A Novel RACH Mechanism for Dense Cellular-IoT Deployments

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***Abstract*—Cellular Internet of Things (C-IoT) is one of the emerging 5G technologies. 4G LTE being the most promising cellular technology so far and is a suitor for serving C-IoT devices. In future millions of C-IoT devices will be deployed in the coverage of a single 4G LTE base station. However, the existing random access (RACH) mechanism in 4G LTE is not designed to connect millions of devices. Hence, in this paper, we propose a novel RACH mechanism that allows millions of C-IoT devices to associate with the base station within the existing 4G LTE framework. 3GPP has proposed an extended access barring mechanism to solve this problem for machine type communication (MTC). We compare the performance of the proposed RACH mechanism with the existing 3GPP extended access barring mechanism through analysis. Further, through simulation results, we show that the proposed mechanism is faster and saves power when compared to existing 3GPP extended access barring mechanism under perfect synchronization.**

***Index Terms*—4G, 5G, C-IoT, IoT, MTC, Random access channel.**

I. Introduction

Cellular Internet of Things (C-IoT) [1] is one of the key emerging technologies in 5G system, which allows millions of devices connect to a single base station (BS). The C-IoT devices are typically small in size and they can be densely deployed in any type of terrain (i.e., rural or urban). Most of the C-IoT devices are deployed in fixed remote locations and are required to run for years on a single battery backup. Hence, these C-IoT devices need to be energy efficient. C-IoT devices wake up to transmit a small amount of data and they go to sleep state once the data is transmitted. While they are awake they try to access the network through RACH attempts and if the RACH attempt is not successful, the device resides in contention state which increases the power consumption. To save power a device must access the network with less number of RACH attempts.

C-IoT applications can be broadly categorized into two types [2]: Device generated Frequent Data (DFD) and Device generated Non-frequent Data (DNFD). Frequent Data can be urgent data like health monitoring, fire monitoring, traffic monitoring or non-urgent data like pollution monitoring, temperature monitoring. Non-frequent Data can be utility bills like electricity, water, gas. DFD C-IoT devices need access to BS within a short stipulated time frame whereas DNFD devices need energy efficient access to the BS, because these

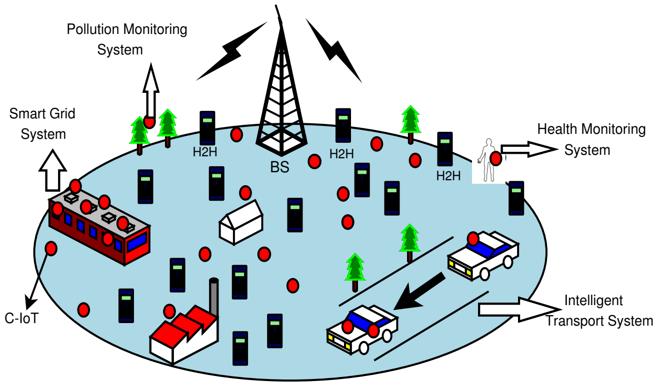

Fig. 1. Applications of Cellular IoT.

DNFDs has to run on a small battery for many years. In this work we give few guidelines on selecting parameters for these two major categories of C-IoT devices.

In 4G LTE, available RACH preambles are limited and if million devices contend then they all stay in contention phase by colliding among themselves in every radio frame [3]. This becomes a challenge for an operator to enable more C-IoT devices under a single BS. To address this problem, 3GPP proposed a solution of extended access barring (EAB) mechanism in Release 11 [4] for MTC devices. In this paper we use MTC and C-IoT interchangeably. In 3GPP EAB mechanism, BS restricts access to a class (low priority) of user equipment's (UE) when the network is overloaded. This barring information is transmitted to the corresponding UEs using system information block (SIB) messages. Alternately, researchers are also focusing towards NB-IoT [5] in which dedicated bandwidth is allocated for C-IoT.

