Received December 11, 2020, accepted December 28, 2020, date of publication January 5, 2021, date of current version January 14, 2021.

*Digital Object Identifier 10.1109/ACCESS.2021.3049439*

# A Successive Interference Cancellation Based Random Access Channel Mechanism for Machine-to-Machine Communications in Cellular Internet-of-Things

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This work was supported in part by the Science and Engineering Research Board (SERB), Govt. of India through its Early Career Research (ECR) Award (Ref. No. ECR/2016/001377), and the Department of Science and Technology (DST), Govt. of India (Ref. No. TMD/CERI/BEE/2016/059(G) and DST/TMD/MI/OGMI/2018/3(G)).

**ABSTRACT** In Cellular Internet-of-Things, random access channel (RACH) mechanism is used by machine-to-machine communication (M2M) devices to connect to a base station (BS) for any information exchange. However, increase in the number of M2M devices increases the network contention and reduces the number of RACH successes. In order to address this problem, we propose a successive interference cancellation based non-orthogonal random access (SIC-NORA) mechanism. In the proposed mechanism, each M2M device is allowed to repeat its transmission in a finite number of time slots within a radio frame. The messages of two devices that collide in the same slot can be decoded if the difference in the arrival time of their messages is greater than the predetermined threshold. Upon the successful RACH from an M2M device, the BS applies SIC in the current and all previous slots of the radio frame to decode messages of other devices for enhanced RACH success. A Markov chain model of the proposed mechanism is developed and the corresponding steady-state probabilities are derived. Through extensive numerical results, we show that the proposed mechanism performs better than state-of-the-art RACH mechanisms in terms of number of RACH successes and average access delay. Further, the proposed mechanism improves the success rate by 65.3% and 30.3% as compared to NORA and SIC-based RACH mechanism, respectively. Moreover, there is 29.6% and 15% reduction in the number of time slots required for $2 \times 10^5$ devices to get success with the proposed mechanism as compared to NORA and SIC-based RACH mechanism, respectively, at the corresponding optimal value of radio frame length.

**INDEX TERMS** Machine-to-machine (M2M) communications, Markov chain model, non-orthogonal random access (NORA), random access channel (RACH), successive interference cancellation (SIC).

## I. INTRODUCTION

Iinternet-of-Things (IoT) has led to the deployment of millions of machine-to-machine communication (M2M) devices. In cellular IoT, a large number of these devices can connect to a single base station (BS). Initially, all such M2M devices reside in radio resource control (RRC)-idle state, wherein, these devices do not have any data to transmit and are not connected to the BS. Whenever an M2M device gets ready to transmit data, it wakes up and attempts to connect to the BS. This connection mechanism from RRC-idle to RRC-connect state is termed as random access channel (RACH) mechanism [1].

A typical RACH mechanism involves exchange of four unique messages between each M2M device and the BS as shown in Fig. 1. Initially, the BS broadcasts a system

The associate editor coordinating the review of this manuscript and approving it for publication was Yanli Xu.

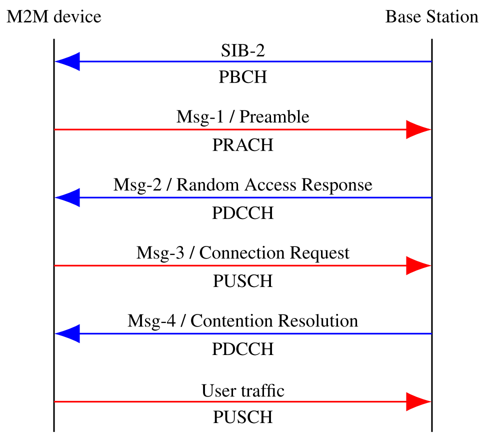


**FIGURE 1. The random access mechanism [1].**

information block (SIB)-2 message over the physical broadcast channel (PBCH) to initiate the RACH mechanism. Each M2M device that successfully decodes SIB-2, activates a preamble uniformly at random from the set of available orthogonal preambles and transmits the same to the BS as Message-1 (Msg-1) over the shared physical random access channel (PRACH). The Msg-1 does not contain the device identity. Thus, the BS cannot find the identity of devices that have activated a particular preamble from Msg-1. For each decoded preamble, the BS replies with a random access response message (Msg-2) over the physical downlink control channel (PDCCH). The Msg-2 indicates the uplink resources (channel) allocated for transmission of Msg-3. Each M2M device that successfully receives Msg-2, transmits a connection request message (Msg-3) that contains a unique device identity over the physical uplink shared channel (PUSCH). In case a given preamble is activated by only one M2M device during the exchange of Msg-1, the BS can successfully decode its Msg-3, and subsequently identify the device. For each successfully decoded Msg-3, the BS responds with contention resolution message (Msg-4) over PDCCH to inform the device of RACH success. Later, each connected device can communicate with the BS on the data channel. In case, more than one device activate a given preamble during Msg-1 transmission, all of them get the same resource for Msg-3 transmission. This in-turn leads to a collision in Msg-3 and the BS fails to decode Msg-3 of such devices. Thus, such devices will not receive Msg-4 and freshly start the RACH mechanism after a random back-off [2].

It has been suggested in [3] that the successive interference cancellation (SIC) can be utilized to improve the RACH success rate [3]. Motivated by this, a non-orthogonal random access (NORA) mechanism has been proposed in [4] that utilizes the *intra-slot* SIC (SIC within the same slot) in order to decode the Msg-3 in presence of collisions. It is assumed that the Msg-3 of two devices, that have collided in the same slot, can be decoded if the inter-arrival time of their Msg-3 is greater than $\tau$ in a given slot. Here, $\tau$ denotes the root mean square of the delay spread. On the contrary, an SIC-based RACH mechanism, which utilizes *inter-slot* SIC (SIC in the previous slots) to decode the Msg-3 of collided devices, has been proposed in [5] and [6]. In this mechanism, the devices are allowed to repeat their transmissions in a finite number of time slots in a given radio frame. In [5] and [6], it has been assumed that each Msg-3 carries information about all its previous transmissions. After successfully decoding Msg-3 of a particular device, the BS extracts the time slots where the device has previously transmitted and recursively performs SIC to successfully obtain the Msg-3 of other devices in the previous slots. However, to the best of our knowledge, the joint utilization of both *intra-slot* and *inter-slot* SIC has not been addressed in the literature. Thus, in this paper, we propose a novel SIC-NORA mechanism that utilizes both *intra-slot* and *inter-slot* SIC to improve the throughput. In the proposed mechanism, each M2M device is allowed to repeat its transmission in a finite number of time slots within a radio frame. It is considered that the messages of two devices that collide in the same slot can be decoded if the difference in the arrival time of their messages is greater than the predetermined threshold. Upon the successful RACH from an M2M device in a slot, the BS applies SIC in the current and all previous slots of the radio frame to decode messages of other devices for enhanced RACH success. The contributions of this work are as follows.

- The proposed SIC-NORA mechanism is represented using a Markov chain model and analytical expressions for the corresponding state transition probabilities and steady-state probabilities are derived.
- A numerical analysis is used to obtain the probability of successful SIC.
- The analytical expression for the number of RACH successes is derived.
- Through extensive numerical results, we show that the proposed mechanism outperforms the existing ones in terms of average number of RACH successes, number of supported devices, and average access delay. The effect of repetition rate on the performance of the proposed mechanism is also studied.
- The effect of physical layer impairments on the performance of the proposed mechanism is analyzed.

The rest of the paper is organized as follows. The related work is presented in Section II. The system model and the proposed RACH mechanism are discussed in Section III. The Markov model of the proposed mechanism along with all transition probabilities is presented in Section IV. In Section V, the steady-state probabilities are derived. The numerical results are presented in Section VI. Finally, Section VII provides some concluding remarks along with possible future works.

