Fast Retrial and Dynamic Access Control Algorithm for LTE-Advanced Based M2M Network

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***Abstract*—Currently, increasing number of devices are connected to networks. Hence, M2M (Machine to Machine) communication, especially LTE/LTE-Advanced based M2M communication, is attracting more and more interests from the telecommunication industry. However, as the current LTE (Long Term evolution) system is designed for Human to Human system, it may be unable to support the massive M2M devices. This paper proposes a fast retrial and dynamic random access algorithm for LTE-Advanced network. It drastically reduces the delay of access comparing the back-off algorithm. In the meantime, it successfully prevents the system from severe congestion, which is inevitable in back-off algorithm when the arrival rate of random access is very high. To make the dynamic control of random access feasible in practical scenario, an estimation algorithm of the access arrival rate is also proposed in this paper. Simulation results reveal that the algorithm is able to provide better delay performance and greater throughput comparing with the back-off schemes defined in the LTE network.**

***Index Terms*—M2M, Random Access, Dynamic control, LTE-Advance**

I. Introduction

M2M (machine to machine) communication is considered to be a new killer application for the next generation communication system, such as LTE-Advanced network. However, current communication systems are designed for Human to Human communication, while M2M applications are characterized by some unique features such as massive nodes, extremely high frequency of accessing [1], [2] and so on. Hence, in order to better support M2M applications, it is necessary to introduce some specific optimization for M2M communication to the LTE-Advanced system. One of the most important issue is designing an effective medium access scheme to handle the high frequency of access of the massive MTC (machine-type communications) devices.

Random access is popular for medium access control. Moreover, time slotted random access is adopted in 2G (2rd Generation), 3G (3rd Generation) and LTE (Long Term Evolution) for initiating uplink access because of its channel efficiency in licensed channels [3]. Back-off algorithm has been adopted in LTE to alleviate grave congestion following random access collision. Sharma et al. [4] studied the performance of back-off based random access in IEEE 802.11 DCF. Nevertheless, Back-off scheme brings about great time delay and fails to deal with circumstances with extremely high arrival rate of accesses, especially when there are massive nodes. Aldous et al. [5] evaluated the ultimate instability of exponential back-off protocol with transmission control for random access. Rivest et al. [6] and Hauksson et al. [7] proposed algorithms adopting other dynamic medium access control methods to improve the delay and loss performance of the system. However, they can only be used in single channel. Choi et al. [8] proposed a multichannel random access with fast retrial. It can successfully limit the time delay in random access. However, it is unable to sustain stable even when the arrival rate of access is not very high.

In this paper, a fast retrial and dynamic access control algorithm is proposed to deal with the congestion in multichannel random access under extremely high arrival rate of access. It is able to achieve a comparatively low delay, in addition to effectively utilizing the channels. Furthermore, it works well even when the arrival rate of access is higher than the limitation of time slotted aloha scheme e^{-1} [9].

The paper is organized as follows: Section II introduces the system model, and describes the proposed algorithm in detail. In Section III, the algorithm's performance is analyzed. Section IV shows simulation results. Finally, the paper is concluded in section V.

II. System Model and Optimized Algorithm

A. Uplink random access

Consider that in a LTE-Advance system, there are numerous MTC nodes. Each node needs to conduct a contention-based random access procedure to obtain an uplink channel. The physical resource of random access in LTE-Advance includes preambles and random access opportunities. In LTE-Advance, each cell is allocated with 64 preambles, and some preambles are assigned to non-contention-based random access. For cells below 1.5km radii, all 64 preambles are orthogonal to each other as they are derived from single root Zadoff-Chu sequence. In larger cells, though 64 preambles are not perfectly orthogonal to each other as they are derived from multiple root sequences, the cross-correlation is low [10]. Hence, we assume that all preamble are orthogonal to each other and one preamble is denoted as a logical channel in this paper. According to the current LTE-Advance network definition, time slotted aloha is adopted in random access. In which each node can send a random access request in the dedicated time slot (random access opportunity).

