

Modelling and Performance Analysis of Contention Resolution Scheme for Massive IoT Devices in Random Access to LTE-A Networks

Oishwarya Roy¹, Aastha Kumari², and Dr. Atul Kumar Pandey³

¹Birla Institute of Technology Mesra/Electronics and Communication, Ranchi, India

²⁻³Birla Institute of Technology Mesra / Electronics and Communication, Ranchi, India

Email: royoish2000@gmail.com, {kumariaastha131@, atulkrpandey@}gmail.com

Abstract— The Long-Term Evolution Advanced (LTE-A) networks have great potential to support the Internet of Things (IoT). A massive number of IoT devices want to access the network to get radio resources for data transmission. This results in a high level of preamble collisions and access delay. To, resolve these problems Distributed Queuing Random Access (DQRA) based contention resolution schemes are found more suitable. In this context, we developed generalized mathematical modelling to estimate the average access delay for sequential, parallel, and parallel with pipelined contention resolution schemes. The performance analysis shows that the proposed model matches the existing simulation results.

Index Terms— IOT, LTE-A, DQRA, ACCESS DELAY

I. INTRODUCTION

Long-Term Evolution Advanced (LTE-A) is a wireless mobile communication standard. It provides faster data rate, lower latency, and better spectral efficiency through the use of advanced technologies such as carrier aggregation, Multiple Input Multiple Output (MIMO), and higher-order modulation [1]. LTE-A supports machine-to-machine (M2M) communications that contain a massive number of devices in a wide range of applications, thus forming massive IoT. The deployment of massive IoT devices has the potential to transform many industries, including agriculture, healthcare, transportation, and manufacturing [2]. However, it also presents several challenges, including data security, network congestion, and power management. A massive number of IoT devices require early contention access for data transmission, resulting in a higher level of access delay due to preamble collisions. Earlier ALOHA-like contention-based mechanisms [3-4] are utilized for massive IoT devices to perform contention access procedures for preamble transmission. Since it has been proven that ALOHA is not suitable for high-traffic load conditions because this leads to a high collision probability, low throughput, and large access delay due to congestion in Random Access channels [3-4]. These limitations in ALOHA can be overcome by utilizing the distributed queuing random access (DQRA) based mechanism [5]. In the DQRA-based mechanism, time is portioned into contention access and data transmission part. It is based on a tree-splitting mechanism where each device is organized into a contention resolution queue (CRQ) and data transmission queue (DTQ) for collision resolution and data transmission respectively. It provides an optimum behaviour in terms of throughput and access delay. These features make DQRA based mechanism more suitable to perform random access for massive IoT devices in LTE-A networks. This has motivated us for the modelling and performance analysis of DQRA-based

contention resolution schemes in terms of access delay. In this context, several DQRA-based contention resolution schemes are briefly described and investigated in the related work.

The rest of the paper is organized as follows, section II summarises related work section 3 presents the analytical model to estimate average access delay, section 4 provides simulation result and performance analysis and finally conclusion and future work is mentioned in section 5.

II. RELATED WORK:

Over the last few years, there are several implementations of DQRA-based algorithms into LTE-A structure to address this concern. In [6], the authors proposed a DQRA-based protocol for LTE-A networks denoted as DQAL that minimizes the probability of collision in the access phases and reduces the access delay for M2M communications. This can be achieved through the virtual mapping of LTE resources to virtual groups. In [7] authors proposed a distributed queueing-based Random Access (DRQA) where mini-slots are mapped virtually into preambles in the context of LTE-A networks. In DQRA, preamble collision is resolved sequentially one by one in a Random Access (RA) slot. If M number of preamble collisions occur in the current RA slot then it requires next M RA slots to resolve it. In DQAL, several collided groups utilize different preambles in one RA slot, while in DQRA only one collided group retransmits in each RA slot. Compared to DQAL, DQRA is much simpler and performs better in contrast to the conventional LTE Random Access mechanism for a large number of simultaneous arrivals. DQRA offers a low probability of collision, reduced access and reduced energy consumption. In [8], the authors proposed another DQRA-based mechanism that performs preamble grouping and can resolve up to M collided preambles in an RA slot. If M collided preambles exist, it spends only $\lceil M/G \rceil$ RA slots. This is the main advantage of Yoon's mechanism over Laya's mechanism. However, It fails to provide the desired level of parallelism when the number of devices involved in preamble selection is small. In [9], authors considered massive access issues in cellular-based M2M communication by taking advantage of distributed queueing-based mechanisms to solve over division problem. In this proposed method Base Station (BS) first estimates the number of colliding devices in a RA slot and based on this result BS divides these collided devices randomly into a predefined number of groups, Next, BS sends these groups to the tail of a logic queue. Also, developed an analytical model for access delay calculation. In [10], authors provided analytical modelling of the DQRA [7] mechanism to estimate maximum access delay and the average number of preamble transmissions. In [11], authors developed a new scheme to handle the massive LTE-A networks. In this scheme, entire preambles are divided into M subgroups and therefore contention is resolved independently in each subgroup in a parallel and pipeline model. This scheme shows a considerable amount of improvement in terms of average access delay in contrast to Laya's and Yoon's models [7, 8]. In [12], authors provided a general theoretical performance analysis of distributed queue for massive machine type communication (mMTC) in terms of the probability distribution, mean and variance of throughput, delay, and energy consumption.