Along side 3GPP EAB mechanism there are other solutions in the literature which use costly solutions like heterogeneous BS deployments [6], [7] which increases the capital or they use BS assisted solutions [8], [9] which increase the overhead on BS. In this work, we propose a Fast RACH Mechanism (FRM) that enables densely deployed C-IoT devices connect to BS in less time and with least power consumption. This is an access barring mechanism and it doesn't require additional bandwidth or any assistance from BS. Hence this mechanism is cheaper and it won't introduce any over head at BS. We have built an analytical model to evaluate our proposed work and we compared the proposed mechanism with 3GPP EAB

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mechanism through simulations and analysis.

The rest of the paper is organized as follows. Section II presents related work on existing solutions. Section III describes the existing 3GPP EAB and proposed FRM Mechanisms in detail. In Section IV, we describe an analytical model and Section V gives the performance evaluation with simulation results. Finally, Section VI presents conclusions and directions for future work.

II. Related Works

In this Section, we discuss the existing RACH solutions for C-IoT devices. In [6] authors have proposed clustering of devices and each cluster has a cluster head. Instead of all devices contending with a macro BS for RACH, they contend only with other devices in the same cluster. Cluster head resolves contention for devices under a cluster domain. There can still be preamble collisions among intra cluster and inter cluster devices. Once the contention is resolved, cluster head establishes a communication channel for these devices. In [7] authors propose a similar solution employing heterogeneous network architecture where instead of a cluster head they use a mini BS and tried to solve the problem. In both cases the mechanisms are using additional infrastructure to solve the problem and it also increases the capital expenditure of the operator.

In [8] authors proposed a q-array tree splitting algorithm to resolve collision among the C-IoT devices. Their proposal includes a new field in MSG4 which instructs the colliding UE to choose a preamble within a new confined set of preambles, also it suggests a radio frame for the UE to transmit the next RACH. The q-array tree grows until each UE gets a unique radio frame and preamble to transmit excluding the contention resolved UEs. In this mechanism the BS assists UEs in resolving the contention. In [9] authors have proposed a BS assisted RACH mechanism in which BS sends a back-off value in broadcast message which is obtained from the successfully connected UEs.

The existing literature does not provide energy efficient or cost effective solutions. Hence, we propose a cost effective access barring mechanism which efficiently uses the RACH resources when BS is not assisting the UE. We compared the proposed mechanism with 3GPP EAB.

III. RACH Mechanisms

RACH is used for associating a user to the BS. In LTE, each UE picks a preamble out of available preambles and transmit in the RACH slot of a radio frame. Say there is only one RACH slot per radio frame, in such a case collisions will happen if two devices pick a same preamble. The number of available preambles are limited and if multiple UEs contend they will collide. If such a system has to be used for C-IoT devices deployed in millions under a single base station then the network will fail to associate the users. So there is a need for a procedure which orthogonalizes the RACH transmission so that all the million devices can connect to BS.

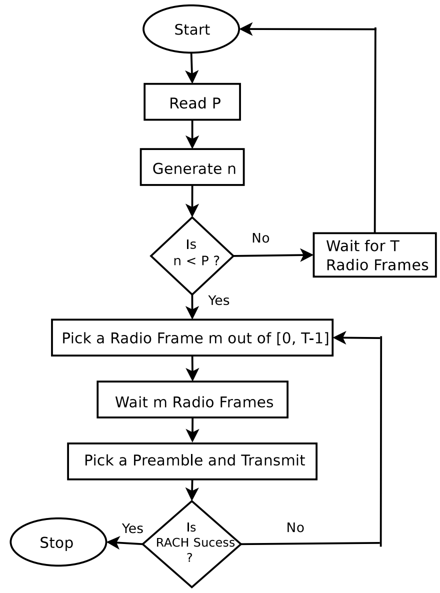

Fig. 2. 3GPP extended access barring mechanism

In the following Sections, we describe two different RACH mechanism. The mechanism are described assuming an LTE framework with one RACH resource per radio frame with limited number of preambles. A collision will happen if two or more C-IoT devices pick same preamble.

