Performance Analysis of M2M Communication Networks for QoS-differentiated Smart Grid Applications

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***Abstract*—We study the performance of Machine-to-Machine (M2M) communications in Long Term Evolution Advanced (LTE-A) networks. The proposed analysis is applied to the random access procedure within LTE-A for the calculation of the average overall delay, by considering multiple classes of M2M devices with diverse Quality-of-Service (QoS) requirements. The QoS differentiation is expressed through different Access Class Barring (ACB) parameters and backoff times for the various QoS classes. For the packet arrival process of M2M devices we consider an ON-OFF arrival process, which is a realistic approach, especially for M2M communications in Smart Grid environments. Furthermore, the proposed analysis is suitable for smart grid communication networks, where multiple M2M gateways are installed in different points of the network. The comparison of analytical results with simulations reveals the high accuracy of the proposed analysis.**

I. Introduction

Machine-to-Machine (M2M) communications have been considered as a promising solution for the interconnectivity of machines that exchange information without any human interaction [1]. M2M communications has drawn much attention mainly due to their numerous applications, such as public safety, surveillance systems, health monitoring, building automation and smart energy [2]. These advantages, together with the expectation that M2M communications will generate major revenues to network operators, trigger the need of efficient infrastructures for the interconnection of M2M devices.

The rapid growth of the M2M devices population is expected to generate additional stress to the communication infrastructure, together with the increase of traffic exchanged between Human-to-Human (H2H) communication devices. To this end, the Long Term Evolution Advanced (LTE-A) technology is expected to provide connectivity among devices and machines that require minimal or no human intervention. The utilization of LTE-A provides numerous advantages for the flexible and cost effective interconnection of M2M devices, which in many cases are located in areas with low accessibility [3]. Nevertheless, the LTE-A network has been originally designed for H2H services and therefore, more efficient ways should be designed for the network access of M2M devices, in order to minimize congestions under the presence of a huge number of M2M devices [4].

Smart grid is a major Machine Type Communication (MTC) use case, since smart grids utilize metering devices that operate autonomously and exchange information with the grid's operator. In the smart grid environment, different devices are employed for various applications, such as generation and distribution infrastructure monitoring and protection, smart metering, demand response and home network devices control [5]. The presence of an enormous amount of M2M devices with diverse demands require scheduling mechanisms that are able to provide QoS guarantees. These mechanisms should jointly consider the requirements of each smart grid application (e.g. delay constraints and energy efficiency), as well as the characteristics of the traffic generated from M2M devices.

In this paper, we develop an analytical framework for the calculation of the overall access delay and throughput in LTE-A-based M2M networks. The overall access delay is defined as the time period from the instant when the packet is generated until the M2M device successfully transmits a preamble. Our analysis incorporates the various steps of the Random Access (RA) procedure of LTE-A networks, i.e. the Access Class Barring (ACB) and the backoff procedures, while the presence of H2H devices is also taken into account. The proposed analysis takes into account different classes of M2M devices with diverse QoS requirements, by incorporating different values for the ACB parameters and backoff times. In order to support smart grid applications, we consider M2M devices, which collect power consumption and demand status from home appliances and send this information to the base station through a gateway that is installed in each residence. Furthermore, in order to model the packet arrival procedure of M2M devices, we consider an ON-OFF arrival model, which is a realistic solution compared to other packet arrival models that are used in similar analyses found in the literature (e.g. Poisson arrivals). The consideration of an ON-OFF arrival process is suitable for the modeling of traffic generated from M2M devices that are used for smart grid applications [6]; M2M traffic has different characteristics compared to H2H traffic, as it mainly refers to sporadic transmissions for data collection and monitoring [7], where connections alternate between periods of transmission (ON) and silent periods (OFF). For the evaluation of the proposed analytical model we compare its results to computer simulations; this comparison proves the high accuracy of the proposed analysis. It should be noted

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that the utilization of analytical models for the performance evaluation of the LTE-A-based M2M network is an efficient and concrete approach that provides near-real time results, in contrast to time-consuming simulations.

