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Advanced Random Access Channel Congestion Detection Model for Internet of Thing Based on Long Term Evolution and Mathematical Analysis

Bouba Goni Mahamadou, Mbainaibeye Jérôme, James K. Tamgno, Claude Lishou

Abstract— **The Long Term Evolution is one of the very last evolutions in mobile communication systems that offer a much wider bandwidth than its predecessors. This explains its massive deployment for the Internet of Things (IoT) also called Machine to Machine (M2M) communication or Machine Type Communication (MTC). With the IoT, the network is subject to recurrent congestion when densely charged which is due to increased uplink solicitation. Collisions occur during this process that leads to the congestion which minimizes the quality of service (QoS). In this paper we propose a new model to resolve the problem. We first determine the interval of use of preambles during which the success rate is the highest. We determine the maximal preamble utilization threshold (R_{limit}) beyond which QoS is no more guaranteed. The novelty of our model is that once R_{limit} threshold is reached, a contention resolution scheme could be activated and will remain until the threshold drops below R_{limit}. Our model can give better results if applied to contention resolution. Also, a mathematical analysis is developed and demonstrates the proof of the proposed model and its performance in term of using of the available preambles.**

Index Terms— **Machine Type Communication, Long Term Evolution, Radio Access Network, Overload, Random Access Channel, Congestion, Mathematical Analysis**

I. INTRODUCTION

The Internet of Things (IoT) is a recent communication paradigm that envisions a near future, in which everyday objects will be equipped with microcontrollers, transceivers for digital communication, and appropriate protocol stacks that will make them able to communicate with each other, with users or with a remote server, becoming part of the Internet [1]. These objects are able to collect, store, transmit and process data from the physical world. It is a paradigm that finds its application in many different areas, such as home automation, industry, medical aid, mobile health care, help for the elderly, intelligent energy management and smart grids, automobiles, agriculture, traffic management, and many others [2]. Several standardization bodies, among which IEEE and 3GPP, are working to set standards for it [3]. Its deployment on the LTE network is exponentially increasing, which is not without causing enormous challenges when we know that the LTE is designed for basic Human-to-Human (H2H) communications type (large downlink bandwidth and narrow uplink bandwidth). The IoT is meanwhile very greedy in the uplink band as the MTC devices transmit much more packets than they receive. We are talking about 26 [4] to near 50 [5] billion of connected objects by 2020. MTC devices have to compete for resources to get access to network. This is done through the RACH process where congestion often happens.

II. BACKGROUND

A. *Random Access Procedure*

In the LTE system, access to the network is through a RACH process in which UEs use preambles broadcasted at regular time slots by the base station (a total of 64 preambles). The preambles are generated from the sequences of the Zadoff-Chu algorithm include a cyclic prefix (CP), a sequence and a guard time as in Fig.1.

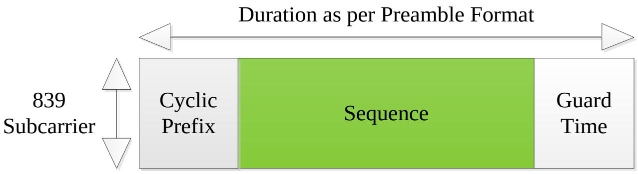

Fig. 1 Random Access (RA) preamble structure [6]

Two types of access exist in LTE:

- **Contention-free access:** Among the 64 preambles, 10 are dedicated to specific uses of high priorities in contention-free access. During contention-free access, the connection is initiated by the base station which, at the same time, provides the UE with the necessary resources. This is applied to priority communications such as emergency alert messages and specific uses.
- **Contention-based access:** In the case of contention-based access, UEs compete for the 54 remaining preambles in the RACH process. The random access request consists of this preamble, which is a digital signature transmitted by the UEs in a time slot. The RACH process is consist of four steps [7]:

Four steps of the RACH process are describes in Fig.2:

Step 1 (Preamble Send): In this step, each UE sends the access request by sending one of the 54 orthogonal predefined preambles, as well as a temporary identity Random Access - Radio Network Temporary Identifier (RA-RNTI) which is actually based on the time interval in which the preamble is issued;

Step 2 (Random Access Response): In this step, the base station transmits the access response that contains the detected preamble index, the timing for step 3, the time offset (so the UE can modify its schedule to compensate for round-trip delay), and the uplink resources necessary for UE to perform step 3;

Step 3 (Connection Request): After obtaining the resources in step 2, the UE sends a connection request to the base

Bouba Goni Mahamadou, LTI Laboratory, ESP/UCAD, Senegal
Mbainaibeye Jérôme, University of Doba, Doba, Chad
James K. Tamgno, LTI & RSI Research Group, ESMT, Dakar Senegal
Claude Lishou, LTI Laboratory, ESP/UCAD, Senegal

station. This message contains the identity of the Cell Radio Network Temporary Identifier (C-RNTI) in which the UE is located and the reason of the request;

Step 4 (Contention Resolution): The base station responds with a contention resolution message. Each device that has received this message compares the identity in the message with the identity passed in the previous step. In the case of correspondence between these identities, access is granted. Otherwise, the UE back-off and go back to step 1.

When two or more UEs use a same preamble, collisions can be detected by the base station, based on the difference in preamble transmission delays. Then, it will not send a response for this preamble. The UEs concerned will then be required to resume the operation. However, if these UEs are equidistant from the base station, the collision will not be detected and the response from step 2 will be sent to all UEs having used this preamble. In this case, the collision is resolved by the contention resolution in step 4. Only the retained UE will have access to the network, the others are led to resume the operation for a given number of iterations.

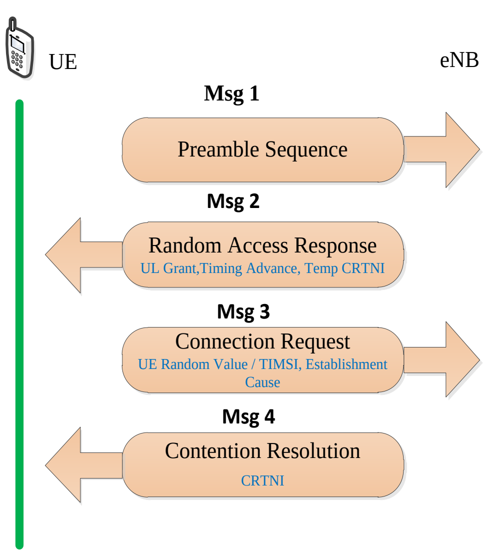

Fig. 2 RACH Process [8]

B. *Congestion Resolution*

In order to solve network overload problems due to a very high number of requests from MTC devices and recurrent collisions that occur in these high-load environments causing congestion during access to LTE, 3GPP proposed the following solutions [9]:

1) **Access Class Barring (ACB):** In the ACB, the UEs are divided into 16 classes. Classes 0-9 are called normal classes; class 10 is dedicated to emergencies while classes 11-15 are dedicated to specific uses of high priority.

The principle of the ACB consists in the fact that the base station (eNodeB) broadcasts at regular time slots a probability p ($p \in [0-1]$) called ACB factor towards all the UEs belonging to classes 0-9. The UEs accessing the network generate a number q ($q \in [0-1]$). If the q generated number by the UE is less than p ($q<p$), UE is allowed to proceed with RACH process. Otherwise, it has to wait a $T_{barring}$ time (barring time) before resuming the process. By this way, it is possible for the base station to control the collisions and network overloads by assigning an optimal value to $\boldsymbol{p}$. $T_{barring}$ can be calculated by (1) [9]:

$$T\_barring = (0.7 + 0.6 * rand) * ac\_BarringTime \qquad (1)$$

Where *rand* is a random number generated by the MTC device after passing a first failed ACB check and before a second attempt. The values of *ac_BarringTime* can range from 4s to 512s.