A. 3GPP Extended Access Barring Mechanism

In this mechanism the BS will broadcast a number $P \in \mathbb{R} \cap [0, 1]$. Where P is the probability with which a device contends. The C-IoT devices listen to P and generates a uniformly distributed number $n \in \mathbb{R} \cap [0, 1]$. If $n < P$ then the device picks a radio frame m uniformly distributed between $[0, T-1]$ radio frames and transmits in that particular radio frame by again picking a preamble uniformly distributed out of K available preambles. If the RACH fails then the device picks another radio frame out of $[0, T-1]$ and repeats until the RACH mechanism succeeds. If $n > P$ then the C-IoT device waits for T radio frames to elapse and tries again. Fig. 2 shows the 3GPP EAB mechanism.

This mechanism can be visualized as a wave of devices trying to connect while the next wave waits for T radio frames and it goes on. In this mechanism we are controlling the access to BS with two parameters P and T. This mechanism doesn't give a constant association rate in the scenario used in this paper where million device wake up at the same time. Whereas the proposed mechanism explained in th next section gives a constant association rate.

B. Proposed Fast RACH Mechanism

In the proposed mechanism the C-IoT device will listen to a number $P \in \mathbb{R} \cap [0, 1]$ which is broadcast in the downlink and the device reads the values Y and X based on the device category where Y and X are constant positive integers such that $(Y \times P) < 1$. The Y and X are not necessarily be transmitted by BS, they can be hard coded into the C-IoT device based on the C-IoT category. The device generates a

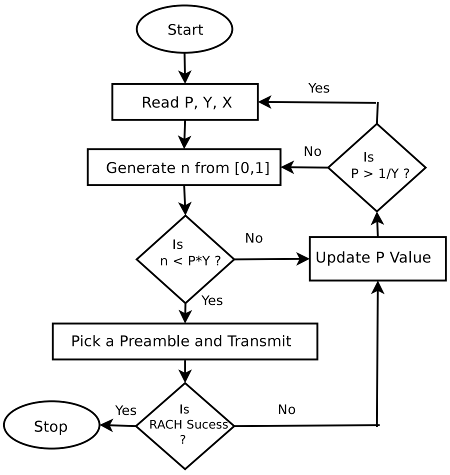

Fig. 3. Proposed fast RACH mechanism

uniformly distributed number $n \in \mathbb{R} \cap [0,1]$. If $n < (Y \times P)$ then the device transmits by picking a preamble uniformly distributed out of K available preambles. If the RACH fails then the device updates P according to the expression

$$P = min(\frac{1}{Y}, \frac{1}{max(1, \frac{1}{P} - X)}) \tag{1}$$

and starts over in the next radio frame if $P < \frac{1}{Y}$. If $n > (Y \times P)$ then the C-IoT device updates P according to (1) and it starts over in the next radio frame if $P < \frac{1}{Y}$. If $P > \frac{1}{Y}$ then the C-IoT device reads P from BS and starts over in the next radio frame. Fig. 3 shows the FRM Mechanism. These two values define the category of the C-IoT device. We control the access to BS with three parameters P, Y, and X. This will help us to fine tune the access to make a constant number of devices connect in every radio frame.

IV. Analysis

We categorize the C-IoT devices into DFD and DNFD where DFD needs a fast association and DNFD needs an efficient association. To support the above two categories we came up with a few guidelines while selecting the parameters for the RACH mechanisms. Say an LTE BS has K available preambles and N devices are trying to connect in a single radio frame then the number of devices succeeding in the given radio frame E_{succ} and probability of success for a given device P_{succ} are given by

$$E_{succ}(N) = N \times \left(\frac{K-1}{K}\right)^{N-1} \tag{2}$$

$$\text{and } P_{succ}(N) = \frac{E_{succ}(N)}{N} \tag{3}$$

respectively. The equations (2) and (3) are valid only when N and K are integers. If N is not an integer then we can approximate (2) and (3) by taking a weighted average with the nearest integers of N as shown in

$$\begin{aligned}\tilde{E}_{succ}(N) \approx & (\lceil N \rceil - N) \times E_{succ}(\lfloor N \rfloor) \\ & + (N - \lfloor N \rfloor) \times E_{succ}(\lceil N \rceil)\end{aligned} \tag{4}$$