III. ANALYTICAL MODEL TO ESTIMATE AVERAGE ACCESS DELAY:

The mathematical modelling and performance analysis of contention resolution schemes for massive IoT devices in random access to LTE-A networks involves studying the behaviour of a large number of IoT devices attempting to access the network simultaneously. The objective is to ensure that the devices are able to successfully connect to the network and transmit their data without experiencing any significant delay or loss. So, next, we are developing a generalized mathematical expression to estimate the average access delay for sequential, parallel, and parallel and pipeline contention resolution schemes.

A. Average Access Delay For Parallel And Pipelining Contention Resolution Scheme:

Average access delay is the average time it takes to retrieve a resource or service, measuring latency and responsiveness in systems or networks. In the parallel and pipeline contention resolution model, all the preambles are divided into subgroups and each subgroup has its own queue where the devices are placed, and then collision resolution occurs in a parallel manner. The devices that are first in line for a subgroup choose preambles between $s \times \frac{Np}{Ng}$ and $(s+1) \times \frac{Np}{Ng} - 1$ if there are any collisions that need to be resolved. Devices are then added to the queue for subgroup $[p \times \frac{Np}{Ng}]$. Based on the analytical modelling provided in [10], the average access delay of parallel and pipeline contention resolution scheme can be estimated as follows:

$$T_{\max}(M, N) = 1 + \sum_{i=2}^m \sum_{s=\frac{Np}{Ng}}^{(s+1) \times \frac{Np}{Ng} - 1} \left\{ p\left(\frac{p \times Ng}{Np}, \frac{s \times Np}{Ng}\right) * K T_{\max}\left(P * \frac{Ng}{Np}, Ng\right) / N * Ng \right\} \quad (1)$$

$P = 0, 1, 2, 3$ (Preamble Id)
 $S = 0, 1, \dots$ (Preamble subgroup number)
 N_p is non-dedicated Preamble subgroups is 56
 N_g is number of preamble subgroups is 8 which is the grouping size
 M is the total number of devices (1000 – 100000)
 N is the total number of channels; the value is 64
 K is the number of collided groups; the value is 8
 N_g is total number of channels divided by number of preambles, i.e., N/K

B. Average Access Delay For Parallel Contention Resolution Scheme:

In parallel contention resolution the total number of preambles are divided by the number of collided preambles and the contention resolution of those devices takes place parallelly. The average access delay is calculated with a slight modification in equation (1). In the parallel and pipeline models, we use subgroups but in the parallel model, we are not using subgroups. Hence, it is clear that if we put s (no. of subgroups) = 0 in (1) then we get the formula of the parallel contention resolution scheme as represented by equation (2).

$$T_{max}(M, N) = 1 + \sum_{i=2}^M \sum_{k=1}^{\min\{\frac{M}{i}, N_g\}} \{p(i, K) \times K T_{max}(i, N_g) / N \times N_g\} \quad (2)$$

here, $(N/k) = N_g$ and $p(i, k) = \frac{c_k^N c_i^M \dots c_i^{M-(k-1)i}}{N^M} \times \frac{N!}{(N-(M-ki))!}$