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Assuming that there are N orthogonal preambles, that is, there are N parallel logical channels (mentioned as channels in this paper) in one random access opportunity (mentioned as slot). In each slot, if more than one MTC nodes have sent the same preamble, a collision will happen. Fig. 1 illustrates a abstract system with 4 logical channels and 3 random accesses in the first slot.

The contention-based random access procedure in LTE-Advance is outlined in Fig. 2, and it is further described below. Readers can get more information about the contention-based random access from [3], [11].

1) Random access preamble. Each ue randomly select a preamble from the contention-based-group and transmit it in a nearby random access opportunity.
2) Random access response. The eNodeB correlates all possible preambles in each random access opportunity with the received preamble. With the detected preambles, the eNodeB assigns uplink resources related MTC nodes and broadcasts the the information.
3) Scheduled Transmission. MTC nodes transmits unique identity with the allocated uplink resource.
4) Contention resolution. In step 3, more than one MTC nodes which had sent the same preamble may response. In this case, the eNodeB is unable to decode the identities from these nodes. So these nodes will not receive the notification of the reception step 3 in the dedicated time window, and they will go to step 1.

In the back-off algorithm of current LTE, before conducting step 1, each node needs to wait for a randomly determined number of slots (back-off time). Where the back-off time follows Uniform distribution on [0, maximum back-off slot]. If the random access procedure is unsuccessful after maximum retrial times of step 1, the random access will be abandoned.

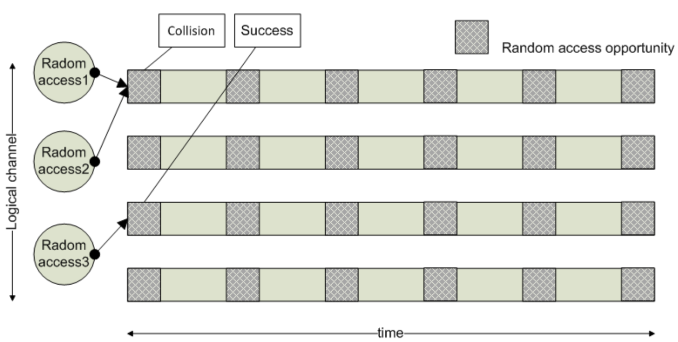

Fig. 1. A system with 4 logical channel

B. Proposed algorithm

In the proposed algorithm, MTC nodes which have suffered from collision will send a preamble immediately in the next random access opportunity. Before every random access opportunity, the eNodeB broadcasts an access rate. For all MTC nodes that need to conduct a random access, they send a preamble at a rate of α. The parameter α is dynamically determined by the eNodeB and timely broadcasted by it. If a MTC node is about to send a access request, it randomly choose one channel from all channels with equal possibility. If a collision happens, it will retry in the next slot with a randomly chosen channel. The flow diagram of the proposed algorithm (first random access requests) is shown in Fig. 2:

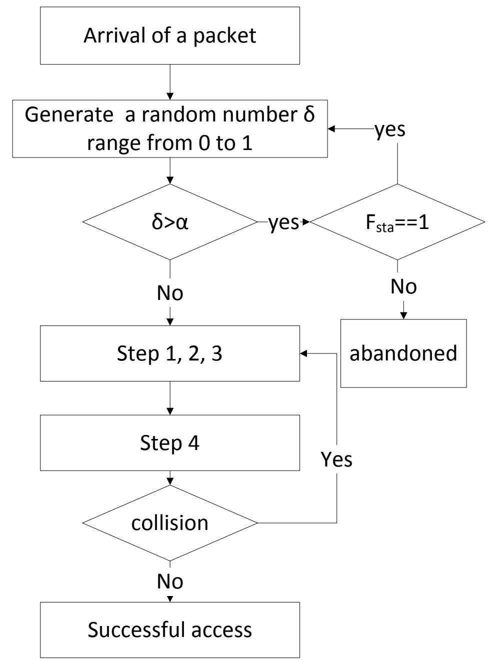

Fig. 2. flow diagram of the proposed algorithm

Now, we define the following notations. They will be used in parameter determinations and performance evaluation.