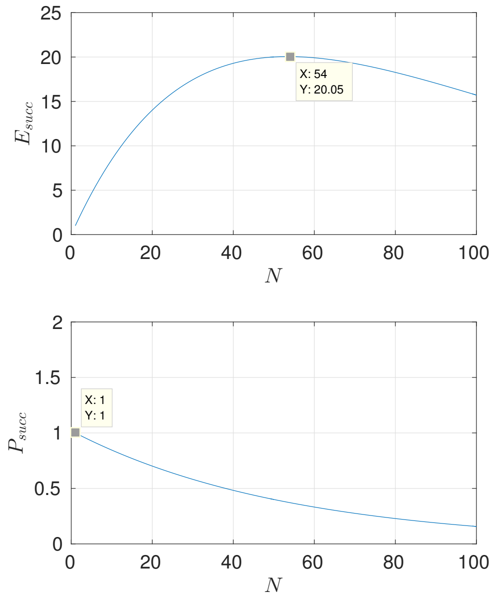

Fig. 4. E_{succ} and P_{succ} over N when system has 54 preambles

$$\tilde{P}_{succ}(N) \approx \frac{\tilde{E}_{succ}(N)}{N}. \tag{5}$$

For DFD devices E_{succ} has to be maximized and for DNFD devices P_{succ} has to be maximized. Fig. 4 shows that $N = K$ is where maximum number of devices are associated in a radio frame and when $N = 1$ a device can be associated with maximum probability. These two results will help in selecting parameters for the two categories of devices. In the next section we define the analysis model for the two access mechanisms.

A. 3GPP Extended Access Barring Mechanism

Fig. 5 shows the state model of the 3GPP EAB mechanism. Let $b_{l,k}$ be a state in the model which represents the number of devices in the given state. $b_{l,k}(j)$ be the number of devices in state $b_{l,k}$ at radio frame j. $b_{0,k}$ are the states where devices wait to go into $b_{1,k}$. With $\frac{P}{T}$ probability a device in state $b_{0,0}$ will move to $b_{1,k}$ where P is the probability and T is the number of radio frames given in III-A. $b_{0,k}$ and $b_{1,k}$ are calculated using (6) and (7).

$$b_{0,k}(j) = \begin{cases} b_{0,T-1} & \text{if } k = 0 \\ (1-P) \times b_{0,1} & \text{if } k = 1 \\ b_{0,k-1} & \text{else} \end{cases} \tag{6}$$

$$b_{1,k}(j) = \begin{cases} \frac{P \times b_{0,0}(j-1)}{T} + \frac{(1-Q(j-1)) \times b_{1,0}(j-1)}{T} & \text{if } k = T-1 \\ \frac{P \times b_{0,0}(j-1)}{T} + b_{1,k+1}(j-1) + \frac{(1-Q(j-1)) \times b_{1,0}(j-1)}{T} & \text{else} \end{cases} \tag{7}$$

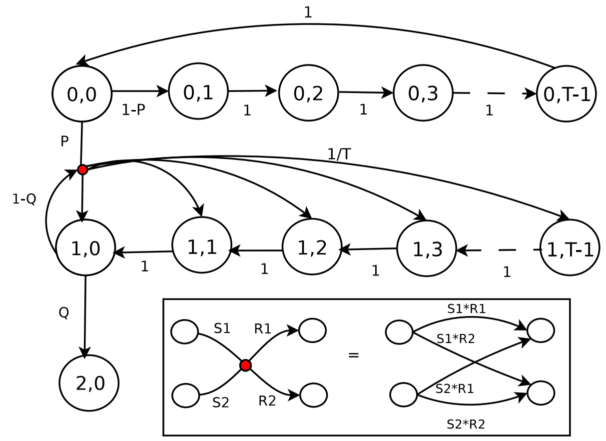

Fig. 5. State diagram of existing 3GPP extended access barring mechanism

In $b_{1,k}$ the devices try to orthogonalize and transmit over T radio frames and with $Q(j)$ probability given by

