Intelligent RACH Access Techniques to Support M2M Traffic in Cellular Networks

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Abstract - **This paper provides a thorough investigation into the use of Q-learning as a means of supporting machine-to-machine (M2M) traffic over cellular networks through the random access channel (RACH). A new back-off scheme is proposed for RACH access, which provides separate frames for M2M and conventional cellular (H2H) retransmissions, and is capable of dynamically adapting the frame size in order to maximise channel throughput. Analytical models are developed to examine the interaction of H2H and M2M traffic on the RACH channel, and to evaluate the throughput performance of both slotted ALOHA and Q-learning-based access schemes. It is shown that Q-learning can be effectively applied for M2M traffic, significantly increasing the throughput capability of the channel with respect to conventional slotted ALOHA access. Dynamic adaptation of the back-off frames is shown to offer further improvements relative to a fixed-frame scheme.**

Index Terms—Machine-to-machine, medium access control, cellular networks, Q-learning, ALOHA, RACH.

I. INTRODUCTION

Recent technological developments are changing the perception of wireless communication from the traditional human-centric view towards human independent communications. This is due to the increase in the number of devices that require connection to wireless networks. It has been argued in [1] that there are more electrical/electronic or mechanical objects in the world than people. It is estimated in [2], [3] that by 2020, up to 50 billion devices will require access to a communication network for industrial and domestic applications. This number is significant compared to the estimated human population of 8.3 billion. With this large difference in the ratio of the number of machines to humans, it will be difficult for such devices to be directly controlled by humans, and hence there is a need for them to communicate amongst themselves, with or without human intervention. This can be achieved through what is commonly referred to as machine-to-machine (M2M) communication, machine type communication (MTC), or device-to-device (D2D) communication [3]-[6].

M2M communication will enable interaction between various devices with or without human intervention. M2M devices may be sensors, actuators, embedded processors, radio frequency identification (RFID) tags, smart meters, etc., [7]. The devices may be connected using wired or wireless access networks. Although wired networks are considered to be reliable and secure, they are very expensive to roll out and are not very flexible. As a result, many standards are not considering wired networks as an option for M2M communication. On the other hand, a wireless network is capable of providing excellent coverage, flexibility, mobility, and roaming capability. Hence, wireless access networks, which may be short range or long range (e.g. cellular), are considered as the most suitable option to deploy M2M communication [6].

To realise cellular M2M communication, different wireless communication standardisation bodies, including 3GPP, are actively involved in research to provide global standards. Initial access to a cellular network is through the random access channel (RACH) which has a limited capacity. One of the major challenges identified by 3GPP in supporting M2M communication is the potential for RACH overload, due to the significant increase in traffic load that will arise from large numbers of M2M devices. A number of solutions to this problem have been suggested by the 3GPP but they involve significant changes to the standards. In this paper, a relatively simple approach is presented that can enhance the capacity of the access channel through the use of Q-learning for M2M traffic. A key benefit of this approach is that it does not require any changes to the existing cellular network standards. We propose a solution that avoids RACH overload in supporting M2M traffic over existing cellular networks.

The primary aim of this paper is to demonstrate how H2H and M2M traffic can effectively share the RACH of a cellular system by using Q-learning to control M2M traffic, through the

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use of an intelligent back-off strategy for H2H traffic without altering the access procedures for existing H2H traffic.

This is achieved through the following contributions:

- A novel scheme that allows adaptation of frame size as an effective implementation of frame-based Q-learning RACH access.
- An analytical model that determines the impact of additional M2M traffic on the existing H2H as well as the inefficiency of the s-ALOHA scheme to support the additional load**.** The model also predicts the throughput performance of the QL-RACH and FB-QL-RACH schemes. In addition, the model shows how high aggregated traffic resulting from H2H and M2M collisions is the main factor that renders the s-ALOHA channel useless especially at high load.
- Evaluation and comparison of the throughput performance of the proposed approach with conventional RACH access, for coexisting M2M and H2H scenarios.