The rest of the paper is organized as follows. The related work is presented in Section II, while Section III describes the network model. Section IV presents the proposed analytical model for the access delay and throughput calculation, which is evaluated in Section V. Section VI concludes the paper.

II. Related Work

In recent years, there has been an extensive research effort on the study of the performance of M2M communication networks, mainly through simulation [8]-[11]. However, significant work has also been conducted on the formulation of analytical models for M2M networks. The main target of these models is the analytical calculation of important performance metrics, such as collision probabilities, delay and system throughput. The utilization of analytical models provides an efficient solution to determine these performance metrics, which can be performed in relatively very short time, in comparison to the time-consuming simulations, which are typically performed by using troublesome simulation tools.

The analytical models for the performance evaluation of M2M networks that are presented in the literature can be classified according to the incorporated network features. These features include the ACB and backoff mechanisms, the support of QoS services, the consideration of multiple preambles and the co-existence of M2M and H2H devices. The latter feature is incorporated in [12], by considering two subsets of the available preamble set, one for H2H and another for M2M devices. The backoff procedure is considered in [13], for the average delay and throughput calculation; however, this analysis considers a single type of M2M devices, while it does not incorporate the ACB mechanism feature. The authors in [14] propose a cooperative ACB mechanism without the consideration of QoS classes with different priorities, where the ACB parameters are selected based on the network congestion levels. The analysis in [15] considers a large amount of M2M devices with diverse QoS requirements, where fixed access grant time intervals are allocated to classes with similar QoS requirements; however, the ACB and backoff mechanisms, as well as the co-existence of of M2M and H2H devices are not considered in the analysis of [15].

A widely accepted solution for modeling the packet arrival procedure is the assumption of exponentially distributed inter-arrival times (Poisson traffic) [16]-[18]. However, this assumption cannot be considered as a realistic approach for M2M devices, mainly due to the duty-cycling nature of the traffic generated from many M2M applications, where M2M devices are in an OFF state and they just wake up from time to time to transmit data [4]. To this end, the authors in [19] consider the Interrupted Poisson Process (IPP), in order to model the M2M traffic arrival process. However, the model in [19] does not consider the co-existence of M2M and H2H devices and the presence of queues for the average delay calculation.

In the current paper, we present an analytical model for the calculation of the overall average access delay and the system throughput, under the random access procedure of LTE-A networks. The proposed model overcomes the limitations of the existing models in the literature, by incorporating differentiated ACB and backoff procedures, in order to support multiple M2M classes with diverse QoS guarantees, while also considering a more realistic ON-OFF procedure for the modeling of the packet arrival process of M2M devices.

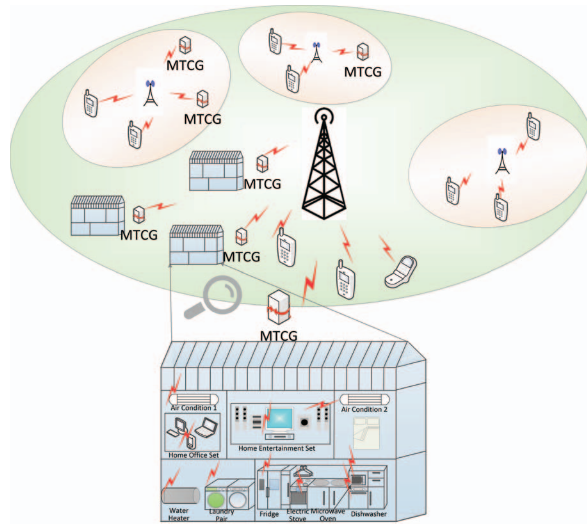

Fig. 1. M2M and H2H communications in LTE-A networks.