Several improved versions of the ACB have been performed to increase its performance. The separate approach of ACB for M2M and H2H [10][11]. Improvements of Extended Access Barring (EAB) have also been proposed in [12] [13]. For UEs under cover of several base stations, a cooperative approach has been proposed [14] to allow an optimal choice of E-NodeB for the EU. The works presented in [15] [16] provide priority random access joined to the dynamic ACB mechanism to improve the performance of the RACH. The improvement of the ACB, in most cases, leads to an increase of the access time on which, once a certain threshold is reached, can be a real problem. In order to overcome this problem, the authors of [17] have proposed and developed a scalable ACB system based on the game.

2) **Separate RACH Resources for MTC:** This scheme separates resources for H2H and M2M. When resources are not shared, the network is subject to recurring congestion. The separation of RACH resources between H2H and M2M reduces the impact of each other. A study of the separation of resources is done in [18]. It proposes two methods: the first method, called "Method 1", consists of completely dividing all available preambles into two disjoint subsets. The second method, called "Method 2", also consists of dividing the set into two subsets, but one of them is shared by the H2H and MTC clients. This means that one is reserved for the customers H2H and the other shared between H2H and MTC. However, the division of RACH resources into two groups does not seem efficient. This is a method that may very quickly become ineffective if the M2M traffic becomes excessively high and the H2H traffic remains low and vice versa.

3) **Dynamic Allocation of RACH Resources:** In this scheme, resources are allocated to M2M and H2H devices. The network can predict in advance whether the network will be overloaded by excessive access attempts caused by the large number of MTC devices. The network then dynamically allocates additional resources for the RACH procedure. As proposed in [19], M2M devices are categorized by types. In this approach, when the base station accepts the access request of an M2M device, in addition to granting access, it also allocates certain resources to devices of the same type, in which M2M devices of the same type can be content with access resources. Compared to the regular static RACH allocation, the dynamic resource allocation provided a big improvement [20] of the probability of successful access as well as time access. It is a solution that can be effective to some extent. However, it is limited by the unavailability of additional resources.

4) **Backoff Specific Scheme:** In this scheme, a lower back-off time is assigned to conventional UEs than to MTC devices. This reduces the collision and congestion in the access network. Unfortunately, this pattern causes considerable delays, which negatively impacts high priority applications that are very sensitive to delays. The authors of [21] suggested a pure back-off scheme as well as a mixed back-off and ACB scheme based on cell load information. This system can provide performance improvements when the

network is experiencing a low level of congestion in the RACH. It cannot, however, solve very high congestion levels [22].

5) **Slotted Access:** This is an approach that defines access slots for MTC devices, so that the MTC device can perform RACH process only at the beginning of its dedicated time slot. This means that an MTC device cannot access the network when it wants, but only in its predefined time slot. This solution also reduces access level congestion. In [23], the authors have shown that randomly assigning slots to H2H and M2M devices may reduce the performance of this approach, while pre-assigning resources can increase efficiency up to three times.

6) **Pull based Access (Paging):** In this scheme, RACH process is not initiated by the M2M devices but rather by the base station. M2M devices are in idle mode. M2M servers trigger the random access process via the network (Paging) to collect data from M2M devices. This is a useful mechanism when it comes to, for example, reading smart meter data [24] in the smart gird network. Although it can simply mitigate overload problems at RACH, it can create an overload in the paging channel. Overloading of the paging channel is discussed in [25] and [26]. The authors of [27] have developed an analytical model for evaluating the performance of group paging in LTE.