In Section II, this paper presents background information on the cellular M2M standardisation process, and briefly introduces related work and our proposed approach. Section III explains the existing cellular network RACH access mechanism and describes a learning-based RACH access scheme. Section IV provides an application scenario with H2H and M2M users sharing the existing RACH of a cellular network. Also, some fundamental analytical expressions on which our analytical model is built are presented. An analytical model to predict the throughput capability of the RACH access schemes is presented in Section V. Section VI describes the development of simulation models, presents and discusses the simulation results. Section VII introduces dynamic frame-size adaptation, and provides some results, discussion, and analysis. Finally, Section VIII concludes the work in this paper.

II. Background

Supporting M2M traffic on an existing cellular network is considered in this paper because of its prevalence, ubiquity, mobility, and roaming support [8]. However, the process faces some challenges since such networks are only designed to support traditional human-to-human (H2H) communication. This issue draws the attention of many wireless communication standardization organisations, including 3GPP and the IEEE, which have paid a lot of attention as to how existing cellular networks can support M2M traffic [5]. The 3GPP Technical Report in [9] identifies radio access network (RAN) overload as the most likely challenge in supporting M2M traffic over cellular networks. Cellular networks (from 2G through to LTE) are initially accessed using random access through the RACH [10]. 5G networks (envisaged for M2M communication) are expected to employ RACH structures and access techniques similar to that of its predecessors.

In the conventional random access scheme, slotted ALOHA (s-ALOHA) restricts transmission to slots in order to avoid overlap of user transmissions. The RACH of a cellular network is structured into frames in which access attempts are only allowed in slots. Despite its poor throughput performance, traditional s-ALOHA has been the random access scheme used for RACH access in cellular networks. This is because of its simplicity and ability to handle multiple spatially-distributed nodes accessing a single channel. In addition, because the RACH is not a heavily loaded channel, s-ALOHA (being a simple protocol) is a perfect and adequate scheme for conventional H2H communications. However, as pointed out in [11], [12], supporting M2M traffic (in addition to the existing H2H traffic) will increase RACH access contention significantly. This effect will render the s-ALOHA scheme inefficient and lead to overload, affecting the RACH access performance. Therefore, the existing cellular network requires some adjustment, or the RACH access strategy needs to be altered in order to control the traffic while supporting M2M communication. The latter option is more straightforward, as it could just apply to new M2M devices, without the need to alter the cellular infrastructure. Providing a scheme that has better performance than s-ALOHA for M2M users accessing the RACH should improve the RACH throughput for M2M users as well as the overall system performance, whilst leaving the standard H2H user access strategy unchanged.

In this paper, the Q-learning RACH (QL-RACH) access scheme is applied to control M2M traffic in sharing the LTE RACH with existing H2H traffic. A frame-based back-off strategy (FB-QL-RACH) is also applied to QL-RACH to further improve its performance. Chu et al. [13], [14] use a Q-learning slot selection strategy and show that it is a better scheme than blind transmission in wireless sensor networks (WSNs). Our recent work in [15], [16] developed a simulation model of the QL-RACH and FB-QL-RACH schemes. The present paper introduces a novel scheme that allows dynamic adaptation of frame size as an effective implementation of the FB-QL-RACH scheme. This scheme has the ability to make the H2H back-off frame size (BFZ) dynamic, which is shown to have better performance than a fixed frame size. The paper additionally provides an analytical model for thorough investigation of H2H and M2M traffic behaviour in sharing the RACH, which also allows us to predict their throughput performance. In addition, the analysis serves to validate the simulation results obtained in [15], [16]. This is achieved by developing a model that first studies the impact of additional M2M traffic on existing H2H users when the s-ALOHA scheme is used to control RACH access. The interaction of two different schemes, s-ALOHA and QL-RACH, for H2H and M2M users, respectively, is analysed and the effect of uncontrolled H2H traffic (using s-ALOHA) on the performance of the QL-RACH scheme is shown. The performance predictions and analysis justify the realisation of the FB-QL-RACH scheme. The models and realised schemes are generic, i.e., applicable to all cellular network standards, since they have similar RACH signaling channels, functional structures, and access schemes.