III. Network Model

A. An overview of the Random Access procedure

We consider the macrocell of Fig. 1 with a macro enodeB and a number of small cells, which are operated by small-cell enodeBs. The network supports both H2H and M2M devices; H2H devices are serviced by the small-cell enodeB when they are in the coverage area of the corresponding small cell, otherwise they are serviced by the macro enodeB. On the other hand, M2M devices may select to connect to a small-cell enodeB or to the macro enodeB. The selection of LTE-A as the access network that connects M2M devices to the infrastructure is based on the fact that LTE-A provides longevity, scalability and lower service cost, compared to other wireless solutions.

In LTE-A networks, M2M devices are connected to the enodeBs either directly, or via an MTC Gateway (MTCG) [20]. In order to support smart grid applications, we consider the latter case where M2M devices collect power consumption and demand status from home appliances. This information is transferred from each house to the MTCG (Fig. 1), which then forwards it to the enodeB. Evidently, the following analysis can be applied to any M2M network configuration that utilizes an MTCG. Furthermore, we consider that the network supports multiple classes of M2M devices. These classes are differentiated based on the packet generation rate and the supported QoS guarantees. Due to the small data that is transmitted by each M2M device, we assume that the network supports only a single packet size for all classes of M2M devices.

In LTE-A, when a device wishes to transmit a packet, it performs a RA procedure, in order to gain access to the network resources. This RA procedure can be *contention-based* or *contention-free* [20]. The contention-based RA procedure

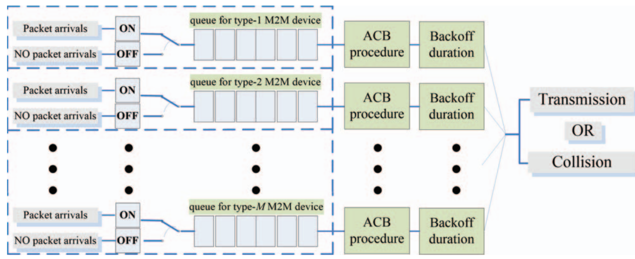

Fig. 2. Generic diagram of the queuing model with M queues.

involves four basic steps. In the first step, a device selects one of the preamble sequences and transmits it through the Physical Random Access Channel (PRACH). If two devices select the same preamble, collision occurs and the devices have to retransmit another preamble. The retransmission procedure is based on specific parameters, such as the maximum number of retransmissions and the available set of PRACH resources. In the second step the enodeB sends a Random Access Response (RAR) through the Physical Downlink Shared Channel (PDSCH). This RAR message informs the device for the uplink scheduling grant that should be used for the transmission of the message during the third step. If a device does not receive a RAR message within a specific time window, the device considers that the access attempt has failed and retransmits a new preamble after a random backoff time. If the network supports differentiated QoS-classes, diverse backoff times are considered, so that backoff times of low-priority QoS classes are higher compared to the backoff times of high-priority QoS classes. The third step involves the transmission of the actual RA message through the Physical Uplink Shared Channel (PUSCH), which contains the resource block request of the device. Finally, the last step involves the contention resolution by using the PDSCH. A detailed description of the four steps of the contention-based RA procedure can be found in [20]. On the other hand, in contention-free RA the enodeB may apply reserved preambles for the initialization of the RA procedure. Under this RA scheme, enodeBs assign a preamble to the device, which then transmits the assigned preamble to the enodeB. Finally, the enodeB responds with a RAR.

Under contention-based RA, collision may occur when two devices select the same preamble. In order to minimize the collision probability, a device may follow a preliminary stage before start transmitting a preamble. This stage is called ACB and is based on an Access Probability (AP) that is broadcasted by the enodeB, together with an Access Class (AC) barring time. Prior the RA procedure initialization, the device randomly selects a number between zero and one. If this number is less than the AP, then the device is allowed to initiate the RA procedure; otherwise the device waits for an ACB time before reselecting a random number. This ACB mechanism can be extended in order to support differentiated QoS classes, by assigning different AP values and AC barring times to the various QoS classes.