## II. RELATED WORK

The increase in the number of M2M devices increases the network congestion and reduces the number of

RACH successes. In order to address this issue, 3GPP has proposed an extended access barring mechanism in [7] that controls the number of RACH accesses in a radio frame by using access class barring parameter to improve the RACH successes. To further enhance the RACH success rate many mechanisms have been proposed in the literature. A fast RACH mechanism has been proposed in [8] that allows a fixed number of devices to contend in a time slot that results in more number of RACH successes. In [9], a distributed queue based approach has been proposed that allows the M2M devices to self organize themselves into a logical queue and start RACH mechanism based on the device's position in the logical queue in order to improve the success rate. The concept of preamble priority awareness has been introduced in [10] to analyse its impact on the PDCCH. In this mechanism, the random access response and contention resolution messages have been scheduled to avoid the blocking of these messages to improve the success probability of priority devices that are defined based on the random access approach. In [11], a novel random access scheme has been proposed that generates the virtual preambles by associating actual preambles with the PRACH indices. This in turn reduces the preamble collisions and improves the success rate. A quality of service based dynamic adaptive mechanism (QDAM) has been proposed in [12] which is a combination of dynamic RACH resource allocation and access class barring mechanisms. Initially, the priority has been given to the delay sensitive devices. Based on the number of failed devices, the access class barring parameter has been adaptively adjusted to control the number of contending devices in [12]. Markov-chain-based access class barring (M-ACB) scheme has been proposed in [13] to reduce the congestion of M2M devices consist of both delay sensitive devices (DSDs) and delay tolerant devices (DTDs). A 6-D Markov chain model has been presented to model the preamble allocation to both the classes and to estimate the number of active devices to contend in the next time slot. Then, the barring factor and allocated preambles have been adjusted dynamically based on the estimate in order to improve performance metrics such as time delay, success rate, and collision rate [13]. A novel time distributed initial access mechanism has been proposed in [14] that groups the smart meters and available preambles and allows each smart meter to calculate its start time for RACH access. This reduces the network overhead in [14]. A two-phase cluster-based group paging (CBGP) scheme has been proposed in [15] that forms the clusters in each paging group of the cell. Each M2M device in a cluster communicates with the cluster head using IEEE 802.11ah during the data collection phase and then forwards to the BS in data transmission phase which reduces the access delay and increases the successful access probability of M2M devices [15]. In [16], a simulation study has been carried out to study the impact of increasing number of devices on RACH success rate in the presence of only M2M traffic as well as mixed traffic. It has been concluded that the RACH performance is not affected by the available preambles and is limited by PDCCH resources [16]. In [17], the authors have shown the effectiveness of the machine learning techniques in detecting the number of users that have transmitted a given preamble so as to control the network traffic in order to improve the success rate. A flexible preamble allocation scheme has been proposed in [18] that enables the base station to fine tune the preamble allocation to reduce the collisions and energy consumption. In [19], a novel collaborative distributed Q-learning approach has been proposed that enables the M2M devices to uniquely identify the random access (RA) slots for their transmission. The Q-learning approach in [19] minimizes the congestion level of RA slots as a cost function to enhance the success rate. A compressed sensing-based random access channel mechanism has been proposed in [20] to reduce the overall access delay by reducing the preamble collisions. A novel random access preambles have been adopted and each device allocated with a unique preamble. Then, the compressed sensing technique has been used to detect the active users accurately [20]. In [21], the authors have obtained the joint probability density function of number of successful and collided devices in a radio frame opportunity (RAO) which can be used to estimate the number of contending devices in the next RAO.

A compressed sensing based random access scheme has been proposed in [22] that compresses the four message exchange in conventional random access scheme to two message exchange in order to improve the successful access probability and access delay. In this mechanism, each user combines the preamble (generated from the Gaussian distribution) with the connection request message and transmit this summation in PRACH. Then, the BS decodes the messages of each device based on the sparsity condition and transmit power. To each successful message, the BS responds with connection setup message [22]. A novel random access mechanism with secondary access class barring has been proposed in [23] that allows the barred devices during the primary access class barring (PACB) to utilize the hidden random access opportunities (RAOs) using secondary access class barring (SACB). The information about the hidden RAOs is intimated by the BS so that the barred devices in PACB can utilize these mined RAOs in the second round using SACB. The proposed mechanism in [23] reduces the delay and energy consumption by achieving an efficiency of 53% compare to the typical RACH mechanism with 37% success rate. In [24], an analytical framework has been proposed to optimize the RACH performance by optimizing the access throughput by properly adjusting the ACB parameter and uniform backoff window size according to the number of M2M devices and the traffic from each device. The analytical framework proposed in [24] has been extended in [25] to analyse the effect of data transmission rate which is defined as the number of data packets transmitted per time slot on the optimal access throughput. An analysis of energy harvesting based ACB mechanism has been carried out in [26] to study the joint effect of an energy-threshold-based activation policy and the ACB mechanism on the RACH performance in terms of random access success probability and average access delay. In [27], the application of non-orthogonal preambles generated from Gaussian distribution sequences and Zadoff-Chu (ZC) sequences has been considered to further enhance the success probability of massive multiple-input and multiple-output (MIMO) based grant-free random access (mGFRA). It has been observed in [27] that the ZC sequences outperforms the Gaussian distribution sequences in terms of success probability. However, the non-orthogonal preambles do not necessarily provide better performance than their orthogonal counterpart.

Arrival time based multiple preamble detection mechanism has been proposed in [28] that detects the number of preambles by estimating the round-trip delay using maximum likelihood criterion. This helps in the determination of multiple preambles in NORA. Further, a low complexity approach based on variational inference has been proposed to detect a large number of collided preambles [28]. A novel random access method namely preamble barring has been proposed in [29] that aims at estimating the traffic load by using probabilistic resource separation at preamble stage. Then, the optimal throughput has been achieved at the connection phase using the estimated load [29]. A throughput oriented non-orthogonal random access scheme has been proposed in [30] that employs tagged preambles technique. With this technique, multiple devices choosing the same preamble can be identified as a non-orthogonal multiple access group. This enables the multiple devices to share the same PRACH by multiplexing in the power domain [30]. In [31], a compressive random access (CRA) scheme has been studied along with the conventional CRA-based random access scheme for M2M communication. It has been shown in [31] that the CRA scheme outperforms the conventional CRA scheme in terms of throughput as the length of the payload can be adjusted adaptively based on the number of active devices. A distributed method based on non-orthogonal multiple access, Q-learning, and adaptive power control has been proposed in [32]. The proposed method in [32] dynamically allocates the random access slots to the M2M devices in order to improve the throughput. In [33], a novel online algorithm has been proposed to dynamically distribute the preambles over different groups based on priority. In addition access class barring mechanism has been adopted that improves the average delay as compared to the fixed preamble allocation. A distributive method to estimate the backoff parameter has been proposed in [34] in order to optimize the throughput. It has been concluded in [34] that the estimation interval has significant impact on the achievable throughput as the optimal throughput can be achieved when the estimation interval is fixed or changes slowly. However, it cannot be achieved when the number of devices varies quickly as it takes more time to estimate the backoff parameter. In [35], a dynamic rate adaptation (DRA) scheme has been proposed to obtain an optimal service rate for different traffic arrival patterns of time-driven, event-driven, and loop-driven M2M applications. DRA scheme monitors the real time traffic arrivals based on which the service rate distribution between M2M applications can be adjusted at each instant using mean value theorem of integrals and generalized processor sharing in order to improve the throughput, delay, and energy consumption [35]. An efficient mission-critical user priority-based random access scheme has been proposed in [36] for the coexisting public safety-long term evaluation (PS-LTE) and LTE-marine networks. The proposed scheme in [36] gives high priority to the PS-LTE users which have mission-critical service requirements while allocating RACH resources in order to improve the performance metrics such as number of RACH attempts, the number of collisions, and the average access delay. In [37], a grant-free protocol with collision avoidance (CA) method at the user side and collision resolution (CR) method at the BS side has been explored separately. Further, the closed-form expressions for throughput and success probability have been derived for both CA method and typical CR method known as power domain multiple access (PDMA). It has been concluded in [37] that there is a upper bound for CA method. However, the performance of PDMA can be possibly improved with variable power levels. A distributed overload control algorithm namely M2M-opportunistic splitting algorithm (M2M-OSA) has been proposed in [38] that allows the M2M devices to randomly select a time slot without centralized controllers. The proposed algorithm in [38] allows the devices to randomly select the uplink resources for transmission. Devices selecting same resource block apply the opportunistic splitting to get the winner device which is allowed to transmit in that resource block. It has been concluded in [38] that M2M-OSA reduces the blocking probability, access delay, and energy consumption as compared to the dynamic access class barring mechanism. Two enhancement schemes of 3GPP EAB mechanism have been proposed in [39] in order to enhance the performance metrics such as access success probability, number of preamble transmissions, and access delay. The first mechanism focuses on the utilization of ACB in conjunction with EAB in which an unbarred access class perform an ACB check before accessing the resources. Second one is the utilization of collision avoidance backoff in addition to EAB where the devices in an unbarred class wait for a random backoff before accessing the resources [39].