N	number of random access channels
λ	New arrivals of random access
λ'	combined arrivals of random access, including new and time-domain backlogged arrivals
M	number of retrial access in current random access opportunity.
α	the rate of sending a preamble in random access
p_{uu}	The possibility of a channel is used
p_{nc}	The possibility of a channel has no collision
p_{uu}	The possibility of a channel is not used
n_{nc}	Number of logical channels with no collision in the current slot
n_{uu}	Number of unused channels in the current slot
n_{ac}	number of logical channel with a successful random access in the current slot
p_{su}	the possibility that an access and be succeed at last
p_{ac}	the possibility that an access is accepted in current slot
F_{sta}	When it equals to 1, the system is considered to be stable. When it equals to 0, it is considered to be unstable.
W	contention resolution window

C. The determination of α and F_{sta}

According to the flow diagram of the algorithm, each MTC node needs to receive α and F_{sta} from the eNodeB before each slot.

Proposition 1: Assuming that the combined arrivals in a time slot follow Poisson distribution with a mean λ'. There are M retrials and N logical channel$(N > 1, 0 \leq M < N)$. In the proposed algorithm, the optimal α follows:

$$\alpha = \max(0, \min((N - M - 1)\frac{N}{(N-1)\lambda'}, 1)) \qquad (1)$$

Proof: Without loss of generality, in the $i^{th}, (i = 1, 2, 3 \cdots N)$ channel, the combined arrivals follow Poisson with mean $\frac{\lambda'}{N}$. The retrial accesses n_i^r, and combined arrivals n_i^c in the i^{th} channel follow the following distribution:

$$P(n_i^r = k) = C_M^k (\frac{1}{N})^k (\frac{N-1}{N})^{M-k}, k = 1, 2, \cdots M \quad (2)$$

$$P(n_i^c = j) = \frac{(\frac{\alpha\lambda'}{N})^j}{j!} e^{-\frac{\alpha\lambda'}{N}}, 0 < \alpha \leq 1 \quad (3)$$

The accessing in the $i^{(th)}$ channel will succeed if, in the same slot, the channel is only used by one MTC device. Hence, the possibility of success random access in the $i^{(th)}$ channel $p_{i,ac}$ follows:

$$\begin{aligned} p_{i,ac} &= P(n_i^r + n_i^c = 1) \\ &= P(n_i^r = 0, n_i^c = 1) + P(n_i^r = 1, n_i^c = 0) \\ &= C_M^1 (\tfrac{1}{N})(\tfrac{N-1}{N})^{M-1} \cdot e^{-\frac{\alpha\lambda'}{N}} + C_M^0 (\tfrac{N-1}{N})^M \cdot \tfrac{\alpha\lambda'}{N} e^{-\frac{\alpha\lambda'}{N}} \end{aligned} \quad (4)$$

$p_{i,ac}$ achieves the maximum value when α is determined as equation (1).

Without loss of generality, it can be applied to other channels. Hence, in the proposed algorithm, equation (1) denotes the optimal α of the system.

■

Therefore, the eNodeB can determine the optimized α with λ' and M. The estimating of these two parameters is presented as follow:

Estimation of the new arrival rate λ: When the system is stable, the leaving rate(throughput) of the system equals to the arrival rate of new access. Hence, we can reach an reliable estimation of the arrival rate of new accesses λ with the leaving rate of the system. Denote F_k as the number of successful accesses in k^{th} slot. We have:

$$\tilde{\lambda}_k = \begin{cases} \sum_{i=1}^{L} \frac{F_{k-i}}{L} & k - L > j \\ \sum_{i=j}^{k-1} \frac{F_i}{k-j} & k - L \leq j \end{cases} \quad (5)$$

where $j-1$ is nearest slot that is considered unstable.