The RACH is a signaling channel in the uplink direction through which user equipment (UE) initially accesses an eNB through the RAN. Therefore, the RACH is very important and needs to be protected against any possibility of congestion that could cause overload. Since M2M communication is expected to comprise a massive number of devices that will significantly increase the frequency of RACH access, supporting M2M traffic over a cellular network necessitates good congestion control. Significant efforts have been made by different standards organisations and researchers to provide solutions that alleviate the negative impact of supporting M2M traffic on a cellular network.

3GPP in its standardisation process [9] proposed the access class barring (ACB) scheme as a RACH overload control mechanism to support M2M traffic in LTE-A. A cooperative ACB scheme is proposed in [17], where the access parameters are based on the network congestion level. A separate RACH scheme has also been proposed in [9] as another solution to the RACH overload problem, which is adopted in [18] for LTE applications. It is important to note that all of the above solutions will require the involvement of a central entity (BS or eNB) to control the RACH access, and this will demand modification of the existing signaling mechanisms and cellular system standards.

In this paper, taking into consideration the coexistence of M2M and H2H, we control the M2M traffic by allowing machines to learn how to acquire dedicated slots amongst themselves without involvement of a central entity.

III. RACH ACCESS SCHEMES

As introduced earlier, the RACH is the initial means through which a user is connected with the network. On the basis that users are dispersed throughout a cell and need opportunistic initial access to the system, random access is the only option. This section describes the random access scheme used by conventional LTE networks when supporting H2H traffic, and then proposes a new RACH access scheme that will be used to control M2M traffic.

A. RACH Access Scheme

Similar RACH mechanisms and access schemes are used by all cellular standards. For example, in GSM/GPRS, the RACH is structured by dividing time into many equal-size slots that are mapped onto selected slots within the repeating multi-frame structure in the network [19]. The RACH slot availability depends on the control channel arrangement, based on the cell capacity. WCDMA and LTE/LTE-A use similar RACH mechanisms with some differences in the structure. Here, the random access opportunities (RAOs) are presented by signatures and preambles [20]. In LTE, a contention-based random access procedure is performed by selecting one of the available preambles in each RAO. The selected preamble is sent on a RA time slot which is mapped onto a channel called the physical random access channel (PRACH) [20]-[23]. In addition, the PRACH is configured in a frame-based structure with a period of 10 ms. The number of RAO slots per frame depends on the adopted PRACH configuration. Up to 6 configurations are presented in [23]. A PRACH configuration index of 12 is used in this work, where there is a RAO after every other sub-frame, providing 5 RAOs in every frame. The RACH procedure is performed to: establish connection to an idle UE and re-establish a connection after a radio link fails, to initiate handover, and to provide for uplink/downlink data transmission to and from an unsynchronized UE. The procedure is implemented through message exchange in four steps, as illustrated in Fig 1. See [22] for details about the RACH access procedure.

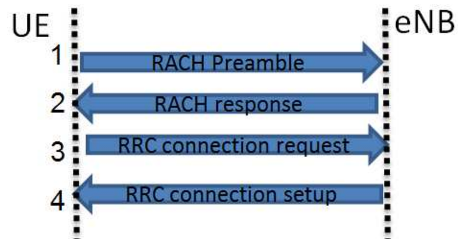

Fig. 1. Representation of RACH access procedure.

The nature of the PRACH configuration in which preambles are transmitted in RA slots makes s-ALOHA an effective scheme for H2H users to access the RACH in conventional cellular networks. This is because of its ability to simply handle multiple spatially distributed nodes accessing a single channel, as it requires no prior channel information before transmission. Collisions occur when more than one user sends preambles in the same RA slot. A common collision resolution mechanism is adopted by all cellular standards, where a uniform back-off with retransmission cut-off strategy is used. For further details about the different types of retransmission strategies and algorithms, see [24]. Collisions (especially at high traffic loads) lead to lost user requests and potentially poor throughput performance. The maximum throughput obtained using Aloha is approximately 37% of the channel capacity [25]. In LTE, request loss is minimised by allowing a certain number of retransmissions after some back-off time within a fixed window. The retransmissions, at some point, aggregate traffic that exceeds the channel capacity, causing a bottle-neck at the uplink that renders the channel unstable. For full details of s-ALOHA instability, see [25], [26].