III. SYSTEM MODEL

During the RACH access process in a low-load network environment, the success rate of requests is very high with low delay. But as soon as a strong load is felt, this rate decreases very quickly to reach a critical threshold and the delay reaches inconceivable level. Since the 3GPP has not proposed a method of detection or prevention of overload, we propose an overload detection method so that the network can anticipate an overload situation to enable it to set up a suitable overload resolution solution on optimal time. Our method is first to determine the resource utilization (preambles) interval in which the success rate is highest $(R_1 \leq R_{used} \leq R_{limit})$. Assuming the network not loaded at the beginning, eNodeB monitors the number of preambles used. If the preamble utilization threshold reaches R_{limit}, we assume that the threshold is reached; meaning that the collision rate is going very high in contrary of success rate which drop down drastically. Based on this observation, we envisage the activation of contention resolution method, which will remain until the number of used preambles (R_{used}) drops below the R_{limit} threshold.

We assume a stable power for the MTC and the base station, we also assume that the base station is not able to successfully decode any type of transmission where a preamble is selected by more than one MTC in the same interval access time and therefore does not send any response to the corresponding MTCs. Note that random access can only take place in a frequency block specified by the base station. So, the Physical Random Access Channel (PRACH) is the physical layer responsible for mapping the RACH. In our work, the RACH configuration index is 6. This means that the RACH occurs every 5ms in a frequency band of 180 kHz for the duration of 1ms to 3ms. We denote by R the number of available preambles and N the number of MTCs transmitting the preambles in a time interval T_A called activation time $0 \leq t \leq T_A$, with a probability p(t) during which p(t) follows a beta distribution with parameters α = 3, β = 4 as in [9] is given by (2):

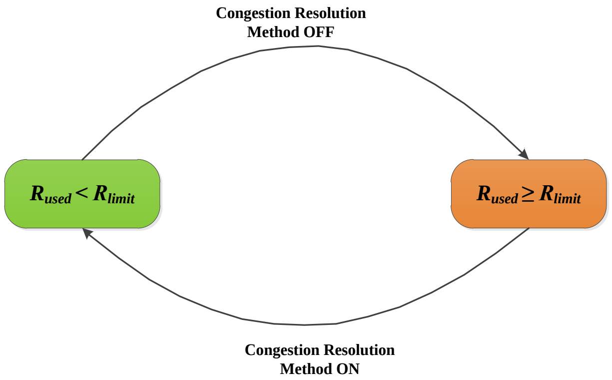

Fig. 3 Proposed congestion detection scheme

$$p(t) = \frac{t^{(\alpha-1)}(T_A - t)^{\beta-1}}{T_A^{\alpha+\beta-1} Beta(\alpha,\beta)} \quad (2)$$

Where Beta (α, β) is a beta function

It is considered that there is I_A access in the activation time interval and that the access time is smaller than the interval between two access channels. I_A is divided into several activation times where the first activation time starts at $t_{(i-1)}$ and ends at t_i.

The number of supposed new arrivals is given by (3) [9]:

$$\lambda_i = N \int_{t_{i-1}}^{t_i} g(t)dt \quad (3)$$

Where $i = 1,2,3, \ldots, I_A$

We consider that the preambles are equiprobable with the probability equal to 1/R. The probability for which one of the N MTCs chooses one and only one preamble successfully is given by the binomial law expressed by (4):

$$P_{success} = \binom{N}{1} \left(\frac{1}{R}\right)^1 \left(1 - \frac{1}{R}\right)^{N-1} \quad (4)$$

After simplification, the final expression of the success probability is given by (5):

$$P\_success = \frac{N}{R}(1 - \frac{1}{R})^{N-1} \quad (5)$$

The probability for which one of the N MTCs does not transmit any preamble (Idle) is given by the binomial law expressed by (6):

$$P_{Idle} = \binom{N}{0} \left(\frac{1}{R}\right)^0 \left(1 - \frac{1}{R}\right)^{N-0} \quad (6)$$