A non-orthogonal random access mechanism (NORA) has been proposed in [4] that utilizes the *intra-slot* SIC to improve the RACH success rate. In NORA, the BS can decode the Msg-3 of multiple devices that it has simultaneously received in the same slot (intra-slot) with different transmit powers. This is possible only if these devices are situated at prescribed distances from the BS. However, inter-slot SIC has not been considered. On contrary, the authors in [5] have proposed to utilize the *inter-slot* SIC, wherein, the devices are allowed to transmit repeatedly for a finite number of times in a given radio frame, and thereafter, the success rate is improved by applying back-and-forth (inter-slot) SIC at the BS. An analytical model of the SIC-based RACH mechanism proposed in [5] has been presented in [6]. However, to the best of our knowledge, the joint utilization of both *intra-slot* and *inter-slot* SIC has not been addressed in the literature. Thus, in this paper, we propose a novel SIC-NORA mechanism that utilizes both *intra-slot* (motivated by NORA) and *inter-slot* (motivated by SIC-based RACH mechanism) SIC to improve the throughput significantly. In the proposed mechanism, each M2M device is allowed to repeat its transmission in a finite number of time slots within a radio frame. The messages of two devices that collide in the same slot can be decoded if the difference in the arrival time of their messages is greater than the predetermined threshold. Upon the successful RACH from an M2M device, the BS applies SIC in the current and all previous slots of the radio frame to decode messages of other devices for enhanced RACH success.

## III. SYSTEM MODEL

We consider a cellular IoT scenario with $N$ M2M devices namely $D_1, D_2, \cdots, D_N$ in the coverage of a single BS as shown in Fig. 2. An M2M device with no data to transmit will be in sleep state and a device with data to transmit needs to contend for the radio frame to initiate the RACH message exchange as shown in Fig. 1. A device that enters the radio frame starts the RACH mechanism. Once a device gets successful RACH, the device communicates with the BS on the data channel. In Fig. 2, we depict a scenario wherein $D_4$, $D_5$, $D_9$, and $D_{13}$ are in sleep state. $D_1$, $D_{11}$, and $D_{14}$ are contending to enter into a radio frame to start RACH mechanism. $D_2$, $D_6$, $D_7$, $D_{10}$, $D_{12}$, and $D_N$ get access to the radio frame and starts the RACH mechanism. Finally, $D_3$, $D_8$, and $D_{15}$ got successful RACH and communicates to the BS on data channel.

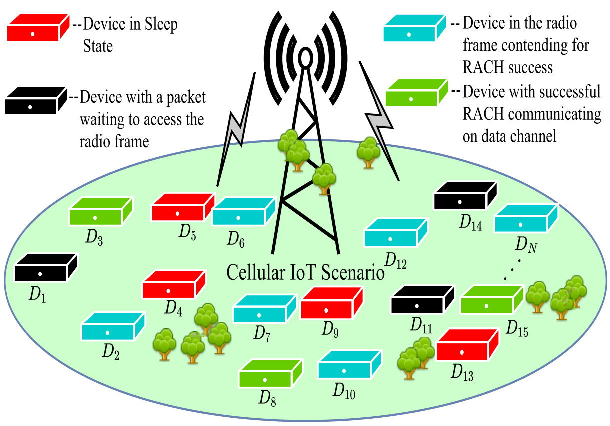


**FIGURE 2.** Cellular IoT Scenario.

**Algorithm 1:** Algorithm for the Proposed SIC-NORA Mechanism With Generalized Repetition Rate

**Input:** $\mathcal{C}$, $Y$, and $Z$
**Output:** Success

1 **if** *There is a packet to transmit* **then**
2 Generate a number $n \in [0, 1]$ uniformly at random;
3 **if** $n < \mathcal{C}Y$ **then**
4 Generate $R$, either constant or with a distribution;
5 Select $R$ distinct time slots uniformly from the set $\{0, 1, \cdots, T-1\}$;
6 Wait for the next transmission slot from the ascending order set of $R$ time slots;
7 Start RACH message exchange as shown in Fig. 1;
8 **if** *RACH success* **then**
9 Decode all its previously transmitted resource blocks;
10 Apply SIC at all the previously transmitted resource blocks;
11 **if** *There is a successful SIC* **then**
12 Repeat Steps 9 to 11 till the number of successfully decoded packets with SIC is zero;
13 **end**
14 **else if** *There is a collision between two devices* **then**
15 **if** *The difference in the time of arrival is greater than* $\tau$ **then**
16 RACH success with *Intra-slot* SIC;
17 Repeat Steps Steps 9 to 11;
18 **end**
19 **else if** *R transmissions completed* **then**
20 Wait for the cycle to finish;
21 Update $\mathcal{C}$;
22 **if** $\mathcal{C} > \frac{1}{Y}$ **then**
23 Go to Step 2;
24 **else**
25 Go to Step 4;
26 **end**
27 **else**
28 Go to Step 6;
29 **end**
30 **else**
31 Go to 20;
32 **end**
33 **else**
34 Wait for the cycle to finish and go to Step 1
35 **end**

### A. PROPOSED SIC-NORA MECHANISM

The proposed mechanism allows the devices to repeat their transmissions in a finite number of time slots and it is assumed that the Msg-3 carries information about the time slots where Msg-3 has been repeated, as in [6]. Thereafter, the BS can decode the Msg-3 of two devices that have collided in a time slot if their time of arrival is greater than $\tau$, as in [4]. By using successfully decoded Msg-3, the BS applies SIC at all the previously transmitted time slots and this process repeats every time Msg-3 of a device gets successfully decoded.

In the proposed mechanism, the BS broadcasts a number $\mathcal{C} \in [0, 1]$, in SIB-2, to all the M2M devices in its coverage, where, $\mathcal{C}$ is the reciprocal of the average number of active devices as described in Algo. 1. Further, the BS broadcasts the average number of RACH accesses in a radio frame that comprises of $T$ time slots and the average number of RACH successes in the radio frame, denoted by $Y$ and $Z$, respectively. The number $Y$ is computed as the product of the number of available preambles ($K$), total number of time slots in a radio frame ($T$), and a variable fractional coefficient ($F$) which is obtained as [2]

$$Y = F\,K\,T\,. \tag{1}$$

Here, $F \in [0, 1]$ is added to control the number of RACH accesses in a radio frame. After successful reception of SIB-2, each device generates a number $n \in [0, 1]$ uniformly at random and a device with $n \leq \mathcal{C}Y$ enters into the radio frame. All the other M2M devices with $n > \mathcal{C}\,Y$ wait for the current frame to get finished and restart the mechanism with updated value of $\mathcal{C}$. The updated value of $\mathcal{C}$ is the reciprocal of the number of unsuccessful devices at the beginning of the radio frame which is obtained by subtracting the number of RACH successes ($Z$) from the average number of unsuccessful devices in the previous radio frame. Therefore, with $\mathcal{C}_r$ being the reciprocal of the number of contending devices at any radio frame $r$, the value of $\mathcal{C}_{r+1}$, which is the reciprocal of the number of unsuccessful devices at radio frame $(r+1)$, is obtained as

$$\mathcal{C}_{r+1} = \min\left\{\frac{1}{Y}, \frac{1}{\max\left\{1, \frac{1}{\mathcal{C}_r} - Z\right\}}\right\}. \tag{2}$$

This update procedure continues until all the devices get access to the BS. However, whenever the number of unsuccessful devices at a radio frame $(r+1)$ is less than the average number of allowable RACH accesses in a given radio frame ($Y$), all the remaining devices are allowed to contend in that radio frame. A device that enters the radio frame uniformly selects $R$ ($R < T$) distinct numbers from the set $\{0, 1, 2, \cdots, T-1\}$ and creates an ordered set $\{s_1, s_2, \cdots, s_R\}$, where, $s_1 < s_2 < \cdots < s_R$. Here, $R$ represents the repetition rate for number of RACH accesses within a given frame by a device and can be optimized to improve the throughput. A device with the first number as $s_1$ waits for $s_1$ time slots and starts the RACH message exchange as shown in Fig. 1. In case the device gets RACH success, it terminates its remaining Msg-3 transmissions in upcoming selected slots. Similar to NORA mechanism in [4], if there is a collision between Msg-3 of two devices and the difference of their time of arrival is greater than $\tau$, then it is assumed that the BS can decode the Msg-3 of both the devices using *intra-slot* SIC and notifies their status of RACH success with Msg-4. A device with unsuccessful transmission at slot $s_i$, waits for its next selected slot for re-transmission. This process repeats until all $R$ transmissions get exhausted. After RACH success of a device, the BS decodes all the previously selected slots of the device from Msg-3 and applies *inter-slot* SIC. This in-turn helps the BS to decode Msg-3 of other devices. Thus, the BS recursively applies the *inter-slot* SIC every time Msg-3 of a device is decoded successfully. At the end of each radio frame, all unsuccessful devices start afresh in the next cycle with an updated value of $\mathcal{C}$ as given in (2). Throughout the manuscript, we use number of RACH successes and throughput interchangeably.