Due to appropriate dimensioning of the channel, s-ALOHA works effectively with H2H in sending the RACH requests. However, supporting M2M traffic will bring a large number of new devices to the network and an associated increase in the RACH contention, which may render a s-ALOHA channel useless. Therefore, RACH access requires a better scheme to support M2M traffic on the existing cellular network.

B. QL-RACH Scheme

The QL-RACH scheme is realised using Q-learning [27], which is a simplified model of reinforcement learning with an algorithm that enables early system convergence. In general, reinforcement learning can be described as a trial-and-error technique in which an action is decided through learning the system behaviour in a given environment. The action is determined based on prior experience that is built up using reward and punishment [27], [28]. To avoid tampering with existing standards of the cellular network, our approach assumes to have control (RACH access) of M2M users only.

The QL-RACH scheme forces the M2M users to learn to avoid each other during the contention period. The scheme is implemented by considering a virtual frame of the PRACH (M2Mframe) that carries RA slots from the main LTE frame, as shown in Fig 2. For optimum learning, the size of the M2Mframe (number of RA slots) should be equal to the number of M2M users. The slot timing and length are mapped directly onto the PRACH frame. The mode of RACH access here changes from slotted to frame-based Aloha where an M2M user sends a request in the next M2M frame and has only one RAO in each M2Mframe. Q values are used to keep the transmission history in each RA slot, where each M2M user has individual Q-values for every RA slot in the M2M frame. Q-values are weights associated with each slot obtained during the learning process. These are updated at every successful or failed transmission attempt according to the model.

$$Q' = (1 - \alpha)Q + \alpha r \tag{1}$$

where Q is the current Q value, α is the learning rate, and r is the reward or punishment, depending on the status of the sent request.

For a normal situation, a positive value used for the reward is negated for punishment. The value of the learning rate determines the speed of convergence and it needs to be within the same low value range as that used as a reward. For example if +1 is adopted as a reward then the learning rate is chosen within the range of 0 to +1. The closer the learning rate is to +1, the higher the speed of convergence but the lower the ability to maintain convergence. The converse is the case when the learning rate is chosen far lower than +1.

The learning process will result in each M2M user having different Q values for each slot and an M2M user always sends a request in the slot with the highest Q value. If there are multiple slots with the same highest Q value, one is selected at random. Fig. 2 is presented to help a reader clearly understand the Q-learning process, where an example of an M2M user with Q values of the slots in the M2Mframe initialised to zero is demonstrated. At start-up, all slots have the same Q-value and the user selects the first slot at random and transmits successfully. Using a learning rate (α) of 0.01 and a reward of +1, the Q value of the slot is updated using (1).This first slot is the M2M user's preferred slot (in the next M2Mframe) since it has the highest Q-value. However, for the example in Fig. 2, the slot is coincidently selected by a different M2M user and therefore a collision occurs. This reduces the Q value on the update with a punishment of -1. Also, in the next M2Mframe, the M2M user has two preferred slots (2 and 3) with the same highest Q value and will therefore select one at random. This process continues until every M2M user finds a dedicated unique slot in the repeating M2Mframe and this is called a convergence state. This process restricts M2M user access to only one slot per M2M frame, and if a request arrives after a user's slot time, it is queued until the next M2Mframe. In a situation where more than one request is generated within a frame, the requests are queued and treated on a first-in-first-out basis. It is important to note that the network is dimensioned in such a way that the average rate of RACH request generation is less than the average rate of transmission opportunities, which is a fundamental requirement for the system not to be loaded beyond its theoretical capacity.

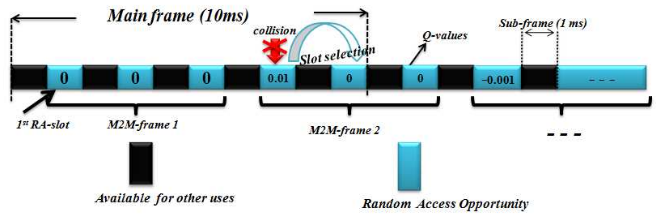

Fig. 2. Representation of M2M frame on LTE main frame with example Q-learning process.