B. Basic assumptions of the proposed analysis

In this paper, we consider that the LTE-A network supports the co-existence of M2M and H2H devices by considering a preamble separation scheme. Under this scheme, H2H devices follow a contention-free RA, while the M2M devices follow a contention-based RA. The set of the available preambles is split into two subsets; the first set is used exclusively for H2H devices, while the second set is dedicated to M2M devices. Therefore, M2M devices have to pass the ACB procedure and then select a preamble. In order to support multiple QoS classes for the M2M devices, we consider different AP and AC values for each QoS class, so that high-priority classes have higher access probabilities over low-priority classes. Furthermore, a second QoS differentiation level is considered for the backoff procedure, by considering different backoff parameters for the various QoS classes. Finally, a different arrival procedure is assumed for the various QoS classes, by considering different queues that are installed at the MTCG. It should be noted that the various features of the system that are used for the QoS differentiation are expressed in a parametric way; therefore the proposed analysis can be used in any network configuration that either supports a single or both QoS differentiation levels (ACB and backoff), or even the case where no QoS differentiation is applied.

IV. Access Delay Analysis

We consider that the LTE-A network of Fig. 1 supports S preambles. This preamble set is divided into two subsets; the first subset s is dedicatedly used by H2H devices, while the second subset $S-s$ by M2M devices. The consideration of these two subsets is in accordance with the 3GPP TR37.868 [21]. Furthermore, we assume M different QoS classes for the M2M devices. The consideration of multiple QoS classes is based on the fact that different M2M devices have different requirements in terms of delay or access rate constraints, and frequency of occurrence. For the support of the different M2M classes, M queues are installed at the MTCG (one for each class), as depicted in Fig. 2. In what follows, we present the proposed analytical model for the overall access delay calculation, which is defined as the delay in the queue together with the time period until the preamble is successfully transmitted, as well as the analysis for the throughput calculation.

A. Queuing delay

The packet arrival procedure in M2M communications is characterized by sporadic periods of transmission and silence [7]. To this end, a suitable solution for modeling the M2M traffic is the ON-OFF model of Fig. 3, which considers slotted transitions between the two states; the consideration of slotted time is in accordance with the LTE-A protocol. This ON-OFF model is applied to all M QoS-classes; therefore for each QoS-class a discrete-time queuing system is considered. For QoS-class m ($m=1,\ldots,M$) the probabilities that the system remains in states ON and OFF are defined as $q_{m,1}$ and $q_{m,2}$, respectively. Furthermore, a packet of QoS-class m arrives at the corresponding queue each time the queuing system is at state ON, with arrival rate that is denoted as λ_m.

By considering the state transition diagram of Fig. 3, the probability of two consecutive arrivals is equal to $\gamma_{m,1}=q_{m,1}$, while the probability that after an arrival the system in at state OFF and returns to state ON is $\gamma_{m,2}=(1-q_{m,1})(1-q_{m,2})$, where $\gamma_{m,n}$ is the inter-arrival time distribution. By taking into account all possible transitions between the two states, the inter-arrival distribution $\gamma_{m,n}$ is generally expressed as:

$$\gamma_{m,n}=\begin{cases} q_{m,1} & n=1 \\ (1-q_{m,1})(1-q_{m,2})\,q_{m,2}^{n-2} & n\geq 2 \end{cases} \tag{1}$$

The mean inter-arrival time $1/\lambda_m$ is calculated by considering the Probability Generating Function (PGF) of $\gamma_{m,n}$:

$$\Gamma_m(z)=\sum_{n=1}^{\infty}\gamma_{m,n}z^n=q_{m,1}z+(1-q_{m,1})(1-q_{m,2})\frac{z^2}{1-q_{m,2}z} \quad (2)$$

Therefore, from (2) we can calculate the overall mean inter-arrival time $1/\lambda_m$, by considering both ON and OFF periods:

$$\frac{1}{\lambda_m}=\left.\frac{d\Gamma_m(z)}{dz}\right|_{z=1}=\frac{2-q_{m,1}-q_{m,2}}{1-q_{m.2}} \quad (3)$$