### B. TIME COMPLEXITY ANALYSIS

At the beginning of the cycle, each of the $D$ STs selects $R$ distinct slots and there are a total of $Y$ devices in the radio frame. Thus, the complexity is $\mathcal{O}(Y)$. Then, at each Slot $t \in \{0, T-1\}$, the selected STs transmit. Whenever there is a success, it applies back-and-forth SIC at all the previous repetitions. Worst case, there are $R-1$ repetitions and $t$ STs within these $t$ time slots for a successful SIC. Thus, the worst case time complexity of the proposed mechanism is given as

$$\begin{aligned} f(T, Y, R) &= \mathcal{O}(Y + (R-1)T(T+1)/2)\,,\\ &= \mathcal{O}(Y + (R-1)T^2 + (R-1)T)/2)\,,\\ &= \mathcal{O}((R-1)T^2)\,. \end{aligned} \tag{3}$$

## IV. ANALYTICAL MODEL

Fig. 3 shows the Markov model of the proposed mechanism for a repetition rate $R$ under the assumption of ideal physical (PHY) channel conditions. Let $S_{r,j}$ defines a state of the Markov chain and $S_{-1,0}$ denotes the sleep state, where, a device resides when it has no data to transmit. As mentioned earlier that all active devices will not get access to the radio frame at first radio frame. Some devices have to wait for the current radio frame to finish to contend for the radio frame. Thus, $S_{0,j}$ for $j \in \{0, 1, \cdots, T-1\}$ represents the waiting state of a device with data to transfer before accessing the radio frame for transmission. $S_{r,0}$ for $r \in \{1, 2, \cdots, R\}$ represents the transmission state corresponds to $r^{th}$ direct transmission. Let $S_{r,j}$ for $j \in \{1, \cdots, T-R\}$ and $r \in \{1, 2, \cdots, R\}$ represents the waiting states before the $r^{th}$ transmission at $S_{r,0}$. A device in $S_{r,j}$ waits for $j$ time slots before transmission. Further, $S_{R+1,j}$ for $j \in \{0, 1, \cdots, T-R-1\}$ represents the waiting state after all unsuccessful $R$ transmissions till the end of the radio frame. Finally, $S_{R+2,0}$ represents the success state. $P_{Sleep}$ denotes the probability with which a device does not have any data to transmit and is in sleep state. $P$ denotes the probability with which a device, with data, enters into the radio frame for transmission which is obtained as

$$P = \frac{V}{L}\,,$$

where, $L$ denotes the average number of devices, with a packet to transmit, contending at $S_{0,0}$ for radio frame and $V$ is the average number of devices to be allowed in a radio frame. $Q_{1,j}$ for $j \in \{0, 1, \cdots, T-R\}$ defines the probability

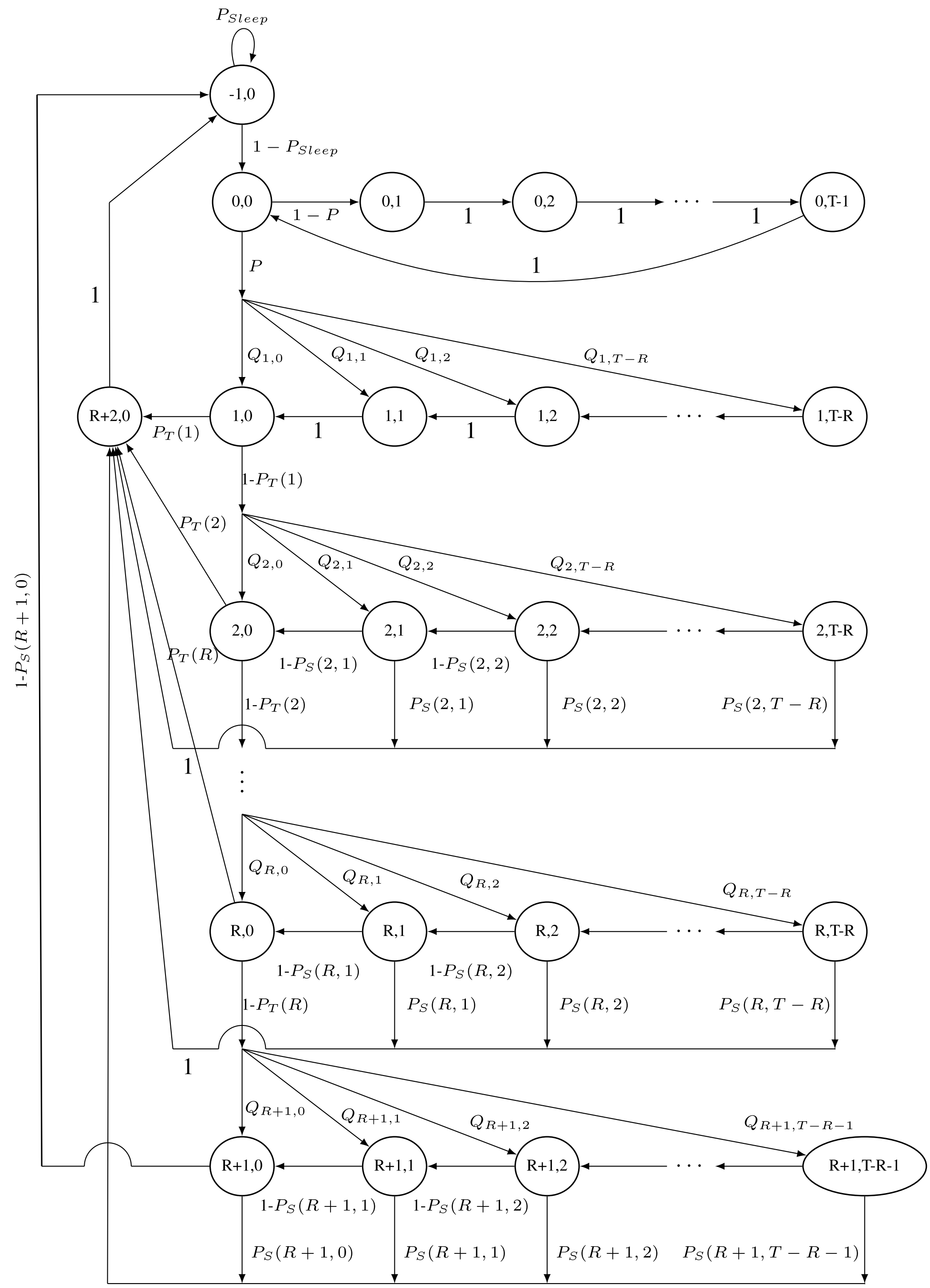


**FIGURE 3.** The Markov model of the proposed SIC-NORA mechanism with generalized repetition rate.

with which a device transit to $S_{1,j}$ once it gets access to the radio frame. Further, $Q_{r,j}$ for $j \in \{0, 1, \cdots, T-R\}$ when $r \in \{2, 3, \cdots, R\}$ and $j \in \{0, 1, \cdots, T-R-1\}$ when $r = R+1$ defines the probability of a transition to $S_{r,j}$ post an unsuccessful transmission with a probability of $(1 - P_T(r-1))$ where, $P_T(r)$ denotes the probability of a success either with direct transmission or with *intra-slot* SIC during $r$th transmission. Finally, $P_S(r, j)$ for $j \in \{1, 2, \cdots, T-R\}$ when $r \in \{2, 3, \cdots, R\}$ and $j \in \{0, 1, \cdots, T-R-1\}$ when $r = R+1$ denotes the probability that a device gets success through SIC. Next, we discuss the derivation of $Q_{r,j}$ and $P_T(r)$. Throughput the manuscript, the notation $\binom{T}{R}$ is defined as

$$\binom{T}{R} = \frac{T!}{(T-R)!R!}$$

### A. DERIVATION OF $Q_{r,j}$

The $Q_{r,j}$ for $j \in \{0, 1, \cdots, T-R\}$ when $r \in \{2, 3, \cdots, R+1\}$ denotes the probability with which a a device transit to $S_{r,j}$ after an unsuccessful transmission at $S_{r-1,0}$ with a probability of $P_T(r-1)$. $Q_{1,j}$ for $j \in \{0, 1, \cdots, T-R\}$ denotes the probability with which a device transit to $S_{1,j}$ after getting access to radio frame with a probability of $P$. A device transit to $S_{1,j}$ for $j \in \{0, 1, \cdots, T-R\}$, if it selects slot $j$ for the first transmission and the remaining $(R-1)$ transmissions from the other $(T-j-1)$ time slots. $Q_{1,j}$ defines the probability of this selection which is given as