When the arrival rate of random access λ is beyond the maximum throughput, the system must be unstable. Hence, we have to find another reliable method to estimate the λ.

Furthermore, in this circumstance, it is meaningless to backlog the access that has not been sent when it arrives, because it is impossible to handle all random access in this condition. So any arrived access will be sent immediately in the nearby slot or be abandoned. Hence, we have $\lambda \equiv \lambda'$.

The unused possibility of a channel follows:

$$p_{uu} = P(n_i^r + n_i^c = 0) = C_M^0 (\frac{N-1}{N})^M \cdot e^{-\frac{\alpha\lambda}{N}} \quad (6)$$

So, we have

$$\lambda = -\frac{N}{\alpha} \ln(p_{uu} \cdot (\frac{N}{N-1})^M) \quad (7)$$

We can estimate the arrival rate of random access with:

$$\lambda_k = -\frac{N}{\alpha} \ln(\tilde{p}_{uu,k} \cdot (\frac{N}{N-1})^{\tilde{M}_k}) \quad (8)$$

where $\tilde{p}_{uu,k} = \begin{cases} \sum_{i=1}^{L} \frac{n_{uu,k-i}}{LN} & k - L > j' \\ \sum_{i=j'}^{k-1} \frac{n_{uu,i}}{k-j'} & k - L \leq j' \end{cases}$, $\tilde{M}_k = \begin{cases} \sum_{i=1}^{L} \frac{M_{k-i}}{L} & k - L > j' \\ \sum_{i=j'}^{k-1} \frac{M_{j'}}{k-j'} & k - L \leq j' \end{cases}$, and $j'-1$ is the nearest slot that is considered stable.

Estimation of the number of retrial random access M: We assume that the eNodeB is able to detect all collisions in step 3, and the retrial slot of the corresponding nodes can be determined with the contention resolution window W. However, it is impossible for the eNodeB to identify the number of accesses in a collided channel. Hence, it is necessary to propose a reliable method to estimate it. Assume that S scheduled transmission have been send during the k^{th} slot, we have:

$$p_{nc} = \begin{cases} 1 & s = 0, 1 \\ C_S^0 (\frac{N-1}{N})^S + C_S^1 \frac{1}{N} (\frac{N-1}{N})^{S-1} & s > 1 \end{cases} \quad (9)$$

We estimate the possibility of no collision happens in certain channel with

$$\tilde{P}_{nc} = n_{accept}/N \quad (10)$$

We have:

$$\tilde{M} = \tilde{S} - n_{ac} \quad (11)$$

Finally, in the $(K+W)_{th}$ slot, $\tilde{S}$ can be calculated with $\tilde{P}_{nc}$ by looking-up a table established according to equation (9), as there is no analytical solution for equation(9), and (9) is a monotone function about S.

Evaluating the combined arrivals λ': The parameter α is dynamically adjusted in each slot. If we denote λ'_k as the combined arrivals in k^{th} slot, we have:

$$\lambda'_k = \begin{cases} \lambda'_{k-1}(1 - \alpha_{k-1}) + \lambda_k & F_{sta,k} = 1, k > 1 \\ \lambda_k & F_{sta,k} = 0, k > 1 \\ 0 & k = 1 \end{cases} \quad (12)$$

The determination of F_{sta}: When λ is higher than the maximum throughput, estimating λ with the leaving rate must result in deviation of the estimation. Hence, it is necessary to identify the unstable state in time. In this paper, we use the non-collision rate of all channels as the indicator. Besides, to limit the delay of succeeded access, the system is also considered to be unstable when $\alpha < \alpha_0$ in this paper.

