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. These massive number of devices must communicate with a single gNodeB (gNB) via the random access channel (RACH) mechanism. However, 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 RACH success rates. 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.

Keywords- Cellular Internet-of-Things, gNodeB, machine type communications (MTC), random access channel, rate-splitting multiple access, received power.

I. INTRODUCTION

wireless communications from human-centric to humanwill 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]. support millions of devices, energy efficiency, and so on [3]. be used and configuration of preamble to resources for msg-

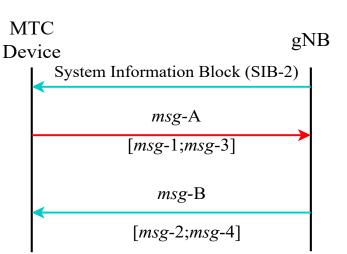


Fig. 1: RACH message exchange for 5G.

The cellular Internet-of-Things (C-IoT) has transformed message exchanges [4]. To reduce the latency and controlsignaling overhead of LTE RACH, 3GPP has proposed a new independent. According to an IHS Markit report [1], this 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 Machine type communications (MTC), on the other hand, under its coverage. All the devices with a packet to transmit which is human independent communication, is designed to reads the SIB-2. Here, SIB-2 indicates the preamble group to Since the MTC devices have to be energy efficient, each 3. After successful decoding of SIB-2, the device starts the device wakes up to transmit the collected data and then RACH mechanism by transmitting message (msg)-A, which returns to sleep. However, in order for information to be is a combination of preamble msg-1 and RRC connection exchanged, the device must be connected to a gNodeB request (data or device identity) msg-3 to the gNB. After (gNB). A random access channel (RACH) mechanism is successful reception of msg-A, gNB responds with msg-B, the mechanism by which a device transitions from a radio which is the combination of RA message msg-2 and RRC resource control (RRC)-idle state to an RRC-connected state. Contention resolution msg-4. The messages from msg-1 to 3rd generation partnership project (3GPP) has proposed an msg-4 are same as defined for LTE RACH. There are three long-term evolution (LTE) RACH mechanism based on four types of responses possible from the gNB to an MTC device

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 (RA response) of four message exchange to indicate the PUSCH for retransmission of msg-3 of msg-A. Then, split into two sub-messages such as the common and private the gNB responds with msg-4 of msg-B. The third one is message. The sub-messages of different users are then super 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].

The two-phase cluster-based group paging scheme was proposed in [6] to handle massive MTCs simultaneous channel access and overcome the limitations of the 3GPP. As a result of the large number of connection requests, congestion is a major limiting factor. Extended access barring (EAB) has been proposed as a connection control mechanism in 3GPP specifications. The EAB has been studied in [7] and two improved EAB schemes have been proposed. Similarly, [8] has proposed a distribution method based on non-orthogonal multiple access (NOMA) and O-learning to dynamically allocate random access slots and handle massive MTC networks. 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 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 a threshold. A successive interference cancellation (SIC)based RACH mechanism has been proposed in [14] that utilizes repetition at the device side and inter-slot SIC at the gNB. Moreover, a SIC-NORA mechanism has been proposed in [15] that utilizes both intra-slot and inter-slot SIC at gNB to further enhance the number of successful devices. However, the mechanisms in [14], [15] 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

based on the type of message received. The first one is no achievable data rate in comparison to NOMA and SDMA. Several existing works focus on downlink and uplink transmission [16], [17], [18], [19], [20], [21]. However, RSMA can improve the quality of service and spectral efficiency for downlink transmission under the perfect channel state information of transmitter (CSIT) [20], [22] or imperfect CSIT. In RSMA, each user's message to be transmitted is positioned and transmitted to the receiver. Further, the receiver decodes the respective sub-messages by applying SIC. However, RSMA faces few challenges during implementation [22]. 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 [21]. 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, the MTC devices with the same preamble use the same resource for msg-3 transmission. On the other hand, the gNB decodes the preamble first, and then it applies SIC to decode the rest of sub-messages from 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.
- 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.

II. SYSTEM MODEL

We consider a C-IoT scenario wherein, M devices namely $J_i \ \forall \ i \in \{1,2,\cdots,M\}$ deployed randomly under the coverage of a single gNB b. These MTC devices are in either of the four states as shown in Fig. 2 [14]. Devices with no robust transmission and general framework in comparison to data to transmit remain in the sleep state. The device with NOMA and space division multiple access (SDMA). It has a packet to transmit wake up and competes for radio frame been shown in [16] that RSMA significantly improves the for the initiation of RACH mechanism. The device in the

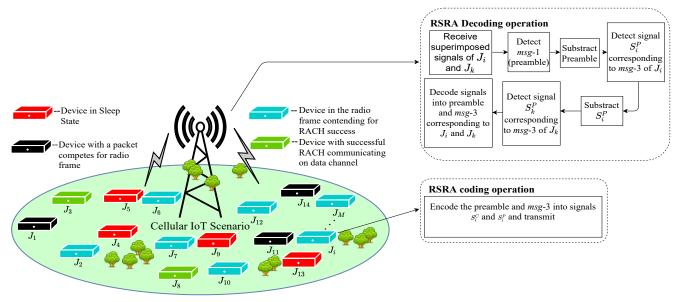


Fig. 2: System model.

a hybrid automatic repeat request.