$$Q_{1,j} = \frac{1}{\binom{T}{R}}\binom{T-j-1}{R-1}.$$

However, the transition to $S_{r,j}$ for $r \in \{2, 3, \cdots, R+1\}$ always depends on the slot it selects during $(r-1)^{th}$ transmission. For a transition to $S_{r,0}$ the device should select two consecutive time slots corresponding to $(r-1)^{th}$ and $r^{th}$ transmissions. For example, consider the transition to $S_{2,0}$. The possible selections of first transmission slot ($t_1$) and second transmission slot ($t_2$) are $(0, 1), (1, 2), \cdots, (T-R, T-R+1)$ and the remaining $(R-2)$ transmissions can be selected from $(T-t_2-1)$ time slots. With all the above selections, a device transit to $S_{2,0}$ post an unsuccessful transmission at $S_{1,0}$. The joint probability density $P_{i,j}(t_1, t_2 = t_1+j+1)$ defined in [40] denotes the selection of time slot $t_1$ for $i$th transmission and $t_2$ for $j$th transmission which is obtained as

$$P_{i,j}(t_1, t_2) = \frac{\binom{t_1}{i-1}\binom{t_2-t_1}{j-i-1}\binom{T-t_2-1}{R-j}}{\binom{T}{R}},$$

where, $i < j$, $(i-1) \leq t_1 < t_2 \leq (T-R+j-1)$, and $(t_1-t_2) > (j-i)$. Thus, $Q_{r,j}$ which denotes the all possible values of $t_1$ for $(r-1)^{th}$ transmission and $t_2$ for $r^{th}$ transmission such that the device transit to $S_{r,j}$ post an unsuccessful transmission at $S_{r-1,0}$ is obtained as

$$\begin{aligned} Q_{r,j} &= \sum_{t_1=r-2}^{T-R+r-j-2} P_{r-1,r}(t_1, t_2 = t_1+j+1), \\ &= \frac{1}{\binom{T}{R}} \sum_{t_1=r-2}^{T-R+r-j-2} \binom{t_1}{r-2}\binom{T-t_1-j-2}{R-r}. \end{aligned}$$

### B. DERIVATION OF $P_T(r)$

$P_T(r)$ denotes the probability that a device gets success either with direct transmission $P_D(r)$ or with *intra-slot* SIC $P_{IS}(r)$ during $r$th transmission. As discussed in Section III-A, $Y = FKT$ is the average number of devices that enter into the radio frame. Let $N_r$ be the number of unsuccessful devices at state $S_{r,0}$. Then, the average number of devices that are transmitting a unique preamble, $M_r$, is $N_r/K$. A successful direct transmission happens in case only one of the $M_r$ devices transmits alone in a given slot. This can also be computed as the selection of the remaining $(R-(r-1))$ repetitions of other $(M_r-1)$ devices from from the other $(T-(r-1))$ time slots. The probability of a successful direct transmission has been derived in [41] for a repetition rate 2. Based on [41], we present the probability of successful direct transmission $P_D(r)$ for a generalized repetition rate as

$$P_D(r) = \left(1 - \frac{R-(r-1)}{T-(r-1)}\right)^{M_r-1}.$$

Further, two devices gets success through *intra-slot* SIC with a probability of $P_a$ [4] in case only these two devices collide in a given time slot. Thus, $P_{IS}(r)$ is the product of $P_a$ and the probability that two device selects the same time slot which is obtained as

$$\begin{aligned} &P_{IS}(r) \\ &= P_a\binom{M_r}{2}\left(\frac{R-(r-1)}{T-(r-1)}\right)^2\left(1-\frac{R-(r-1)}{T-(r-1)}\right)^{M_r-2}, \end{aligned}$$

where, $M_r$ is obtained as

$$M_r = \begin{cases} \dfrac{Y}{K}, & \text{when } r = 1; \\ (1-P_T(r-1))\left(Q_{r,0} + \displaystyle\sum_{i=1}^{T-R} \times \prod_{j=1}^{i}(1-P_S(r,j))\,Q_{r,i}\right)M_{r-1}, & \text{when } r \in [2, R]; \\ (1-P_T(r-1))\left(Q_{r,0} + \displaystyle\sum_{i=1}^{T-R-1} \times \prod_{j=1}^{i}(1-P_S(r,j))\,Q_{r,i}\right)M_{r-1}, & \text{when } r = R+1. \end{cases}$$

Finally, $P_T(r)$ is obtained as

$$P_T(r) = P_D(r) + P_{IS}(r).$$

The transition probability $P_S(r,j)$ is obtained through extensive simulations.

## V. STEADY-STATE ANALYSIS

Let $\Gamma_{r,j}$ denotes the steady-state probability of a state $S_{r,j}$ of the Markov chain as given in Fig. 3. There are three transitions to $S_{-1,0}$. One is self transition with a probability of $P_{Sleep}$, second from $S_{R+2,0}$ with a probability of 1, and final transition from $S_{R+1,0}$ with a probability of $(1-P_S(R+1,0))$. Thus, $\Gamma_{-1,0}$ is obtained as

$$\begin{aligned} &\Gamma_{-1,0} \\ &= P_{Sleep}\Gamma_{-1,0} + (1-P_S(R+1,0))\Gamma_{R+1,0} + \Gamma_{R+2,0}, \\ &= \frac{(1-P_S(R+1,0))\Gamma_{R+1,0} + \Gamma_{R+2,0}}{1-P_{Sleep}}. \end{aligned}$$

There is a single transition from $S_{0,0}$ to $S_{0,1}$ with a probability of $(1-P)$. Thus, $\Gamma_{0,1}$ is obtained as

$$\Gamma_{0,1} = (1-P)\Gamma_{0,0}\,.$$

There is a single transition from $S_{0,j}$ to $S_{0,j+1}$ for $j \in \{1, 2, \cdots, T-2\}$. Thus, $\Gamma_{0,j}$ for $j \in \{2, 3, \cdots, T-1\}$ is obtained as

$$\Gamma_{0,j} = \Gamma_{0,j-1}\,.$$

There are two transitions to $S_{0,0}$. One from $S_{-1,0}$ with a probability of $(1-P_{Sleep})$ and the other from $S_{0,T-1}$ with a probability 1. Thus, $\Gamma_{0,0}$ is obtained as

$$\begin{aligned}\Gamma_{0,0} &= (1-P_{Sleep})\Gamma_{-1,0} + \Gamma_{0,T-1}\,,\\ &= \frac{1-P_{Sleep}}{P}\Gamma_{-1,0}\,.\end{aligned}$$

There is only one transition to $S_{1,T-R}$ and is from $S_{0,0}$ with a probability of $(PQ_{1,T-R})$. However, there are two transitions to $S_{1,j}$ for each $j \in \{0, 1, \cdots, T-R-1\}$. One is from $S_{0,0}$ with a probability of $(PQ_{1,j})$ and other from $S_{1,j+1}$ with a probability of 1. Thus, $\Gamma_{1,j}$ for $j \in \{0, 1, \cdots, T-R\}$ is obtained as

$$\begin{aligned}\Gamma_{1,j} &= PQ_{1,j}\Gamma_{0,0} + \Gamma_{1,j+1}\,,\\ &= (1-P_{Sleep})\left(\sum_{i=j}^{T-R} Q_{1,i}\right)\Gamma_{-1,0}\,. \end{aligned} \tag{4}$$

Similarly, a device transit to $S_{r,j}$, for $j \in \{0, 1, \cdots T-R-1\}$ when $r \in \{2, 3, \cdots, R\}$ and $j \in \{0, 1, \cdots T-R-2\}$ when $r = (R+1)$, either due to an unsuccessful direct transmission at $S_{r-1,0}$ with a probability of $((1-P_T(r-1))Q_{r,j})$ or with an unsuccessful SIC at $S_{r,j+1}$ with a probability of $(1-P_S(r, j+1))$. However, there is a single transition to $S_{r,T-R}$ when $r \in \{2, 3, \cdots, R\}$ and $S_{r,T-R-1}$ when $r = R+1$. Thus, a generalized expression for $\Gamma_{r,j}$ is obtained as

$$\begin{aligned}\Gamma_{r,j} &= (1-P_T(r-1))\left(Q_{r,j} + \sum_{n=j+1}^{B}\right.\\ &\quad \left.\times \prod_{m=j+1}^{n}(1-P_S(r,m))\,Q_{r,m}\right)\Gamma_{r-1,0}\\ &= (1-P_T(r-1))\left(Q_{r,j} + \sum_{n=j+1}^{B}\prod_{m=j+1}^{n}\right.\\ &\quad \left.\times (1-P_S(r,m))\,Q_{r,m}\right)\prod_{i=2}^{r-1}(1-P_T(i-1))\\ &\quad \left(Q_{i,0} + \sum_{n=1}^{T-R}\prod_{m=1}^{n}(1-P_S(i,m))\,Q_{i,m}\right)\\ &\quad \times(1-P_{Sleep})\left(\sum_{i=0}^{T-R}Q_{1,i}\right)\Gamma_{-1,0}\,, \end{aligned} \tag{5}$$

where, $B$ is obtained as

$$B = \begin{cases} T-R, & \text{when } r \in \{2, 3, \cdots, R\}\,;\\ T-R-1, & \text{when } r = R+1\,. \end{cases}$$

