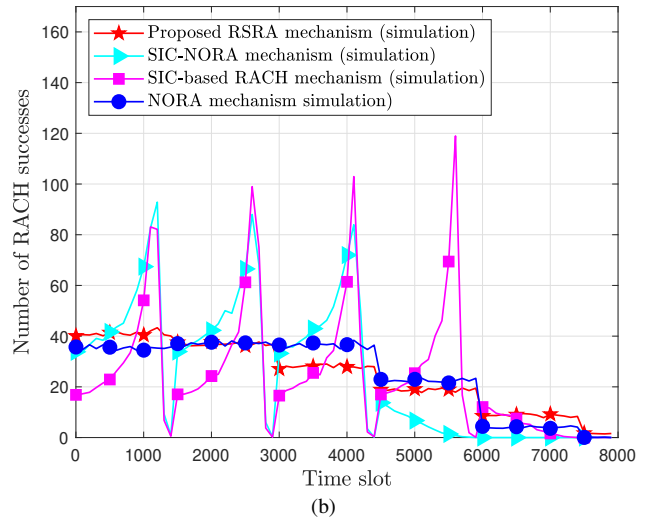
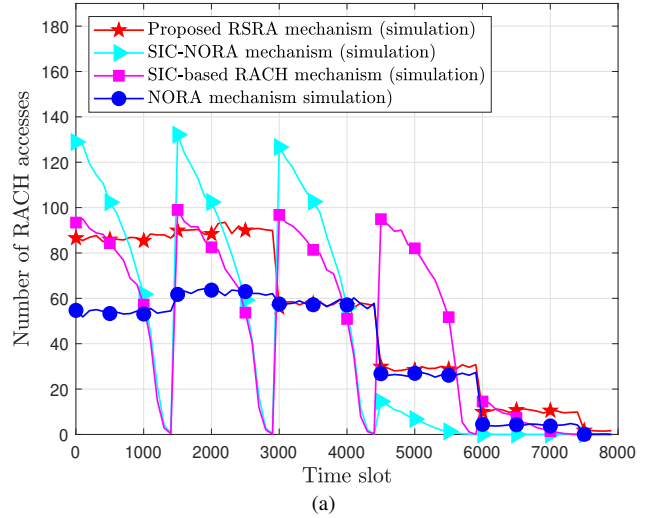


Fig. 3: The performance comparison of the proposed mechanism with the existing mechanisms in terms of (a) average number of contending devices and (b) average number of successful devices in a time slot for $T = 1482$, $K = 54$, $P = 0.9$, and $\Delta P = 7$ dB.

where, r denote the distance of the device from the gNB. The expressions for A_1 and A_2 are obtained as

$$A_1 = 69.55 + 26.16 \log_{10}(f_M) - 13.82 \log_{10}(h_g) - (1.1 \log_{10}(f_M) - 0.7)h_d, \quad (3)$$

$$A_2 = 44.9 - 6.55 \log_{10}(h_g), \quad (4)$$

where, h_g and h_d denote the gNB height and device height in meters, respectively, and f_M is the operating frequency in MHz.

III. NUMERICAL RESULTS

We present the simulation results to compare the performance of the proposed mechanism with the state-of-the-art mechanisms in this section. Further, we compare the perfor-

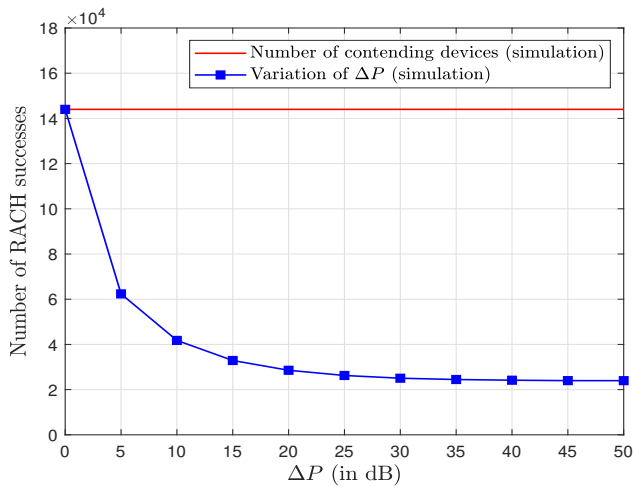


Fig. 4: Number of RACH successes in a radio frame vs ΔP (in dB) for the proposed RSRA mechanism with $P = 1$, $T = 1482$, and $k = 54$.

mance with increasing number of RACH accesses. Finally, we evaluate the effect of ΔP .

We consider a scenario of C-IoT with $M = 2 \times 10^5$ MTC devices uniformly deployed in a circular area of 2 kilometer radius. As per the 3GPP standards, we consider $T = 1482$, $K = 54$, $P_T = 24$ dBm, $f_M = 1500$ MHz, $h_g = 30$ m, and $h_d = 1.5$ m [4], [25]. Further, we consider the total energy consumed for a 2-step RACH mechanism as $264\mu\text{J}$ [26].