C. Average Access Delay For Sequential Contention Resolution Scheme:

In sequential contention resolution scheme preamble collisions are resolved sequentially in each RA slot. Previously we have developed an expression to estimate the access delay for parallel contention resolution scheme. Now in parallel contention resolution scheme if we do not divide the number of preambles with the number of collided groups then contention resolution occur sequentially. If we do that we get exactly that same formula to estimate average access delay as given in [10]. Therefore, The average access delay for sequential contention resolution scheme is defined as follows:

$$T_{max}(M, N) = \sum_{i=2}^M \sum_{K=1}^{\min\{\frac{M}{i}, N\}} P(i, K) \times K \overline{T_{max}}(i, N) \quad (3)$$

Where, K = no. of collided groups, M is number of devices, i = no. of devices in the collided groups and

$$P(i, k) = \frac{c_k^N c_i^M \dots c_i^{M-(k-1)i}}{N^M} * \frac{N!}{(N-(M-Ki))!}.$$

This proves that our mathematical analysis for access delay estimation is accurate.

IV. SIMULATION RESULT AND PERFORMANCE ANALYSIS

Here, we have done the numerical simulation and performance analysis using MATLAB software. All the simulation parameters are considered based on [11]. We considered 65 non –dedicated preamble out of 64 Preambles in LTE-A network. PRACH configuration refers to the parameters associated with the Physical Random Access Channel (PRACH) and its value is considered 3. The random access response window (RAR) window is the period of time when the BS responds to a user device's random access request. The RAR window size is 5ms. Beta distribution is considered for the arrival of devices. The number of devices ranging from 1000 to 10000. The simulation parameters are in Table-4.1.

Average access delay is the average time it takes to retrieve a resource or service, measuring latency and responsiveness in systems or networks.. The average access delay for all the three contention resolution schemes (sequential, parallel, parallel and pipeline) are estimated based on equation (1), (2) and (3) respectively and compared in figure 4.1. From the figure -4.1 it is clear that with the increase of number of massive IoT devices average access delay will also increase.

From the figure -4.1 it is also clear that parallel and pipeline model [11] provides less access delay in comparison to parallel [8] and sequential [7] models. The reason for increase in access delay in sequential [7] than that of parallel [8] and parallel plus pipeline [11] is because with the increase in number of devices their resolution slots

TABLE –IV (1) SIMULATION PARAMETERS

Parameter	Value
PRACH Configuration index	3
Total number of non-dedicated RA preambles	56
Maximum number of preamble retransmissions	20
RAR window size	5 ms
Backoff indicator	480 ms
Barring factor	80%
Barring time	4 s
Number of IoT devices	1000-10000
Arrival distribution (Beta distribution) over	1 s ($\alpha=3$, $\beta=4$)