After simplification, the final expression of the failure probability is given by (7):

$$P_{Idle} = \left(1 - \frac{1}{R}\right)^N \quad (7)$$

Success (successfully transmitted queries) can be achieved by multiplying the probability of success by the amount of available resources defined by (8):

$$Success = R * Psuccess \quad (8)$$

By replacing the success probability by its expression in equation 5, success is given by (9):

$$Success = N\left(1 - \frac{1}{R}\right)^{N-1} \quad (9)$$

The probability of collision is given by (10):

$$P_{collision} = 1 - P_{success} - P_{Idle} \quad (10)$$

By replacing *Psuccess* and P_{Idle} by their expression, the collision probability is given by (11):

$$P_{collision} = 1 - \left(\frac{N+R-1}{R}\right)\left(1-\frac{1}{R}\right)^{N-1} \quad (11)$$

From previous equations, it is clear that the quantity of resources used is the product of the total number of resources by the probability of use (1 - P_{Idle}). This quantity of resources used is given by (12):

$$R_{used} = R * (1 - P_{Idle}) \quad (12)$$

By replacing P_{Idle} by its expression, the quantity of resources used is given by (13):

$$R_{used} = R\left(1-\left(1-\frac{1}{R}\right)^{N}\right) \quad (13)$$

IV. SIMULATION RESULTS

To evaluate the proposed model, we determine the resource utilization interval in term of the success rate of RA transmissions. The implementation and execution of (8) and (12) give the result presented in Fig.4.

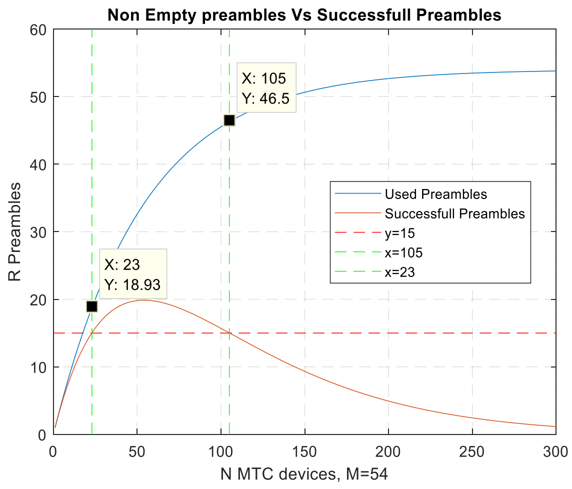

Fig. 2: R_{used} vs Success

The success probability, the failure or idle probability and the collision probability given respectively by (4), (6) and (10) are implemented and executed. The results obtained are presented in Fig.5.

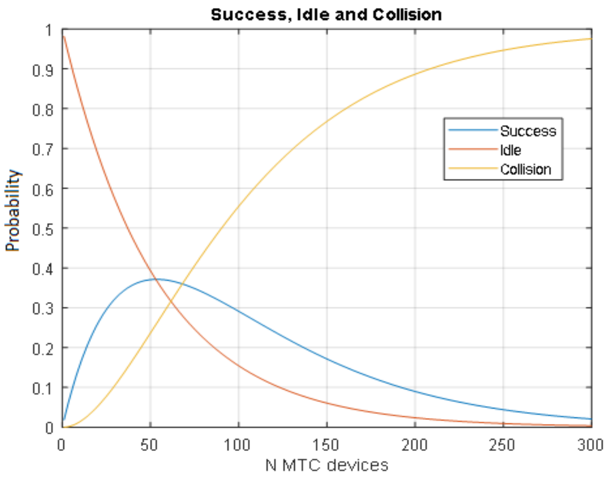

Fig. 3: Success-Collisions-Idle Probability

V. DISCUSSIONS OF THE RESULTS

Fig. 4 shows that the resource utilization interval is located between R_{used} = 18.93 and R_{used} = 46.5 giving a higher success rate when considering this rate above 15 and when taking N=300 (MTC devices) and R = 54 as in [9]. From this interval, it is clear that beyond R_{used}= 46.5 (the threshold called R_{limit} in our work) the success rate falls down drastically and considered as not viable for the network. So, we consider that this is the threshold from which congestion resolution method can be applied. By applying the threshold, we think that the performances of system can be improved when comparing to the case when congestion resolution method is applied without taking in account the threshold.