Assume that S accesses have been sent in k^{th} slot, the Maximum throughput of the system can be reached when $S = 1/\ln(\frac{N}{N-1})$. In this circumstance, the non-collision rate of the channels follows:

$$\begin{aligned} P'_{nc} &= C_S^0 (\tfrac{N-1}{N})^S + C_S^1 \tfrac{1}{N} (\tfrac{N-1}{N})^{S-1} \\ &= \left(1 + \tfrac{1}{(N-1)\ln(\frac{N}{N-1})}\right) e^{-1} \end{aligned} \quad (13)$$

If in the $(k-1)^{th}$ slot, the system is considered to be stable, in the $(k)^{th}$ slot, the system state is determined as follow:

$$F_{sta,k} = \begin{cases} 0 & \tilde{P} < P'_{nc}, or\ \alpha_k - 1 < \alpha_0 \\ 1 & otherwise \end{cases} \quad (14)$$

where $\tilde{P} = \frac{\sum_{i=1}^{L} n_{nc,k-i}}{N}$

When the system is considered to be unstable and the new arrival rate λ becomes small enough to make the system considered stable, it is necessary to shift the system state from unstable to stable in time. Denote $\overline{\alpha} = \frac{\sum_{i=1}^{i=L} \alpha_{k-i}}{L}$. If the system is considered to be unstable in $(k-1)^{th}$ slot, the state of the system in k^{th} is determined as follow:

$$F_{sta,k} = \begin{cases} 1 & \overline{\alpha} < 1 \\ 0 & otherwise \end{cases} \quad (15)$$

Besides, $F_{sta,1}$ is set to be 0.

III. Performance evaluation

According to the results of proposition 1, the system achieves the maximum throughput when

$$\alpha\lambda' = (N-M-1)\frac{N}{(N-1)}, (N > 1, 0 \leq M < N) \quad (16)$$

So, the maximum throughput of the system can be denoted by:

$$\begin{aligned} & P(n_i^r + n_i^c = 1) \\ & = C_M^1(\tfrac{1}{N})(\tfrac{N-1}{N})^{M-1} \cdot e^{-\frac{\alpha\lambda'}{N}} + C_M^0(\tfrac{N-1}{N})^M \cdot \tfrac{\alpha\lambda'}{N} e^{-\frac{\alpha\lambda'}{N}} \\ & = C_M^1(\tfrac{1}{N})(\tfrac{N-1}{N})^{M-1} \cdot e^{-\frac{1}{N}(N-M-1)\frac{N}{(N-1)}} \\ & + C_M^0(\tfrac{N-1}{N})^M \cdot \tfrac{1}{N}(N-M-1)\tfrac{N}{(N-1)} e^{-\frac{1}{N}(N-M-1)\frac{N}{(N-1)}} \\ & = (1-\tfrac{1}{N})^M \cdot e^{-\frac{N-M-1}{N-1}} \end{aligned} \quad (17)$$

when $N > 1, 0 \leq M < N$, we have:

$$e^{-1} \leq (1-\frac{1}{N})^M \cdot e^{-\frac{N-M-1}{N-1}} \leq \frac{1}{2} \quad (18)$$

Hence, the Maximum throughput per slot of the system is:

$$N \cdot (e^{-1} + \delta), 0 \leq \delta \leq \frac{1}{2} - e^{-1} \quad (19)$$

The performance of the system is evaluated separately according to whether the system is considered to be stable.

When the system is considered to be stable, the possibility of successful random access follows:

$$p_{ac} = P(n^r + n^f = 1) * N/(M + \alpha\lambda') \quad (20)$$

where α is determined by equation (1), and $\alpha\lambda' \leq (N-M-1)\frac{N}{(N-1)}$, for α may be smaller than 1 when λ' is very low.

Hence, we have:

$$\begin{aligned} & p_{accept} = P(n^r + n^f = 1) * N/(M + \alpha\lambda') \\ & = \frac{N(C_M^1(\frac{1}{N})(\frac{N-1}{N})^{M-1} \cdot e^{-\frac{\alpha\lambda'}{N}} + C_M^0(\frac{N-1}{N})^M \cdot \frac{\alpha\lambda'}{N} e^{-\frac{\alpha\lambda'}{N}}))}{M+\alpha\lambda'} \\ & \geq \frac{N({}^{N-1}/_N)^M e^{-\frac{N-M-1}{N-1}}}{N+M-{}^{MN}/_{N-1}} \\ & \geq {}^1/_e \end{aligned} \quad (21)$$

When the system is stable, all accesses would retry until they are successfully accepted by the eNodeB. Hence, we have $p_{success} = 1$, and the throughput equals to arrival rate λ.