In steady state, combining M2M users using the QL-RACH scheme with H2H users using s-ALOHA RACH (SA-RACH) access reduces the overall probability of collision since there will be no collision amongst M2M users. In addition, the impact of M2M users on H2H users is also reduced, improving the overall throughout performance.

IV. Application Scenario

The scenario of two coexisting user groups (H2H and M2M) sharing a single PRACH resource is now considered. The M2M user group is represented by various industrial and domestic applications with different M2M devices that send RACH requests to the eNB of the LTE network. Our analysis focuses on the interaction between these user groups where new equations for the probability of RACH request collision are obtained, as well as the combined throughput performance. A collision occurs when more than one user sends the same preamble in the same RA slot. Therefore, in our model, depending on the RACH access scheme used, a collision may occur between users of the same group or between users of different groups. In addition, the probability of collision amongst the same user group will be different from that of the interaction between different user groups. The same applies to the RACH throughput since it depends on the probability of collision.

Two scenarios are considered in this model. The first is the interaction of H2H and M2M user groups, both using the standard SA-RACH scheme. Here the model describes the initial case of the interaction before learning is introduced as a new and more effective approach. In the second scenario, a combined scheme is considered where the user groups have different RACH access schemes. Here the H2H group maintains the existing SA-RACH scheme (in order not to tamper with existing network standards), while the M2M user group uses the QL-RACH access scheme. Steady state is assumed for the QL-RACH scheme, where every M2M user has a dedicated slot and there will be no further collisions among the M2M user groups. Therefore, in this state, the QL-RACH works like a TDMA scheme; hence the interaction of H2H and M2M users here is like s-Aloha combined with TDMA.

We divide the analysis into three categories:

i. The first is the basic analysis where no retransmission is considered. In this analysis, requests from either user group are dropped when a collision occurs.
ii. In the second category, the basic analysis is extended to consider retransmissions where different strategies are applied by the H2H and M2M user groups.
iii. The third category is the analysis of FB-QL-RACH where the H2H traffic in retransmission is re-directed to a separate frame.

In addition, a number of assumptions based on typical LTE operating conditions are considered. These assumptions represent a scenario that allows us to analyse the combined RACH throughput performance (for H2H and M2M) of conventional s-ALOHA according to the standards. These assumptions are:

- All packets for the RACH request have the same length and transmission time τ, which is also equal to the slot length.
- There are a large number of users (i.e. $N \rightarrow \infty$) and therefore the probability of a user generating more than one request in a given small time period is negligible.
- New RACH requests arrive at a rate of λ packets/slot according to a Poisson arrival process.
- The system is perfectly synchronised with every user only transmitting at the beginning of a slot with length equal to the RACH packet.
- All users share a single RACH and this corresponds to providing only one preamble per RA slot.

In general, the traffic load offered to a system with an average arrival rate of λ RACH requests, with N users sending RACH requests to an RA slot of duration τ can be defined as

$$G = \lambda N \tau. \tag{2}$$

V. Analytical Model

In this section, analytical models are developed to determine the impact of additional M2M traffic on the existing H2H and also to establish the inefficiency of the s-ALOHA scheme to support the additional load. In addition, the models are developed to predict the throughput capability using the basic s-ALOHA and QL-RACH schemes in the combined scenario. We make use of the assumptions presented above.

First, consider a single user group in the system. According to the Poisson arrival process using s-ALOHA, the probability of successful transmission from a user in time τ is

$$P_{\text{succ}} = e^{-N\tau\lambda} = e^{-G} \tag{3}$$

and the probability of collision or failure is

$$P_{\text{collision}} = 1 - e^{-G}. \tag{4}$$

The throughput is the fraction of successful transmissions offered to the channel. Therefore, for a traffic load G, the throughput is

$$S = Ge^{-G}. \tag{5}$$

On the other hand, the level of interaction between groups is controlled by individual loads generated by the users, which contributes to the overall system traffic load (G_{total}). Since the H2H load is the existing load in the system, it is therefore fixed during the interaction and the M2M load is varied to complete the desired traffic load. The following equations represent the relationship between the H2H fixed load, the M2M load, and the total traffic load of the system:

$$G_{\text{total}} = G_{\text{H2H}} + G_{\text{M2M}} \tag{6}$$

where G_{H2H}, and G_{M2M} represent the individual user group loads and G_{total} is the total generated load in Erlang.