$$Q(j) = \begin{cases} P_{succ}(b_{1,0}(j)) & \textit{if } b_{1,0}(j) \textit{ is an integer} \\ \tilde{P}_{succ}(b_{1,0}(j)) & else \end{cases} \quad (8)$$

a device in $b_{1,0}$ succeeds and moves to $b_{2,0}$ while the unsuccessful devices stay in $b_{1,k}$ and try to access the BS. State $b_{2,0}(j)$ has the total number of devices successful in radio frame j and is given by

$$b_{2,0}(j) = Q(j) \times b_{1,0}(j). \quad (9)$$

Let $S_s(j)$ be the total number of devices succeeded in j radio frames and $S_a(j)$ be the total number of devices attempted transmission in j radio frames. $S_s(j)$ and $S_a(j)$ are given by

$$S_s(j) = \sum_{i=0}^{j} b_{2,0}(i) \quad (10)$$

$$\text{and } S_a(j) = \sum_{i=0}^{j} b_{1,0}(i). \quad (11)$$

B. Proposed Fast RACH Mechanism

Fig. 6 shows the state model of the proposed mechanism. Let $b_{l,k}(j)$ be the number of devices in state $b_{l,k}$ at radio frame j. In states $b_{0,k}$ the devices wait for their opportunity. With $(Y \times P_k)$ probability a device in state $b_{0,k}$ will move to $b_{1,k}$ where P_k is the probability and is given by (12).

$$p_k = \begin{cases} P & \textit{if } k = 0 \\ \frac{1}{Y} & \textit{if } k = Z-1 \\ min(\frac{1}{Y}, \frac{1}{max(1, \frac{1}{P_{k-1}} - X)}) & else \end{cases} \quad (12)$$

A device in $b_{1,k}$ will transmit and succeeds with probability Q_k. $Q_k(j)$ is the probability with which a device in $b_{1,k}$ will move into $b_{2,k}$ and is given by (13).

$$Q_k(j) = \begin{cases} P_{succ}(b_{1,k}(j)) & \textit{if } b_{1,k}(j) \textit{ is an integer} \\ \tilde{P}_{succ}(b_{1,k}(j)) & else \end{cases} \quad (13)$$

A device in $b_{1,k}$ will move into $b_{0,k+1}$ with probability $1 - Q_k(j)$ due to failure of RACH and a device in $b_{0,k}$ will

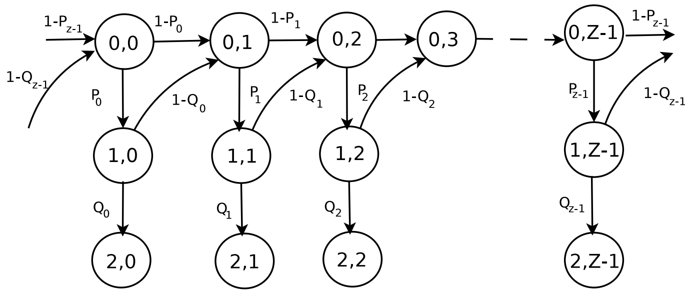

Fig. 6. State diagram of proposed fast RACH mechanism

move into $b_{0,k+1}$ with probability $(1 - (Y \times P_k))$. In this model, $b_{2,k}(j)$ gives the total number of devices successful in radio frame j. $b_{l,k}(j)$ is calculated using the expressions in (14).