Fig.5 shows that if no congestion detection or resolution is applied, success probability reaches its highest value at N=50 and decreases when the number of MTC devices increases. At the same time collision probability increases from 0 to its highest value when N increasing. However, the failure or Idle probability decreases from its higher value to 0 when N increases.

VI. MATHEMATICAL ANALYSIS OF THE PROPOSED MODEL

We operate in this section a mathematical analysis of the model proposed in this work. The objective of this analysis is to study mathematically its proof and its performance.

The success probability is defined by equation 5. Let us consider the number of connected objects *N* as a variable *x* and the available preambles *R* as a constant. We recall that there are 64 preambles, 10 are dedicated to specific uses of high priorities in contention-free access. The UEs will use the 54 remaining preambles or channels in the RACH process. So, the success probability, function of *x* is defined by (14):

$$P(x) = \frac{x}{R}\left(1-\frac{1}{R}\right)^{x-1} \quad (14)$$

By using the neperian logarithm function, the expression of the success probability is given by (15):

$$P(x) = \frac{x}{R} e^{(x-1)\log\left(1-\frac{1}{R}\right)} \quad (15)$$

Let us define $\alpha = \frac{1}{R}$, $\beta = \log\left(1-\frac{1}{R}\right)$.

The success probability is given by (16):

$$P(x) = \alpha x e^{\beta(x-1)} \quad (16)$$

Let us define *f(x)* the first derivation of *P(x)* given by (17):

$$\frac{dP(x)}{dx} = f(x) = \alpha(1+\beta x)e^{\beta(x-1)} \quad (17)$$

The zero of *f(x)* is given by $f(x) = 0$, and the solution of this equation is $x = \frac{-1}{\beta}$. Fig. 6 shows the table of variations of the success probability.

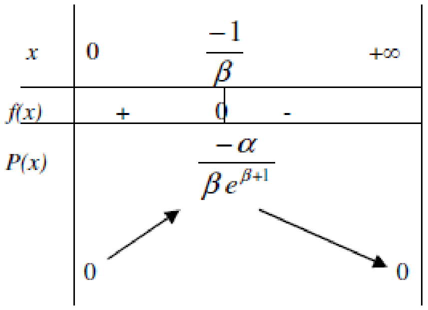

Fig. 6: Variations of the success probability function of connected objects N

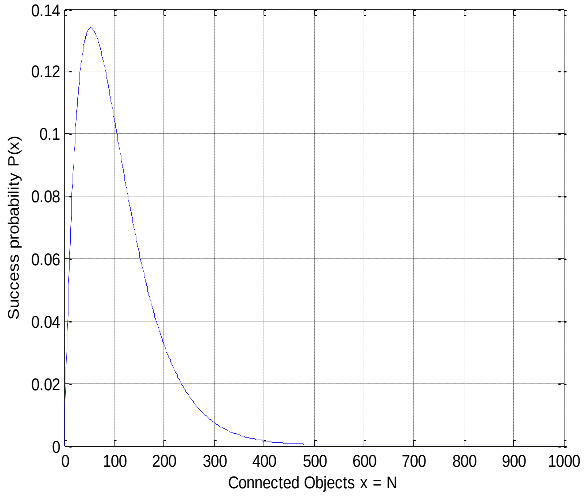

Fig. 7 Curve of the success probability function of connected objects for available preamble R = 54

Fig.6 shows that the success probability is maximal for the number of connected objects $x = N = \frac{-1}{\beta}$. For R = 54, and by using $\beta = \log\left(1-\frac{1}{R}\right)$, we obtain $x = 53.49 \approx 54$.

This result shows that, for 54 preambles available, 54 objects are successfully connected.