Finally, $S_{R+2,0}$ has transitions from $S_{r,0}$ for $r \in \{1, 2, \cdots, R\}$ with a probability of $P_T(r)$ and $S_{r,j}$ for $j \in \{1, 2, \cdots, T-R\}$ when $r \in \{2, 3, \cdots, R\}$ and $j \in \{0, 1, \cdots, T-R-1\}$ when $r = R+1$ with a probability of $P_S(r, j)$. Thus, $\Gamma_{R+2,0}$ is obtained as

$$\begin{aligned}\Gamma_{R+2,0} &= \sum_{r=1}^{R} P_T(r)\Gamma_{r,0} + \sum_{r=2}^{R}\sum_{j=1}^{T-R} P_S(r,j)\Gamma_{r,j}\\ &\quad + \sum_{j=0}^{T-R-1} P_S(R+1,j)\Gamma_{R+1,j}\,. \end{aligned} \tag{6}$$

By substituting (4) and (5) in (6), we can rewrite the expression for $\Gamma_{R+2,0}$ as follows

$$\Gamma_{R+2,0} = z\Gamma_{-1,0}\,, \tag{7}$$

where, $z$ is given by

$$\begin{aligned} z &= (1-P_{Sleep})\left(\sum_{i=0}^{T-R}Q_{1,i}\right)\left[P_T(1) + \sum_{r=2}^{R}P_T(r)\right.\\ &\quad \times(1-P_T(r-1))\left(Q_{r,0} + \sum_{n=1}^{T-R}\prod_{m=1}^{n}(1-P_S(r,m))\right.\\ &\quad \left.\times Q_{r,n}\right)\prod_{i=2}^{r-1}(1-P_T(i-1))\left(Q_{i,0} + \sum_{n=1}^{T-R}\prod_{m=1}^{n}\right.\\ &\quad \left.\times(1-P_S(i,m))\,Q_{i,n}\right) + \sum_{r=2}^{R}\sum_{j=1}^{T-R}P_S(r,j)\\ &\quad (1-P_T(r-1))\left(Q_{r,j} + \sum_{n=j+1}^{T-R}\prod_{m=j+1}^{n}(1-P_S(r,m))\right.\\ &\quad \left.\times Q_{r,n}\right)\prod_{i=2}^{r-1}(1-P_T(i-1))\left(Q_{i,0} + \sum_{n=1}^{T-R}\prod_{m=1}^{n}\right.\\ &\quad \left.\times(1-P_S(i,m))\,Q_{i,n}\right) + \sum_{j=0}^{T-R-1}P_S(R+1,j)\\ &\quad (1-P_T(R))\left(Q_{R+1,j} + \sum_{n=j+1}^{T-R-1}\prod_{m=j+1}^{n}\right.\\ &\quad \left.\times(1-P_S(R+1,m))\,Q_{R+1,n}\right)\prod_{i=2}^{R}(1-P_T(i-1))\\ &\quad \left.\left(Q_{i,0} + \sum_{n=1}^{T-R}\prod_{m=1}^{n}(1-P_S(i,m))\,Q_{i,n}\right)\right]. \end{aligned} \tag{8}$$

In the Markov chain shown in Fig. 3, the sum of all steady-state probabilities should be 1. Thus,

$$\begin{aligned}\Gamma_{-1,0} &+ \sum_{i=0}^{T-1}\Gamma_{0,i} + \sum_{j=0}^{T-R}\Gamma_{1,j} + \sum_{r=2}^{R}\sum_{j=0}^{T-R}\Gamma_{r,j}\\ &+ \sum_{j=0}^{T-R-1}\Gamma_{R+1,j} + \Gamma_{R+2,0} = 1\,. \end{aligned} \tag{9}$$

By substituting (4), (5), and (7) in (9), we can rewrite it as

$$\Gamma_{-1,0} + v\Gamma_{-1,0} + w\Gamma_{-1,0} + x\Gamma_{-1,0} + y\Gamma_{-1,0} + z\Gamma_{-1,0} = 1\,, \quad (10)$$

where, $v$, $w$, $x$, and $y$ are defined as

$$v = \left(\frac{1 - P_{Sleep}}{P}\right)(1 + (P-1)(T-1))\,,$$

$$w = (1 - P_{Sleep})\left[\sum_{j=0}^{T-R}\sum_{i=j}^{T-R} Q_{1,i}\right],$$

$$x = (1 - P_{Sleep})\left[\sum_{i=0}^{T-R} Q_{1,i}\right]\left[\sum_{r=2}^{R}\sum_{j=0}^{T-R}(1 - P_T(r-1)) \times \left(Q_{r,j} + \sum_{n=j+1}^{T-R}\prod_{m=j+1}^{n}(1 - P_S(r,m)) \times Q_{r,m}\right)\prod_{i=2}^{r-1}(1 - P_T(i-1))\left(Q_{i,0} + \sum_{n=1}^{T-R}\prod_{m=1}^{n} \times (1 - P_S(i,m))\, Q_{i,m}\right)\right]$$

$$y = (1 - P_{Sleep})\left[\sum_{i=0}^{T-R} Q_{1,i}\right]\left[\sum_{j=0}^{T-R-1}(1 - P_T(R)) \times \left(Q_{R+1,j} + \sum_{n=j+1}^{T-R-1}\prod_{m=j+1}^{n}(1 - P_S(R+1,m)) \times Q_{R+1,m}\right)\prod_{i=2}^{r-1}(1 - P_T(i-1))\left(Q_{i,0} + \sum_{n=1}^{T-R} \times \prod_{m=1}^{n}(1 - P_S(i,m))\, Q_{i,m}\right)\right]$$

By solving (10), the expression for $\Gamma_{0,0}$ is obtained as

$$\Gamma_{0,0} = \frac{1}{1 + v + w + x + y + z}\,.$$

Next, we present the analytical model for average number of RACH successes in a radio frame for the proposed SIC based RACH mechanism.

Average number of RACH successes is defined as the number of devices on an average gets success (either with direct transmission or SIC). It can also be defined as the number of devices that reach from $S_{0,0}$ to $S_{R+2,0}$. Each device passes through $S_{r,j}$ for $j \in \{0, 1, \cdots, T-R\}$ when $r = 1, \cdots, R$ and $j \in \{0, 1, \cdots, T-R-1\}$ when $r = R+1$. Thus, it can get success in any of the states either due to direct transmission or SIC and transit to $S_{R+2,0}$. The $z$ in (8) denotes the probability of success for a device and $N$ denotes the total number of devices in the system. Thus, $\mathbb{E}(S)$ is obtained as

$$\mathbb{E}(S) = zN\,. \quad (11)$$

## VI. PERFORMANCE ANALYSIS

In this section, we present the numerical results to verify the analytical expressions obtained from the Markov chain model of the proposed mechanism. Wherein, all the results are obtained from the MATLAB using Monte-Carlo simulation. Then, we present the comparison of the proposed SIC-NORA mechanism with the existing NORA [4] and SIC-based RACH mechanisms [6] in terms of the average number of RACH successes and average access delay through extensive simulations. We analyse the effect of number of M2M devices on the RACH success rate. For the numerical analysis in this section, we consider a total of 0.1 million devices are ready to access the BS. Further, we consider $T$ from the set {1482, 2000} and $K$ as 54 [2].