$$b_{l,k}(j) = \begin{cases} b_{0,k-1} - (Q_{k-1}(j) \times b_{1,k-1}(j)) & \textit{if } l = 0 \\ Y \times P_k \times b_{0,k}(j) & \textit{if } l = 1 \\ Q_k(j) \times b_{1,k}(j) & \textit{if } l = 2 \end{cases} \quad (14)$$

In this mechanism $S_s(j)$ and $S_a(j)$ are given by

$$S_s(j) = \sum_{i=0}^{j} \sum_{k=0}^{Z-1} b_{2,k}(i) \quad (15)$$

$$\text{and } S_a(j) = \sum_{i=0}^{j} \sum_{k=0}^{Z-1} b_{1,k}(i). \quad (16)$$

V. Results and Discussion

We have used MATLAB environment for doing the simulation and analysis. For the simulation we assume perfect channel conditions and collision is due to a physical collision of preambles. All the devices start at state $b_{0,0}$ at radio frame 0 and the simulation stops when 99% of the devices are successful. Two cases are considered for evaluation.

- **Case 1:** In this case, we considered DFD type C-IoT devices which need to connect quickly and transmit the data. The parameters for the two algorithms are selected such that in a given radio frame on an average maximum possible devices (i.e., 20) will be connected when available preambles are 54. Table I shows the parameters for simulation and analysis.
- **Case 2:** In this case, we considered DNFD type C-IoT devices which need to connect with less number of attempts in order to save power. The parameters for the two algorithms are selected such that in a given radio frame devices will get connected with maximum probability of success possible. Table II shows the parameters for simulation and analysis.

The following parameters are considered for evaluation a) total number of radio frames needed for association of 99% of the devices (which is $j | \frac{S_s(j)}{N_0} = .99$), b) the average number of attempts made by each connected C-IoT device (which is $\frac{S_a(j)}{N_0}$) which are tabulated in Table I and II, c) the number of devices transmitting in a given radio frame for FRM and

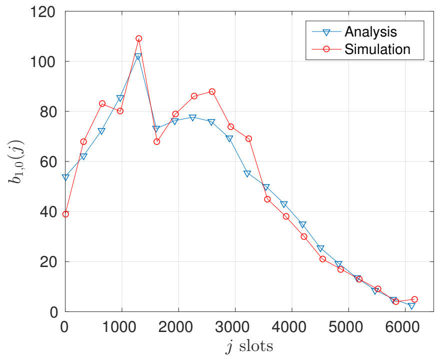

Fig. 7. Number of RACH attempts made in a radio frame for 3GPP EAB mechanism in Case 1

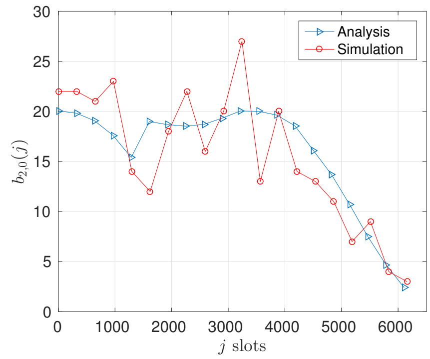

Fig. 8. Number of RACH successes in a given radio frame for 3GPP EAB mechanism in Case 1