When the system is considered unstable, we have $\lambda = \lambda'$.

With the results of proposition1, the system can achieve the maximum throughput with $\alpha = (N-M-1)\frac{N}{(N-1)\lambda'}$.

Therefore, the throughput of the system follows $N \cdot (e^{-1} + \delta), 0 \leq \delta \leq \frac{1}{2} - e^{-1}$.

The success rate of access follows:

$$p_{su} = \frac{(e^{-1} + \delta)}{\lambda} \geq \frac{1}{e\lambda} \quad (22)$$

IV. Simulations

In this section, we use Matlab-based simulation to compare the proposed algorithm with back-off schedule, which is adopted in the current LTE system.

Simulation parameters are shown in table 1. The new arrival rate of new random access has already been normalized. That is, λ denotes the mean number of new random access per channel per slot.

TABLE I. parameter settings

Parameters	Back-off (1)	Back-off (2)	Proposed (1)	Proposed (2)
Number of nodes	1000	1000	1000	1000
Number of preambles	16	16	16	16
Maximum back-off slot	20	40	-	-
Maximum retrial times	5	5	-	-
α_0	-	-	0.2	0.4

We compare the two algorithms with the following indices:

Average delay:	The mean delay of successful accesses
Throughput:	The mean successful access in a slot
Success ratio:	the ratio of accesses that can finally successfully accepted

Fig. 3 shows that the proposed algorithm has a much better delay performance than the back-off algorithm. Fig. 4 shows that the throughput of the proposed algorithm keeps stable when λ is higher than $1/e$. But the throughput in back-off algorithm decreases rapidly when λ is higher than $1/e$. After all, the system fail to keep stable when the arrival rate is higher than the Maximum throughput of the slotted aloha. It is shown that the maximum throughput of the proposed algorithm is higher than that of time slotted Aloha with Poisson arrivals, which is $16/e$ with 16 channels. Besides, the line N/e corresponds to the maximum throughput of slotted aloha with N channels. It is because that, in the proposed algorithm, the number of accesses in each slot no longer

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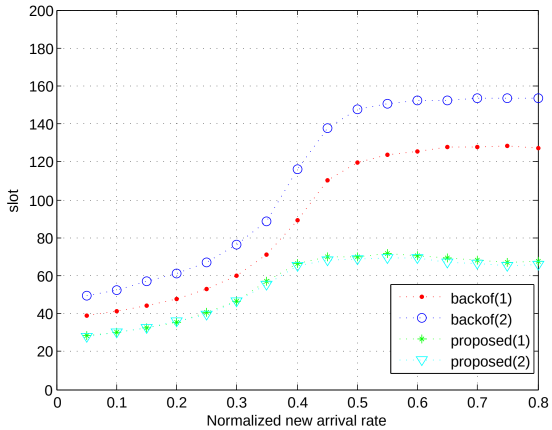