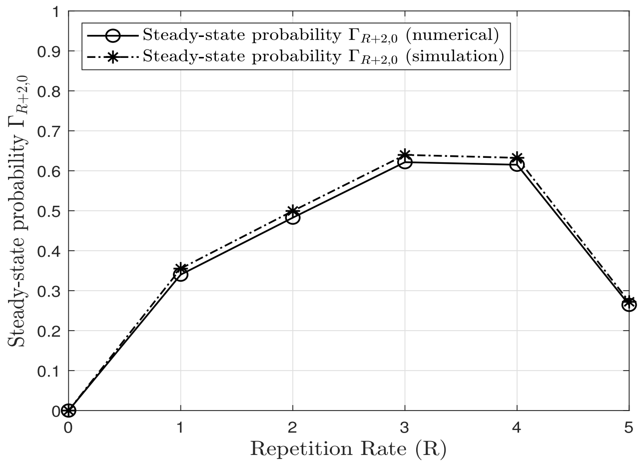


**FIGURE 4. Steady-state probability vs Repetition rate for the proposed mechanism with $T = 1482$, $K = 54$, and $F = 0.8$.**

Fig. 4 shows the numerical and simulation results corresponding to the variation of steady-state probability, $\Gamma_{R+2,0}$, of the proposed mechanism with increasing repetition rate. From Fig. 4, it is observed that the numerical results corresponding to the steady-state probability are matching with the simulations. It is also observed that the repetition rate 3 results in the maximum success probability.

Fig. 5 shows the variation of successful access probability with respect to the repetition rate for the proposed mechanism. From Fig. 5, it is observed that the successful access probability of the proposed mechanism reaches 1 for a repetition rate $R = 3$. When $R < 3$, the successful access probability is less due to the under utilization of the repetition rate. When $R > 3$, the successful access probability is less due to the increasing number of collisions. Fig. 6 shows the numerical results corresponding to the variation of average number of RACH successes with respect to the increased repetition rate. From Fig. 6, it is observed that repetition rate 3 results in maximum number of RACH successes. When $R < 3$, the number of RACH successes are less due to the under utilization of the repetition rate. When $R > 3$, the number of RACH successes are less due to the increasing number

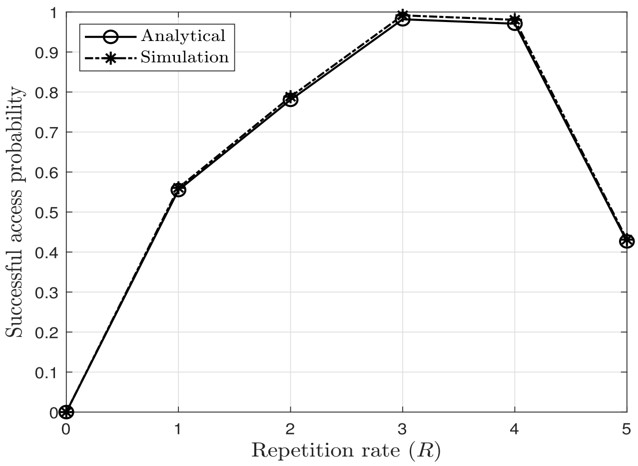


**FIGURE 5.** **Successful access probability vs repetition rate for the proposed mechanism with $T = 1482$, $k = 54$, and $F = 0.8$.**

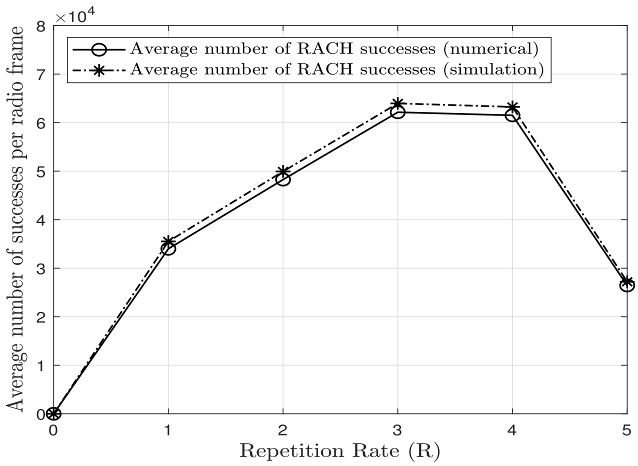


**FIGURE 6.** **Average number of RACH successes made in a radio frame for the proposed mechanism with $T = 1482$, $k = 54$, and $F = 0.8$.**

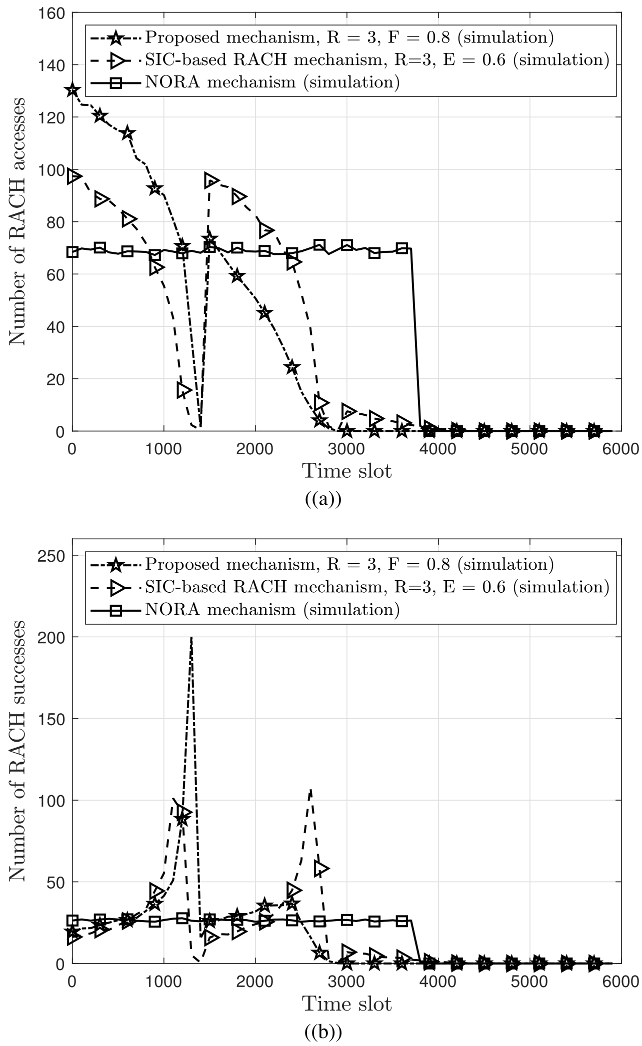


**FIGURE 7.** **(a) Number of RACH accesses and (b) the corresponding RACH successes made in a time slot for NORA, SIC-based RACH mechanism, and the proposed SIC-NORA mechanism with $T = 1482$, $k = 54$, $E = 0.6$, $F = 0.8$, and $R = 3$.**

of collisions. The mean percentage error (MPE) between simulation and analytical results is 3.2%.

Figs. 7(a) and 7(b) show the comparison between the proposed and existing RACH mechanisms in terms of the number of RACH accesses and the corresponding RACH successes, respectively, made in a given time slot. For a fair comparison, we consider the optimal parameter values that results in maximum number of RACH successes for all the respective mechanisms. For NORA mechanism, we consider $\tau = 0.3\,\mu S$ that results in a maximum 26 RACH successes in a given slot when the number of contending devices are 69 [4]. From [6], it is observed that the fractional coefficient $E = 0.6$ is the optimal value for the SIC-based RACH mechanism that results in maximum number of RACH successes in a given frame. Similarly, we consider the fractional coefficient $F = 0.8$ in the proposed mechanism that results in maximum number of RACH successes in a given frame. This value is obtained through extensive simulations. From Fig. 7, it is observed that the proposed mechanism allows on an average 92 devices to contend in a given time slot over a radio frame and it achieves on an average 43 successful connections. In comparison, the NORA and SIC-based mechanisms, respectively, allow on an average (result in) of 69 and 61 devices (26 and 33 device successes). However, it should be observed that the number of RACH successes is less in the initial slots of the proposed mechanism as compared to the NORA mechanism. This happens because the number of contending devices is large in the initial slots due to the repetitions in the proposed mechanism. However, the number of contending devices keeps on reducing with each passing time slot since each successful device terminates its further transmissions. Moreover, the number of devices that are successful with both *intra-slot* and *inter-slot* SIC also increases with the slot number. Thus, the total number of RACH successes for the proposed mechanism increases exponentially with the slot number and maximum can be attained at the last slot of the radio frame as observed in Fig. 7(b). Further, in the proposed RACH mechanism, the number of devices that enter into the first radio frame are high as all the 0.1 million devices contend

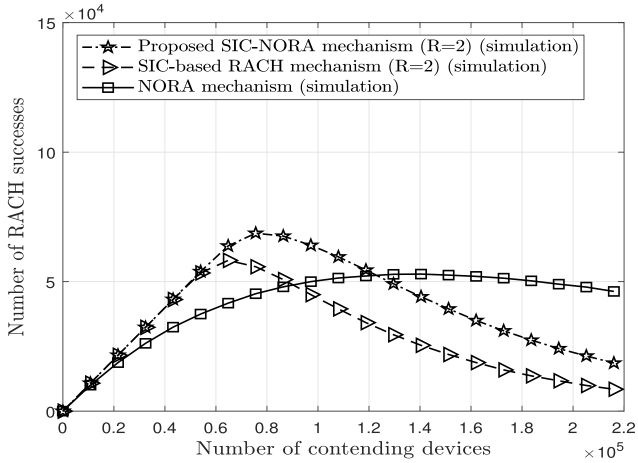


**FIGURE 8.** Number of RACH successes made in a radio frame for NORA, SIC-based RACH mechanism, and the proposed SIC-NORA mechanism with respect to increased number of M2M devices with $T = 2000$ and $k = 54$.