The average queuing delay calculation is based on the queue-size stationary distribution, which is given by extending the corresponding equation of [22] to the multiple QoS-class case:

$$\pi_{m,j}=\begin{cases} 1-\xi_m & j=0 \\ \xi_m(1-\rho_m)\rho_m^{j-1} & j\geq 1 \end{cases} \quad (4)$$

where $\xi_m=\lambda_m/\mu_m$ and μ_m is the m-type queue service rate. The expression of ξ_m is derived from (4) and from the equation of the mean arrival probability to the mean departure probability, i.e. $\lambda_m{=}\mu_m(1{-}\pi_{m,0})$. Also, ρ_m is the unique root of (5), which is based on the single traffic class of [22]:

$$z=\Gamma_m(\mu_m z+(1-\mu_m)) \quad (5)$$

By using (2), the solution of (5) is given by:

$$\rho_m=\frac{1-\mu_m}{\mu_m}\left[\frac{1}{\mu_m\left(1-q_{m,1}-q_{m.2}\right)+q_{m,2}}-1\right] \quad (6)$$

The mean queue length can be calculated through the stationary distribution of the queue size:

$$L_m=\sum_{l=1}^{\infty}l\pi_{m,l}=\frac{\xi_m}{1-\rho_m}=\frac{\lambda_m}{\mu_m\left(1-\rho_m\right)} \quad (7)$$

Finally, the mean waiting time in type-m queue is derived by using (7) and Little's theorem:

$$W_m^{queue}=\frac{L_m}{\lambda_m}=\frac{1}{\mu_m\left(1-\rho_m\right)} \quad (8)$$

It should be noted the mean waiting time in the queue is a function of the queue service rate μ_m, which is equal to the inverse of the mean queue departure time. The latter parameter is equal to the mean duration of the ACB and the backoff procedures, which are calculated in the following subsections.

B. *Mean duration of the ACB and backoff procedures*

The ACB mechanism considers that when an M2M device wishes to initiate RA, it randomly selects a number between zero and one. If this number is less than the AP, the device is allowed to start the RA procedure by initiating the backoff procedure; otherwise, it delays for AC barring time. Since the ACB supports multiple QoS classes [23], we consider that the AP and the AC barring time for type-m M2M devices are P_m and T_m^{AC}, respectively. The values of the parameters P_m and T_m^{AC} are adjusted in order to satisfy the requirements and constraints of the QoS classes. Based on the aforementioned analysis, the average ACB delay for a type-m packet is:

$$\begin{aligned} W_m^{ACB}&=T_m^{AC}\left(1-P_m\right)+T_m^{AC}\left(1-P_m\right)^2+\ldots= \\ &=\textstyle\sum_{l=1}^{\infty}T_m^{AC}\left(1-P_m\right)^l=T_m^{AC}\frac{1-P_m}{P_m} \end{aligned} \quad (9)$$

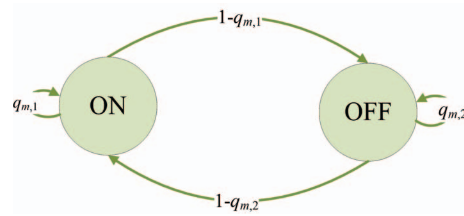

Fig. 3. State transition diagram of the ON-OFF arrival process.

After the ACB procedure, a backoff procedure is initiated. For the calculation of the average backoff duration, we consider the following analysis that extends the analytical model of [13] in order to consider the multiple QoS classes feature; the latter feature is not incorporated in the analysis of [13], where only a single type of M2M devices is assumed. To this end, we consider that the set of $S-s$ preambles, which is available for the contention-based RA, is further divided into M subsets; each subset comprises of c_m preambles that are dedicated to type-m M2M devices, with $\sum_{m=1}^{M}c_m=S{-}s$. By assuming that the first QoS class has the highest priority, while the M-th QoS class has the lowest priority, then the subset of S-s preambles is divided so that $c_1>c_2>\ldots>c_M$. The QoS classes are further differentiated by assuming different backoff window sizes and number of retransmissions for each QoS class. Specifically, for QoS-class m, the backoff window size is denoted as W_m, while the number of retransmissions is denoted as R_m.