Fig. 3. Average delay

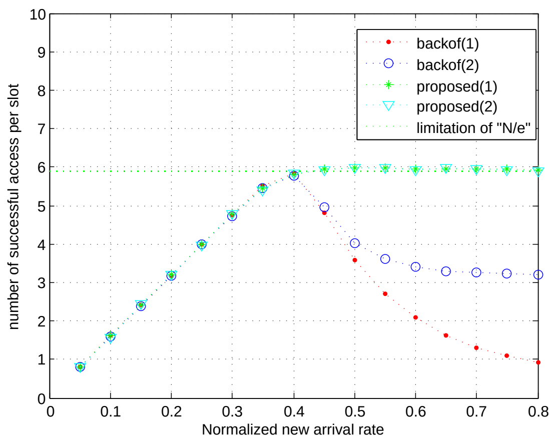

Fig. 4. Throughput

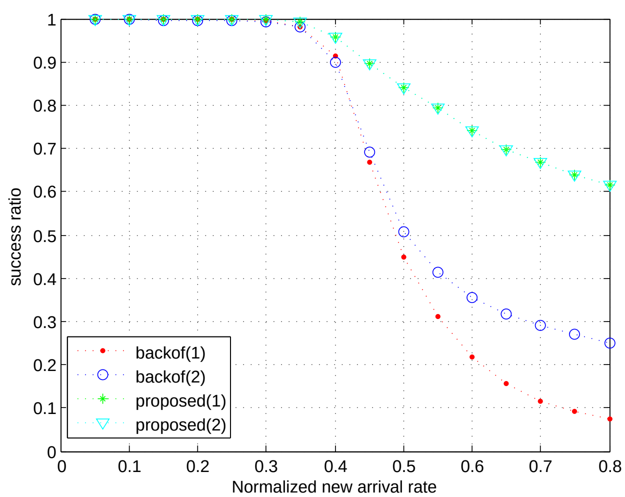

Fig. 5. Success ratio

follows Poisson distribution owing to the fast retrial scheme. Fig. 5 shows that the success ratio of the proposed algorithm keeps stable when λ is higher than $1/e$, while the throughput of back-off algorithm decreases rapidly when λ is higher than $1/e$.

V. Conclusion

Through dynamic control of the contention-based random access, and the fast retrial of collided accesses depends on the reliable estimation methods, the proposed algorithm is able to guarantee the reliability of the system under extremely high rate of access, as shown in analysis and simulations. Besides, the maximum utilization of the channel is close to or even above the extreme utilization of time slotted Aloha system with Poisson arrivals. Moreover, the delay of random access is limited. In conclusion, the proposed algorithm can well serve the M2M applications in LTE-Advance, which are featured by extremely high rate of accesses.

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References

[1] "Service requirements for machine-type communications," tech. rep., 3GPP TS 22.368 V11.2.0, June, 2011.

[2] "System improvements for machine-type communications," tech. rep., 3GPP TR 23.888 V1.2.0, April, 2011.

[3] "Medium access control (mac) protocol specification," tech. rep., 3GPP TS 36.321 V10.2.0, June, 2011.

[4] G. Sharma, A. Ganesh, and P. Key, "Performance analysis of contention based medium access control protocols," *Information Theory, IEEE Transactions on*, vol. 55, pp. 1665 –1682, April 2009.

[5] D. Aldous, "Ultimate instability of exponential back-off protocol for acknowledgment-based transmission control of random access communication channels," *Information Theory, IEEE Transactions on*, vol. 33, pp. 219 – 223, Mar 1987.

[6] R. Rivest, "Network control by bayesian broadcast," *Information Theory, IEEE Transactions on*, vol. 33, pp. 323 – 328, May 1987.

[7] G. Hauksson and M. Alanyali, "Wireless medium access via adaptive backoff: Delay and loss minimization," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, pp. 1777 –1785, April 2008.

[8] Y.-J. Choi, S. Park, and S. Bahk, "Multichannel random access in ofdma wireless networks," *Selected Areas in Communications, IEEE Journal on*, vol. 24, pp. 603 –613, March 2006.

[9] R. G. Dimitri Bertsekas, *Data networks,2nd ed.* Englewood Cliffs, N.J. : Prentice Halls, 1992.

[10] M. Amirijoo, P. Frenger, F. Gunnarsson, J. Moe, and K. Zetterberg, "On self-optimization of the random access procedure in 3g long term evolution," pp. 177 –184, June 2009.

[11] "Evolved universal terrestrial radio access (e-utra) and evolved universal terrestrial radio access network," tech. rep., 3GPP TS 36.300 V10.5.0, September, 2011.