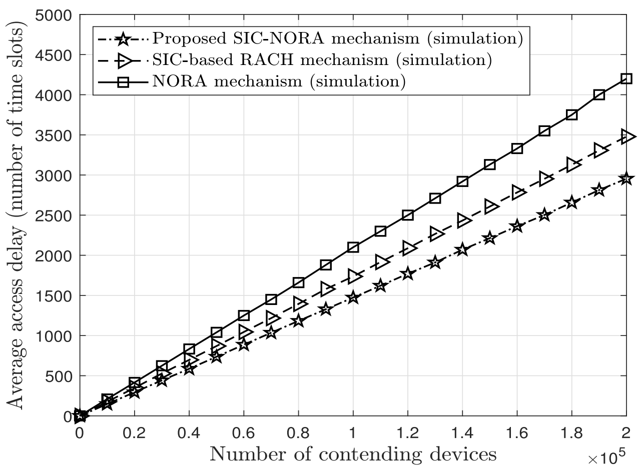


**FIGURE 9.** Average access delay for successfully accessed M2M devices for NORA, SIC based RACH mechanism, and the proposed SIC-NORA mechanism for $R = 3$, $E = 0.6$, and $F = 0.8$.

in the first frame. However, the number of devices that are contending in the subsequent radio frames are very less as most of the devices successfully connect to the BS in the first radio frame.

Fig. 8 shows the impact of the number of contending devices on the average RACH successes. It is observed that the number of RACH successes does not increase linearly with the number of contending devices. All the mechanisms reach a maximum success rate at different number of contending devices. However, it is observed that for the given values of $T$ and $K$, the proposed SIC-NORA mechanism results in maximum number of RACH successes as compared to the existing ones. The existing NORA and SIC based RACH mechanisms results a maximum of $5.1 \times 10^4$ and $5.9 \times 10^4$ RACH successes, respectively. However, the proposed mechanism results in a maximum of $6.9 \times 10^4$ RACH successes as shown in Fig. 8.

Fig. 9 shows the comparison among the proposed mechanism and the existing ones in terms of the average access delay. For fair analysis, we use corresponding optimal value of $T$ for SIC-based RACH mechanism and proposed SIC-NORA mechanism based on the value of $E$ in [6] and $F$ with $R = 3$. It is observed that the average access delay is lower for the proposed mechanism as compared to existing ones and linearly increases with the number of contending devices due to the consideration of optimal $T$. Table 1 shows the performance comparison of the proposed mechanism with the existing mechanisms. From Table 1, it is observed that the proposed mechanism outperforms the existing ones in terms of successful access probability, average throughput, and average access delay.

**TABLE 1.** Performance comparison of the proposed SIC-NORA mechanism with the existing ones.

| Mechanism | Parameter | Value |
|---|---|---|
| 3GPP-EAB [7] | Average throughput | 37% |
| FRM [8] | Average throughput | 37% |
| QDAM [12] | Average throughput<br>Access delay | 91.67% |
| M-ACB [13] | Success rate<br>Time delays | 86%<br>1250 |
| TDIA [14] | Probability of successful preamble transmission | 98% |
| CBGP [15] | Successful access probability<br>Average access delay | 0.75<br>7000 |
| SACB [23] | Average access delay | 500 |
| EH-based ACB [26] | Throughput | 75% |
| Preamble barring [29] | Success probability<br>Normalized throughput | 0.37<br>37% |
| T-NORA [30] | Average throughput<br>Average access delay | <br>2000 |
| CRA [31] | Normalized throughput | 63% |
| GF protocol [37] | Success probability | 0.8 |
| NORA [4] | Successful access probability<br>Average throughput<br>Average access delay | 0.48<br>48%<br>498 |
| SIC-based RACH [6] | Successful access probability<br>Average throughput<br>Average access delay | 0.93<br>93.2%<br>462 |
| Proposed SIC-NORA | Successful access probability<br>Average throughput<br>Average access delay | **0.9853**%<br>**98.53**%<br>**338** |

## *A. THE EFFECT OF PHY LAYER IMPAIRMENTS ON THE SUCCESS RATE*

In the previous subsection, the performance of the proposed mechanism is evaluated under ideal PHY channel conditions. In this subsection, we analyse the effect of PHY layer impairments on the performance of the proposed RACH mechanism. In general, the PHY layer impairments, such as additive noise, error in channel estimation, etc., result in bit error which in-turn causes packet error [42]. Such errors can be detected and corrected up to some extent by employing error correcting codes but cannot be eliminated completely [43]. Hence, in this section, we introduce an arbitrary probability of packet error, denoted by $P_{err}$, to incorporate the effect of PHY layer impairments in our study. Here, $P_{err}$ represents the probability that a device is unsuccessful due to PHY layer impairments even though it alone transmits a unique preamble in a time slot (successful RACH).

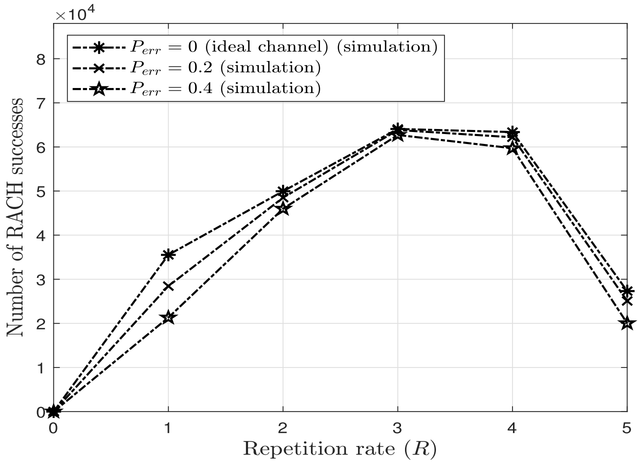


**FIGURE 10.** **Number of RACH successes made in a radio frame for the proposed mechanism with respect to $R$ for various values of $P_{eff}$ with $T = 1482$, $K = 54$, and $F = 0.8$.**

Fig. 10 shows the simulation results to study the effect of $P_{err}$ on the performance of the proposed SIC based RACH mechanism. We consider values of $P_{err} = 0.2$ and 0.4 for a fair comparison. From Fig. 10, it is observed that there is a slight decrease in the number of RACH successes with an increase in $P_{err}$ at $R = 3$. This is due to the optimal utilization of repetition and maximum success rate achieved at repetition rate $R = 3$. Whenever a device transmits in multiple slots due to repetition, there is a higher chance that the device gets an error free transmission in any of its attempts even with PHY layer impairment. Further, there is a high chance that the device gets success with SIC in any of the previously transmitted slots, which in turn improves the overall success rate. This further motivates the importance of inter-slot SIC for increasing RACH success as done in the proposed mechanism. However, when $R < 3$, the effect of $P_{err}$ is more on the success rate due to the less utilization of repetition rate. Further, when $R > 3$, even though the repetition rate is more, the success rate is less due to $P_{eff}$ due to the increased number of collisions. Further, the MPE between the throughput with ideal physical channel and $P_{err} = 0.2$ and 0.4 are 6.66% and 16.52%, respectively.

## VII. CONCLUSION

In this paper, a novel successive interference cancellation based non-orthogonal random access (SIC-NORA) mechanism has been proposed for M2M communications in Cellular IoT. The proposed mechanism has utilized repetitions and performs SIC in the current and all previous slots of the frame to decode messages of devices for improved RACH success. Through extensive simulation results, it has been shown that the proposed SIC-NORA mechanism performs better than existing ones in terms of the number of RACH successes and average access delay. Further, it has been concluded that the proposed mechanism has resulted an improvement of 65.3% and 30.3% as compared to NORA and SIC-based RACH mechanism, respectively. Moreover, there has been 29.6% and 15% reduction in the number of time slots required for $2 \times 10^5$ devices to get success with the proposed mechanism as compared to NORA and SIC-based RACH mechanism, respectively, at the corresponding optimal value of radio frame length. In future, we will test the proposed mechanism in a hardware testbed. Further, we will model 5G RACH mechanism such as early data transmission with SIC.

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