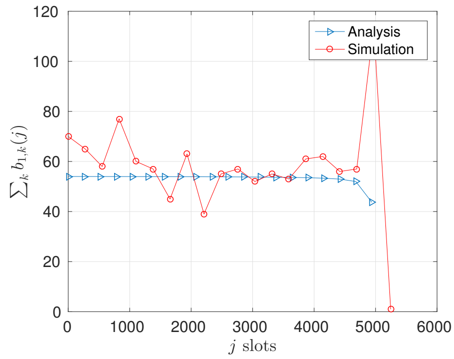

Fig. 9. Number of RACH attempts made in a radio frame for FRM in Case 1

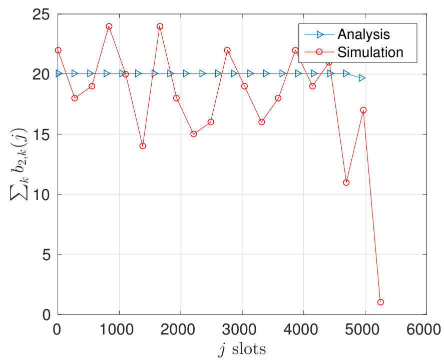

Fig. 10. Number of RACH successes in a radio frame for FRM in Case 1

TABLE I
MODELING PARAMETERS AND RESULTS FOR CASE 1

Parameters	Analysis		Simulation	
Algorithm	3GPP	FRM	3GPP	FRM
P	0.8	10^{-5}	0.8	10^{-5}
Total Devices	10^5	10^5	10^5	10^5
T	1482	-	1482	-
Preambles	54	54	54	54
X	-	20	-	20
Y	-	54	-	54
Results				
99% assoc. time	6109	4939	6160	5246
Avg. attempts	3.16160	2.6437	3.18702	2.84191

3GPP EAB mechanism which are given by $\sum_k b_{1,k}(j)$ and $b_{1,0}(j)$ respectively, and d) number of devices successful in each radio frame for FRM and 3GPP EAB mechanisms which are given by $\sum_k b_{2,k}(j)$ and $b_{2,0}(j)$ respectively which are plotted as graphs. In all cases we compared the performance of both algorithms using the above evaluation parameters and we compared the simulation results with the analysis results.

A. Case 1 Results

For Case 1, we chose the parameters such that on an average 54 devices are contending to access the BS in every radio frame and that will give 20 devices getting connected in every radio frame according to (2). Let us consider 3GPP EAB mechanism, from Fig. 7 we can see that on an average 54 devices are contending in a radio frame. We can see two peaks one between $1000-2000$ and other between $2000-3000$, this is due to the contention caused by the loop in the mechanism between states $b_{1,k}$ which can be seen in Fig. 5 and also after every 1482 radio frames a new set of devices enter the loop. A device can leave the loop only if it succeeds the RACH otherwise the devices queue up in the loop increasing the contention. Fig. 8 shows that on an average 20 devices are getting connected and we can observe two dips between $1000-2000$ and $2000-3000$ which are due to the contention caused in the loop. The analysis results are compared with a single realization of the simulation and the analysis and simulation are nearly matching. The error between analysis and simulation can be reduced by averaging the simulation over multiple realizations. In the analysis and simulation we assume perfect synchronization, which is a reasonable assumption as the devices are machine type and they all wake up at the same time.

Let us consider FRM, Fig. 9 analysis shows that exactly 54 devices are contending in each radio frame and Fig. 10 analysis shows that exactly 20 devices are getting connected in each radio frame. The analysis shows that there is a constant rate in device association and the mechanism is working as expected by giving the maximum association rate possible given by (2). In Fig. 9 we can see a peak at 5000, which is not present in the analysis and this peak is due to lack of averaging over multiple realizations.

From Figs. 7, 8, 9, and 10 we can see that FRM is giving a constant association rate unlike 3GPP EAB Mechanism. From Table. I, we can see that the number of radio frames required to associate 99% of devices is less for FRM and the average attempts made per device are also less for FRM. We can say that FRM is fast and at the same time power saving.

B. Case 2 Results

For Case 2, we chose the parameters such that 1 device contends to access the BS every radio frame and with maximum probability it will get connected according to (3). Let us consider 3GPP EAB mechanism, from Fig. 11 we can see that on an average 1 device is contending in a radio frame and Fig. 12 shows that on an average 1 device is getting connected. But the access trend is not constant as it starts with more number of C-IoT devices and slowly decreases. From Table. II we can see that the number of collisions are more when

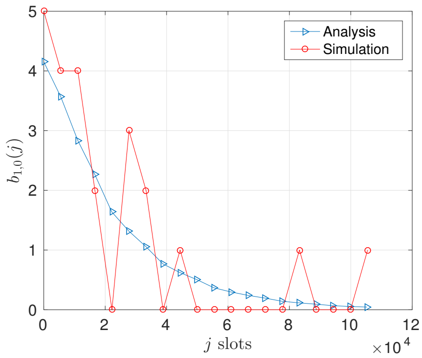

Fig. 11. Number of RACH attempts made in a radio frame for 3GPP EAB mechanism in Case 2