The mean backoff duration calculation is based on the knowledge of the probability $p_{s,m}$ of a successful transmission for type-m M2M devices for every transmission attempt, which is calculated by extending the corresponding formula of [13] to a new equation for each one of the M types of M2M devices:

$$p_{s,m}=\frac{(1-p_{phloss})}{Gp_{t,m}}\sum_{r=1}^{R_m}\left(\sum_{j=1}^{r}jf(j|r,c_m)B(r,G,p_{t,m})\right) \quad (10)$$

where p_{phloss} is the physical layer failure probability (not due to collisions), $f(j|r,c_m)$ is the probability of j successful transmissions over c_m preambles among r parallel transmission attempts, $B(r,G,p_{t,m})=\begin{pmatrix} G \\ r \end{pmatrix}p_{t,m}^r\left(1-p_{t,m}^r\right)^{G-r}$ is the binomial probability distribution function, $p_{t,m}$ is the transmission probability, and G is the number of MTCGs that are installed within the coverage area of the enodeB. The probability $f(j|r,c_m)$ can be calculated by:

$$f(j|r,c_m)=\sum_{i=0}^{r-j+1}B(i,r,1/c_m)f(j{-}I(i)|r{-}i,c_m{-}1) \quad (11)$$

where $I(i)$ equals to 1 if i=1, otherwise $I(i)=0$. The recursive formula of (11) can be solved by considering the following initial conditions, which are based on the analysis of [13]:

$$\begin{aligned} &f(0|0{,}1){=}1, f(1|0{,}1){=}0, f(0|1{,}1){=}0, f(1|1{,}c_m){=}1, \\ &f(0|r,1){=}1, for\ r{>}1,\ f(j|r,1){=}0, for\ j{>}0, r{>}1, \\ &f(j|r,c_m){=}0,\ \text{for}\ j<0\ \text{or}\ \min(r,c_m)<j \end{aligned} \quad (12)$$

The mean backoff duration calculation is also based on the determination of the transmission probability $p_{t,m}$. To this end, we construct the two-dimensional Markov chain of Fig. 4, which represents the RA procedure for type-m M2M

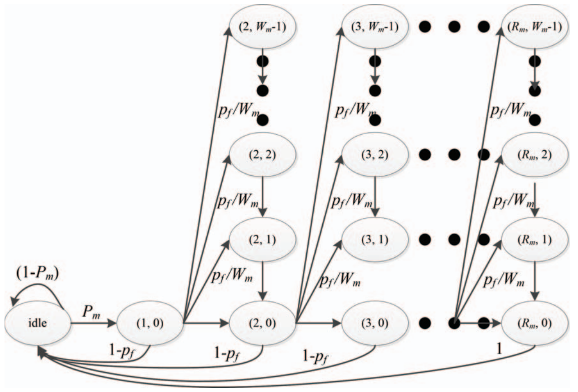

Fig. 4. State transition diagram of the backoff procedure for type-m M2M devices.

devices. Each state (*i, t*) is represented by the number i of retransmission attempts and the backoff counter t, which is decreased in each time slot. Due to the application of the ACB mechanism, the transition from the idle state, to state (1,0) (initiation of the backoff procedure) occurs with a rate that is equal to the probability that a packet of type-m M2M departs from the corresponding queue and is allowed by the ACB mechanism to initiate the backoff procedure (with probability P_m). Furthermore, the system remains at the idle state with a rate that is equal to $(1-P_m)$, when the M2M device selects a random number that is higher than the AP. By solving the Markov chain of Fig. 4, we obtain the state probabilities $\pi_{i,t}^m$:

$$
\begin{aligned}
&\pi_{1,0}^m = P_m \pi_{idle}^m \\
&\pi_{idle}^m = (1-p_{f,m})[1-p_{f,m}+P_m(1+\tfrac{W_m-1}{2}p_{f,m}-\tfrac{W_m-1}{2}p_{f,m}^{R_m}] \\
&\pi_{i,t}^m = \tfrac{W_m-t}{W_m} p_{f,m}^{i-1}\pi_{1,0}^m
\end{aligned}
\tag{13}
$$

where $p_{f,m} = 1-p_{s,m}$ is the failure probability at every transmission of a type-m M2M device. By using the state probabilities, we calculate the transmission probability $p_{t,m}$:

$$
p_{t,m} = \frac{1-p_{f,m}^M}{1-p_{f,m}} P_m = \frac{1-(1-p_{s,m})^M}{p_{s,m}} P_m \tag{14}
$$

The values of the probabilities $p_{t,m}$ and $p_{s,m}$ are obtained from the nonlinear system of (10) and (13), which is solved by using a recursive solution method. Finally, by extending the analysis of [13], the average backoff delay is given by:

$$
W_m^{boff} = \frac{D_m - p_{f,m}^{R_m}\left((R_m-1)\frac{W_m+1}{2}+1\right)}{1-p_{f,m}^{R_m}} \tag{15}
$$

$$
\text{where} \quad D_m = \frac{1+\frac{W_m-1}{2}p_{f,m} - \frac{W_m+1}{2}p_{f,m}^{R_m}}{1-p_{f,m}} \tag{16}
$$

It should be noted that the service rate μ_m, which is used for the calculation of the mean queuing delay W_m^{queue}, is determined by considering that the queue service time is equal to the duration of the ACB and the backoff procedures, i.e. $1/\mu_m = W_m^{ACB} + W_m^{boff}$. Finally, the overall access delay is calculated by summing up W_m^{queue}, W_m^{ACB} and W_m^{boff}.

C. Throughput calculation

The throughput of the RA channel for M2M devices that contend for the utilization of one out or c_m preambles can be calculated by considering the analysis for the backoff delay determination. Precisely, for type-m M2M devices, the throughput is $T_{M2M} = p_{t,m}p_{s,m}G$. As far as the H2H devices is concerned, the throughput of the RA channel can be expressed by the following equation ([12]):

$$
T_{H2H} = \lambda_{H2H} e^{-\left(\frac{\lambda_{H2H}}{s}\right)} \tag{17}
$$

where λ_{H2H} is the arrival rate of connection requests from H2H devices. This expression is valid only for exponentially distributed inter-arrival times (Poisson arrivals), which is a suitable solution for the arrival process of connection requests from H2H devices [12].

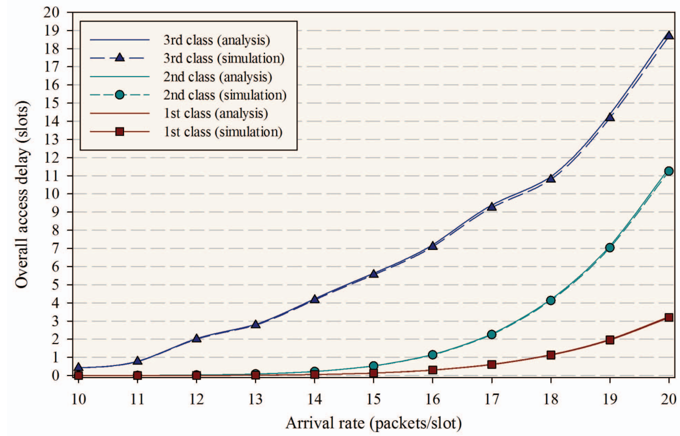

Fig. 5. Analytical and simulation results for the overall access delay of the 3 QoS classes of M2M devices.