By replacing x with its value, we obtain the maximum value of P defined by (18):

$$P_{\max} = P\left(\frac{-1}{\beta}\right) = \frac{-\alpha}{\beta e^{\beta+1}} = \frac{-\frac{1}{R}}{\log(1-\frac{1}{R})\, e^{\log(1-\frac{1}{R})+1}} \tag{18}$$

After simplification, the final expression of the maximal success probability is given by (19):

$$P_{\max} = -\frac{1}{e(R-1)\log(1-\frac{1}{R})} \tag{19}$$

Where e = 2.7183

We may observe, from (19), that the maximal value of the success probability is depending of the available preambles R. So, for R = 54, $Pmax$ = 0.37

Suppose that we are in the case where we have an unlimited number of channels or preamble R. Let us calculate the limit of the maximal success probability for R tending towards infinity:

$$\lim_{R\to+\infty} P_{\max} = \lim_{R\to+\infty} -\frac{1}{e(R-1)\log(1-\frac{1}{R})} = -\frac{1}{(+\infty)\times(0)}$$

This limit is not defined. To obtain mathematically this limit, let us consider the first order limited development of the function $\log\left(1-\frac{1}{R}\right)$.

Let us consider the equation $y = -\frac{1}{R}$. If $R \to +\infty$ then $y \to 0$.

So, $\log(1+y) = y + o\,(y) = \frac{-1}{R} + o\left(\frac{-1}{R}\right)$

By replacing $\log\left(1-\frac{1}{R}\right)$ with $\frac{-1}{R}$, we obtain $Pmax$ given by (20):

$$P_{\max} = -\frac{1}{e(R-1)(1-\frac{1}{R})} = \frac{R}{e(R-1)} \tag{20}$$

Let us now calculate the limit of $Pmax$ while $R \to +\infty$

$$\lim_{R\to+\infty} P_{\max} = \lim_{R\to+\infty} \frac{R}{e(R-1)} = \frac{R}{eR} = \frac{1}{e} = 0.3679 \approx 0.37$$

We conclude, in this mathematical analysis, that the success probability can reach 0.37 for the availability of 54 channels. Furthermore, we have shown that if there exist an unlimited number of channels, the maximal value of the success probability converge also to 0.37.

VII. CONCLUSION AND PERSPECTIVES

Considered to be the first line of defense against LTE congestion, the LTE RACH procedure is prone to congestion when a large number of MTC devices attempt to access the network simultaneously. 3GPP pays particular attention to the resolution of congestion. Thus, it proposed several methods of congestion resolution from which research was conducted for their improvement. However 3GPP did not provide any congestion detection method. Our contribution in this work propose a solution by providing a congestion detection method which, if applied to one of 3GPP's congestion resolution methods, will greatly improve its performance. The simulations allowed us to determine the preamble utilization interval during which the RA success is the highest. It also allowed us to determine the threshold beyond which the QoS is no longer guaranteed. The method gets the eNodeB informed about the state of use of preamble resources, which enable the network to anticipate congestion states by activating a congestion resolution scheme. We have operated a mathematical analysis of the proposed model; we have shown that the probability for one among N MTCs to choose one and only one preamble successfully can reach 0.37 as well for 54 available preambles or channels as for a an infinity of available channels . In our future work, we envisage the implementation of the proposed detection method with 3GPP methods such as ACB, EAB, Separation of Resources or Backoff Scheme to improve its performance.

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,AUTHOR’S BIOGRAPHIES

Bouba Goni Mahamadou received his B.Sc. in Electrical and computer engineering in 2007 from Al-Mergheb University of El-Khoms LIBYA and M.S. in Computer Networks and Telecommunications from Ecole Supérieure Polytechnique – Université Cheikh Anta Diop (ESP/UCAD) Ségénal in 2015. Upon the completion of his M.Sc. degree, he conducted research and implementation of Voice Over 4G - Long Term Evolution telecommunication systems. In 2016, he started his Ph.D. program at ESP/UCAD. His research interests include LTE-A Random Access Channel Congestion detection, LTE-A Congestion resolution, RAN overload, 5G Communications and Machine Type Communication. He is currently assistant lecturer at Université Polytechnique de MONGO, TCHAD, in computer Engineering and telecommunications field.