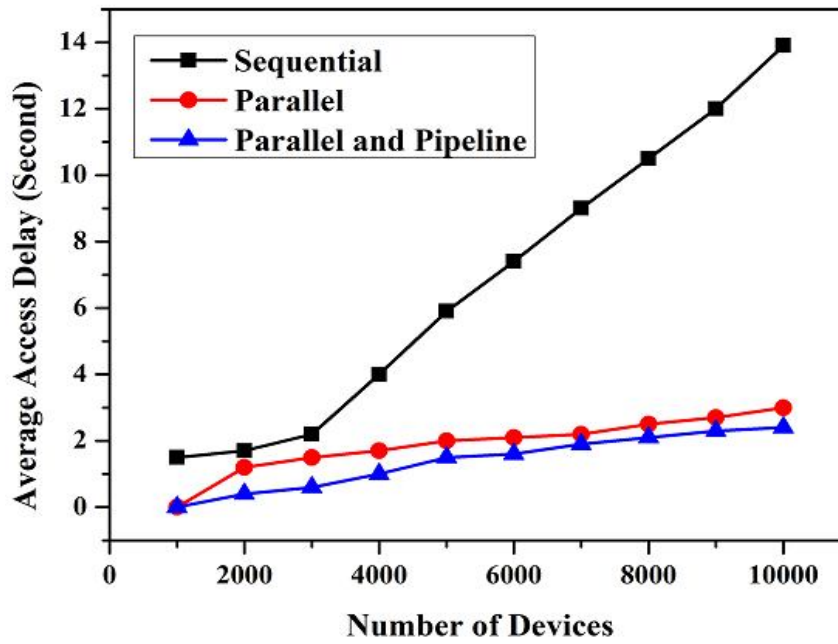


Figure-4(1) Average access delay

increases and as a result the time for the reception of each slot and then resolution in each slot increases. For parallel though the number of slot is less than sequential still the method works haphazardly and there is still scope for improvement. In parallel and pipeline as there is a queue and a dequeue and the preambles in the slots are divided there is less number of slots and resolution occur with ease. So, there is a decrease in average access delay. In contrast to the simulation results provided in [11], we got approximately the same result with 2% error for sequential [7] and parallel plus pipelining [11] models and 5% for the parallel [8] model. This proves the accuracy of our mathematical analysis to estimate the average access delay.

V. CONCLUSION AND FUTURE WORK

We have proposed the mathematical analysis for sequential, parallel, and parallel plus pipelining models and verified it by plotting the graph and comparing it with the base model. Though we have got a percentage error 2% for sequential and parallel plus pipelining models and 5% for the parallel model which is quite similar to the base model. In future, we should combine a sequential, parallel and parallel plus pipelining model to further reduce the access delay and develop a mathematical model for it. We will also try to optimize our mathematical modelling and reduce the percentage error. We would also like to extend our work by calculating throughput and energy consumption.

REFERENCES

- [1] Kanchi, Sravanthi, Shubhrika Sandilya, Deesha Bhosale, Adwait Pitkar, and Mayur Gondhalekar. "Overview of LTE-A technology." In 2013 IEEE global high tech congress on electronics, pp. 195-200. IEEE, 2013.
- [2] Painuly, Sakshi, Sachin Sharma, and Priya Matta. "Future trends and challenges in next generation smart application of 5G-IoT." 2021 5th international conference on computing methodologies and communication (ICCMC). IEEE, 2021.
- [3] Yang, Xiaobin, Abraham Fapojuwo, and Emeka Egbogah. "Performance analysis and parameter optimization of random access backoff algorithm in LTE." In 2012 IEEE Vehicular Technology Conference (VTC Fall), pp. 1-5. IEEE, 2012.
- [4] Yang, Bo, Guangxi Zhu, Weimin Wu, and Youjun Gao. "M2M access performance in LTE-A system." *Transactions on Emerging Telecommunications Technologies* 25, no. 1 (2014): 3-10.
- [5] Laya, Andres, Charalampos Kalalas, Francisco Vazquez-Gallego, Luis Alonso, and Jesus Alonso-Zarate. "Goodbye, aloha!" *IEEE access* 4 (2016): 2029-2044.
- [6] Samir, Ahmed, Mahmoud M. Elmesalawy, Ahmed S. Ali, and Ihab Ali. "An improved LTE RACH protocol for M2M applications." *Mobile Information Systems* 2016 (2016).
- [7] Laya, Andres, Luis Alonso, and Jesus Alonso-Zarate. "Contention resolution queues for massive machine type communications in LTE." In 2015 IEEE 26th annual international symposium on personal, indoor, and mobile radio communications (PIMRC), pp. 2314-2318. IEEE, 2015.
- [8] Yoon, Changbae. "Distributed queuing with preamble grouping for massive IoT devices in LTE random access." In 2016 International Conference on Information and Communication Technology Convergence (ICTC), pp. 103-105. IEEE, 2016.
- [9] Bui, Anh-Tuan H., Chuyen T. Nguyen, Truong C. Thang, and Anh T. Pham. "Design and performance analysis of a novel distributed queue access protocol for cellular-based massive M2M communications." *IEEE Access* 6 (2017): 3008-3019.
- [10] Cheng, Ray-Guang, Zdenek Becvar, and Ping-Hsun Yang. "Modeling of distributed queueing-based random access for machine type communications in mobile networks." *IEEE Communications Letters* 22, no. 1 (2017): 129-132.
- [11] Lee, Kyungjun, and Ju Wook Jang. "An efficient contention resolution scheme for massive IoT devices in random access to LTE-A networks." *IEEE Access* 6 (2018): 67118-67130.
- [12] Li, Yaoyao, Xin Jian, Keping Yu, Neeraj Kumar, and Shaoxiong Cai. "Theoretical performance analysis of distributed queue for massive machine type communications: Throughput, latency, energy consumption." *IEEE Transactions on Network and Service Management* 19, no. 2 (2022): 818-828.