V. Evaluation

In this section we compare results from the proposed analytical model with corresponding results from simulation. To this end, we built an object-oriented simulator using the C++ programming language that creates events based on random numbers. The simulation scenario considers an enodeB that is located at the center of a macrocell and provides connectivity to a number of M2M and H2H devices, which are uniformly positioned in the macrocell. We consider three QoS-classes for the M2M devices, with high, medium and low priorities, respectively. The values of the parameters that are used for the derivation of both analytical and simulation results are listed in Table I. Simulation results are obtained as mean values of 8 runs, while in each run 10^6 packets are generated from both M2M and H2H devices. In Fig. 5 we present analytical and simulation results for the overall access delay of the three QoS-classes, versus the packet arrival rate. For presentation purposes, we assume that the arrival rate λ_m is the same for

TABLE I. Parameter values used in analysis and simulation.

Parameter	Value
Total number of preambles S	54
Preambles for H2H devices s	30
Number of MTCGs G	100
Set of preambles for the 3 M2M classes c_m	(12, 8, 4)
ON-OFF probabilities ($q_{m,1}$,$q_{m,2}$)	(0.7, 0.6), (0.6, 0.5), (0.5, 0.4)
Physical layer failure probability p_{phloss}	0.05
AP for ACB procedure P_m	(0.2, 0.4, 0.6)
AC barring time T_m^{AC}	(1, 2, 4) slots
Backoff window size W_m	(3, 5, 6)
Retransmission attempts R_m	(4, 4, 4)

all QoS-classes and equal to the values of the x-axis of Fig. 5. Furthermore, in Fig. 6 we present analytical and simulation result for the throughput of the corresponding RA channel, for H2H devices and for the three QoS classes of M2M devices. The results of both Fig. 5 and Fig. 6 reveal the high accuracy of the proposed analysis.

It should be noted that the proposed analysis may be used for the extraction of the optimal parameter set that guarantees the QoS requirements of specific M2M devices. This optimization procedure through the utilization of the proposed analysis is realized in very short time, compared to the time-consuming simulations. For example, under the aforementioned evaluation scenario the extraction of all possible preamble sets c_m that result in overall access delay below 50 msec is completed in approximately 12 sec. On the other hand, a single simulation run that considers a single preamble set is executed in 3 min. This fact proves the necessity of the proposed analysis for the fast and effective performance evaluation of M2M networks.

VI. Conclusion

In this paper, we present an analytical framework for the calculation of the overall access delay in LTE-A-based M2M networks. The proposed analysis takes into account the ACB and backoff procedures for M2M devices, which are expressed by different parameters in order to provide QoS differentiation among the multiple M2M devices, as well as the presence of H2H devices. Furthermore, we consider an ON-OFF model for the packet arrival process of M2M devices, which is a realistic approach for modeling the activation/deactivation of M2M devices that are used for smart grid applications. The accuracy of the proposed analytical model is completely satisfactory, as the comparison of analytical and simulation results prove. Our future work includes a more thorough study on the access delay, by deriving the access delay distribution under different preamble selection procedures.

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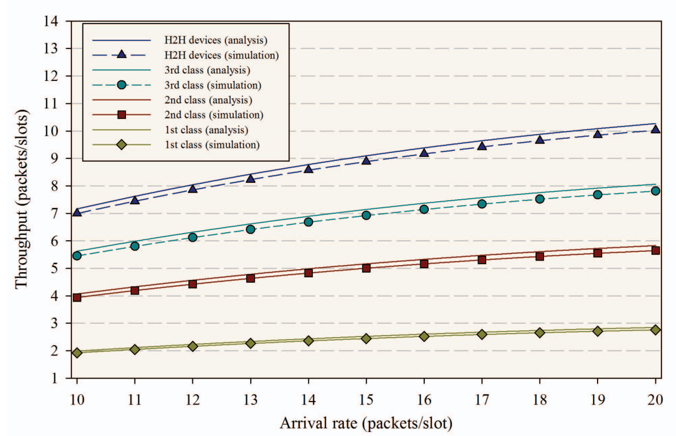

Fig. 6. Analytical and simulation results for the throughput of the H2H devices and the 3 QoS classes of M2M devices.

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