Figs. 3a and 3b show the number of contending devices and the corresponding successful devices in a time slot for all the mechanisms considered in this paper. From Fig. 3, it is observed that there is an average of 69 devices contends in a time slot which then results in an average of 26 successes with NORA mechanism. Further, there are an average of 61 contending devices in a time slot which then results on an average of 33 successes with the SIC-based RACH mechanism. Moreover, the SIC-NORA mechanism allows an average of 92 contending devices and result in an average of 43 successful devices. Finally, we observe that the proposed mechanism allows an average of 87 contending devices which results in an average of 43 successes. Even though the maximum number of RACH successes with the proposed mechanism is same as SIC-NORA mechanism, the proposed mechanism reduces the network congestion and energy consumption in comparison to SIC-NORA mechanism due to single transmission.

Fig. 4 shows the number of successful devices with increasing value of ΔP for the proposed RSRA mechanism with 1.45×10^5 contending devices. Here, we varied ΔP from 0 dB to 50 dB. From Fig. 4, it is observed that the proposed RSRA mechanism can decode all the devices in a perfect ideal scenario, i.e. $\Delta P = 0$ dB. However, it is not possible in practice. We consider the ideal case for a fair analysis of the degradation of success rate with increasing ΔP . It is observed that the number of successful devices reduces exponentially with increasing value of ΔP . Thus, we conclude that the

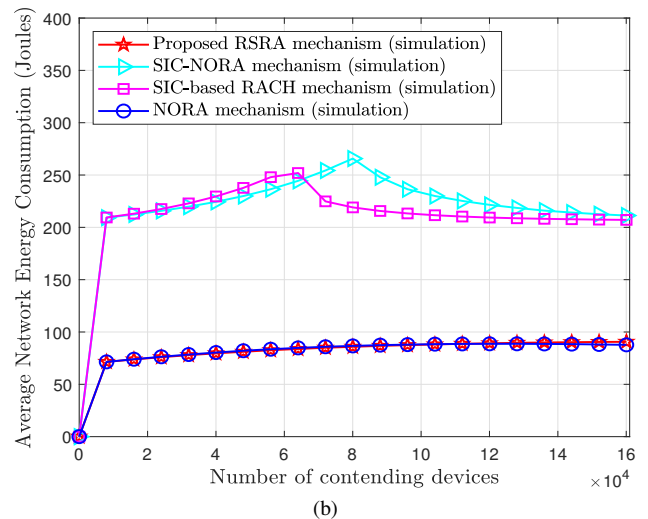
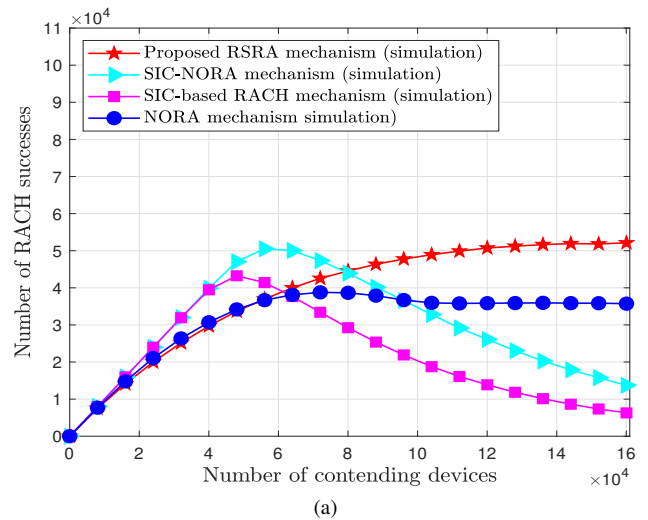


Fig. 5: (a) Average number of successful devices and (b) average network energy consumption in a radio frame with $T = 1482$, $k = 54$, $P = 1$, and $\Delta P = 7$ dB.

receiver design place a crucial role in enhancing the number of successful devices.

Figs. 5a and 5b show the variation of number of RACH successes and the average energy consumption in the network with increasing number of contending devices for all the mechanisms considered in this work. It is observed from Fig. 5a that there is a maximum of 5.19×10^4 successes with the proposed mechanism. Further, it is observed that NORA mechanism, SIC-based RACH mechanism, and SIC-NORA mechanism results in a maximum of 3.82×10^4 , 4.19×10^4 , and 5×10^4 successes, respectively. Thus, it is concluded that the proposed RSRA mechanism outperforms other mechanisms in terms of number of successful devices. Even though the performance of the proposed mechanism is comparable to SIC-NORA mechanism, the energy consumption of the proposed mechanism is less as there is no repetition rate as can be observed from Fig. 5b. The SIC-NORA mechanism consumes

more energy due to the repetition rate which can be avoided in the proposed RSRA mechanism for the same RACH success rate.

IV. CONCLUSION

A rate-splitting random access mechanism has been proposed in this paper to improve the number of successful devices for cellular Internet-of-Things. The MTC devices can transmit *msg-A* in a randomly selected time slot under the proposed mechanism. Following that, the gNB can decode the *msg-3* of multiple collided devices with RSRA in a time slot based on their received power differences. In addition, we have evaluated the performance of the proposed mechanism with varying difference in received powers and number of contending devices. In comparison to state-of-the-art mechanisms, the proposed mechanism can support more number of devices. Furthermore, as the value of difference in received powers increases, the success rate decreases exponentially. This is due to the fact that the gNB cannot decode the devices if the received power difference is less than the threshold. Thus, we conclude that the receiver design is critical in improving the RACH success rate. We will derive the analytical expression for the average number of successful devices in the future for the proposed mechanism.

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