Pr. MBAINAIBEYE Jérôme have received the Master degree in Signal Processing and the PhD degree in Electrical engineering at the National High School of Engineers of Tunis, Tunisia, University of Tunis El Manar in October 1997 and July 2002 respectively. He was an Assistant Professor in the department of Computer Science at the Faculty of Sciences of Bizerte, Tunisia from 2002 to 2007. From May 20 to June 20, 2003, he was a scientific visitor at “ÉQUIPE SIGNAL et IMAGE of Ecole Nationale Supérieure d’Electronique, d’Informatique et de Radiocommunication de Bordeaux (E.N.S.E.I.R.B), University of Bordeaux I, France.

In 2008 he has joined the Faculty of Applied and Exact Sciences in the University of N’djamena, Chad, as an Assistant Professor in Electrical Engineering. Since April 2012, he has joined the Polytechnic High Institute of Mongo (Chad) as Director General. In February 14th, 2017, he has joined the University of Doba (Chad) as Rector. Since July 2014, he is an Associate Professor of Electrical Engineer. He is member of Signal, Image and Pattern Recognition Laboratory of the National High School of Engineers, Tunis, Tunisia and an associated researcher in XLM Signal, Images and Communication laboratory department, University of Poitiers, France. He has published several papers in scientific journals and in international conference proceedings. He also has served as a reviewer of the IEEE International Conference on Sciences of Electronics, Technology of Information and Telecommunications SETIT’2007, the International Conference on Document Analysis and Recognition, ICDAR’ 2007, and the IEEE 3th International Conference on Information & Communication Technologies: From Theory to Application, ICTTA’ 2008. His research activities include Digital Signal Processing, Image Processing, Image Analysis, Image and Video Compression, Communication Technologies, Wavelet Transform and its applications, Biometric systems and applications.

Dr. James K. Tamgno, is a senior lecturer at ESM. He became a Member of IEEE in 2012, he obtained his Ph.D in May 2013 at University Cheikh Anta Diop of Dakar. His research activities are focused on Promotion of African's languages and dialects and Contribution to a Wider Accessibility of ICT, by Circumventing Language Barriers and Lessening the Impact of Illiteracy or Disability. Previously, he has gotten a M.Sc. in Engineering Science from Cheikh Anta DIOP University of Dakar, studied numerical analysis and mathematics at Yaoundé I University of Yaoundé, and worked as a research scientist at Ecole Superieure Mutinationale des Télécommunications (ESMT) of Dakar.

Pr. Claude LISHOU is Professor of Universities at the Ecole Supérieure Polytechnique of Cheikh Anta Diop University in Dakar (Senegal). He teaches several disciplines ranging from industrial computing to new generation networks in the electrical engineering and computer engineering sections. Director of the Virtual Platform of the UCAD, coordinates the information system and oversees the strategy of open and distance training at his university. He leads an internationally renowned research and development laboratory dedicated to the use of ICT in education and training, environment, energy, transport, e-governance. On the scientific level, he is the author and co-author of several publications in scientific journals with international circulation. Professor LISHOU is a member of several scientific societies, member of editorial committees of scientific journals, member of the Networks of Information and Communication Technologies for teaching and research, Editor in chief of the Journal of Sciences for Engineers. For more than two decades, he has supervised and supported dozens of engineers and researchers in these areas, especially in western Africa. Recognized expert in the development of ICT applications and services, he divides his time between teaching, research and consulting with international organizations (OIF, AUF, UNDP, UNESCO, UNCTAD...).