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 \boldsymbol{s}_k^c and \boldsymbol{s}_k^p , respectively. In particular, \boldsymbol{s}_k^c and s_k^p represent the common signal and private signal of the kth device. 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 for transmission. For the calculation of pathloss, we consider

radio frame competes for RACH success. All MTC devices enters into a radio frame by selecting a time slot uniformly that have successfully completed RACH transmit data using from $\{1, 2, \cdots, T\}$. 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 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 the difference in the powers of to msg-3s. In case the difference of a msg-3 of a device with highest received power and the msg-3 of another device with second highest received power is more than ΔP , the gNB can successfully decode msg-3 of the device with highest received power [21]. This process repeats until either all devices are decoded or till the difference in power levels is greater than ΔP as given in Algo. 1. The derivation of the expression for P_R is discussed in the following section.

C. Received Power Calculation

The expression of received power, P_R , (in dB) is given as [23]

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

where, P_T (in dB) denotes the transmitted 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

Algorithm 1: Proposed RSRA algorithm.

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

Okumura-Hata model in this paper [24]. The expression for pathloss in an urban environment is obtained as

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

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

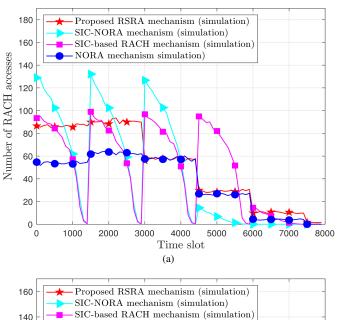
$$A_1 = 69.55 + 26.16 \log_{10}(f_M) - 13.82 \log_{10}(h_g) - (1.1 \log_{10}(f_M) - 0.7)h_d,$$

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

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

III. NUMERICAL RESULTS

mance of the proposed mechanism with the state-of-the- results on an average of 33 successes with the SIC-based art mechanisms in this section. Further, we compare the RACH mechanism. Moreover, the SIC-NORA mechanism



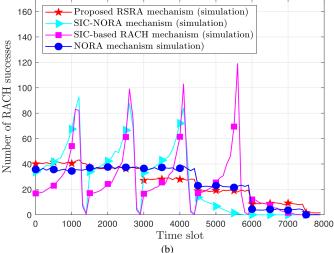


Fig. 3: The performance comparison of the proposed mechanism with the existing mechanisms in terms of (a) average number of contending devices and (b) average number of successful devices in a time slot for T=1482, K=54, P=0.9, and $\Delta P=7$ dB.

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

We consider a scenario of C-IoT with $M=2\times 10^5~{\rm MTC}$ devices uniformly deployed in a circular area of 2 KM radius. As per the 3GPP standards, we consider T = 1482, K = 54, $P_T=24$ dBm, $f_M=1500$ MHz, $h_q=30$ m, and $h_d=1.5$ (3) m [4], [24].

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 We present the simulation results to compare the perfor- average of 61 contending devices in a time slot which then

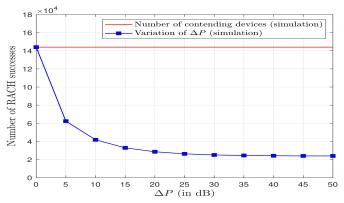


Fig. 4: Number of RACH successes in a radio frame vs ΔP (in dB) for the proposed RSRA mechanism with P=1, T=1482, and k=54.

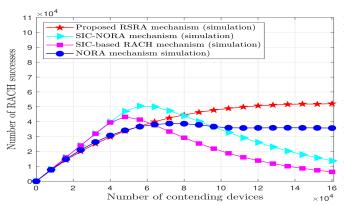


Fig. 5: Average number of successful devices in a radio frame with $T=1482,\ k=54,\ P=1,$ and $\Delta P=7$ dB.

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

Fig. 5 shows the variation of number of RACH successes with increasing number of contending devices for all the

mechanisms considered in this work. It is observed from Fig. 5 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 $3.82\times10^4,\,4.19\times10^4,\,$ and 5×10^4 successes, respectively. Thus, it is concluded that the proposed RSRA mechanism outperform 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.

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-theart 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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