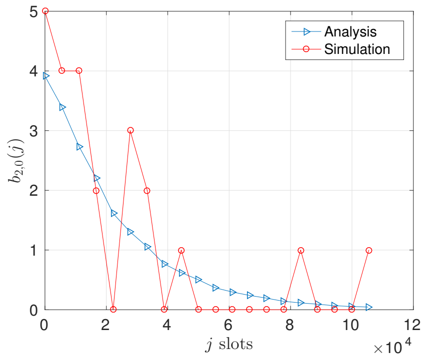

Fig. 12. Number of RACH successes in a radio frame for 3GPP EAB mechanism in Case 2

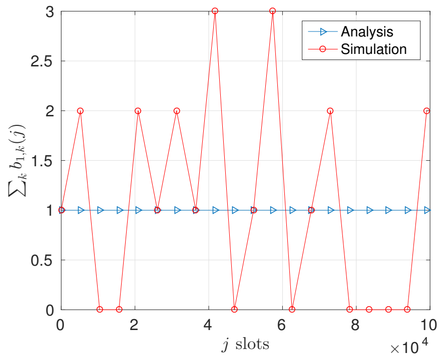

Fig. 13. Number of RACH attempts made in a radio frame for FRM in Case 2

compared to FRM which is due to more devices contending at the beginning and the number decreases gradually as seen from Fig. 11.

Now consider FRM, Fig. 13 shows that on an average 1 device is contending in each radio frame and Fig. 14 shows that 1 device is getting connected in each radio frame. The devices are accessing at a constant rate and due to this the number of collisions are less. The analysis and simulation matches and the error is due to the lack of averaging.

From the Figs. 11, 12, 13, and 14 we can see that FRM is giving a constant association rate unlike 3GPP Mechanism. From Table. II we can see that the number of radio frames required to associate 99% of devices is less for FRM and the average attempts made per device is also less for FRM. We can say that FRM is fast and at the same time power saving.

VI. Conclusion and Future work

We have proposed a novel access barring scheme which gives a constant association rate. We have evaluated the performance of the proposed mechanism and compared against 3GPP EAB mechanism and the presented simulation and analysis results suggest that the proposed mechanism is faster and saves power under the scenario where all the devices are perfectly synchronized. We have also given guidelines for selecting access barring parameters for both the algorithms for the two types of C-IoT devices. As future work, we want to do a steady state analysis over the proposed framework when C-IoT devices wake up with a constant rate and try to connect to the BS. That will give more insights into the performance of both the mechanisms.

TABLE II
Modeling Parameters and Results for Case 2

Parameters	**Analysis**		**Simulation**	
Algorithm	3GPP	FRM	3GPP	FRM
P	0.1	10^{-5}	0.1	10^{-5}
Total Devices	10^5	10^5	10^5	10^5
N	2408	-	2408	-
Preambles	54	54	54	54
X	-	1	-	1
Y	-	1	-	1
Results				
99% assoc. time	105280	99000	105839	99100s
Avg. attempts	1.0174	0.9902	1.03427	1.00956

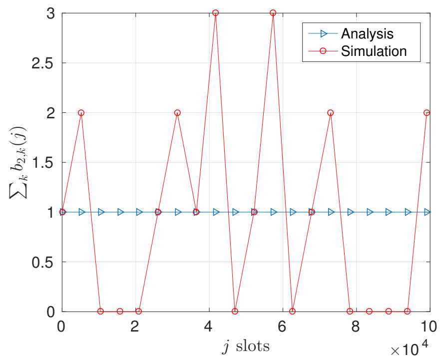

Fig. 14. Number of RACH successes in a radio frame for FRM in Case 2

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