Now, if both H2H and M2M user groups share the RACH in a system using the s-ALOHA scheme, their individual throughput performance in the combined s-ALOHA system can be obtained as

$$S_{\text{Hcomb}_{\text{Aloha}}} = G_{\text{H2H}} e^{-G_{\text{total}}} \tag{7}$$

$$S_{\text{Mcomb}_{\text{Aloha}}} = G_{\text{M2M}} e^{-G_{\text{total}}} \tag{8}$$

where $S_{\text{Hcomb}_{\text{Aloha}}}$ and $S_{\text{Mcomb}_{\text{aloha}}}$ are the H2H and M2M throughputs respectively.

A. Basic throughput analysis of SA-RACH for H2H and QL-RACH for M2M user group access

This analysis is for the combined access of H2H and M2M user groups, where the M2M traffic is controlled using the QL-RACH scheme and H2H traffic maintains the s-ALOHA scheme (SA-RACH). Retransmissions for either user group are not considered here. Since it is assumed that M2M users have converged to their dedicated slots (steady-state condition), the scheme is contention-free (similar to TDMA). Therefore, during interaction of the user groups, there may be collisions between H2H users and M2M users or between H2H users with other H2H users, but there are no collisions amongst the M2M users. The performance of M2M users during the learning process (transition from frame-based s-ALOHA to QL-RACH) is not considered here. However, the running RACH-throughput performance is provided later to quantify the convergence time and also show that even during the learning process, the system offers useful throughput. The probability of successful transmission and probability of collision for H2H and M2M users can be determined using the scenario presented in Fig. 3.

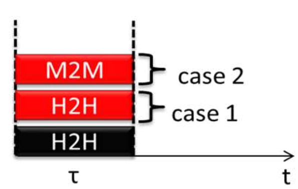

Fig. 3. Collision conditions for H2H transmission.

For the transmission of either a H2H or M2M user to be successful, the scenario of Case 1 and Case 2 shown in Fig. 3 must not happen. Therefore, a H2H transmission will be successful if no other H2H or M2M user transmits in the same slot. For the first case, the probability of no collision from H2H is

$$P_{\mathrm{no}_{\mathrm{coll}_{\mathrm{H2H}}}} = e^{-G_{\mathrm{H2H}}}. \tag{9}$$

On the other hand, since M2M transmission is frame-based and we assume convergence (no collisions amongst the M2M users), to obtain the probability of M2M transmission we need to consider the part of the M2Mframe in which the M2M user transmits. Over the long term, this is equal to the M2M traffic (G_{M2M}). Thus, the probability that an M2M user will transmit successfully in time τ is

$$P_{\mathrm{M}_{\mathrm{succ}}} = G_{\mathrm{M2M}} \tag{10}$$

and the probability that H2H suffers no collision from an M2M user is $1 - G_{\mathrm{M2M}}$. Therefore, the probability of successful H2H transmission in time τ using the combined scheme is

$$P_{\mathrm{H}_{\mathrm{succ}\mathrm{Q}_{\mathrm{Aloha}}}} = e^{-G_{\mathrm{H2H}}}(1 - G_{\mathrm{M2M}}),\, G_{\mathrm{M2M}} \leq 1. \tag{11}$$

Hence, the H2H throughput of the combined SA-RACH and QL-RACH ($S_{\mathrm{HQ}_{\mathrm{Aloha}}}$) is

$$S_{\mathrm{HQ}_{\mathrm{Aloha}}} = G_{\mathrm{H2H}} e^{-G_{\mathrm{H2H}}}(1 - G_{\mathrm{M2M}}). \tag{12}$$

To obtain the combined performance of M2M users, here M2M transmissions will only suffer from collisions from H2H users, i.e., there are no collisions between M2M users since every user has a dedicated RA slot. This scenario is presented in Fig. 4, where the probability of a successful M2M transmission in RA slot τ is equal to the probability that an M2M user suffers no collision from any H2H user. This is similar to (9) in Case 1 and the M2M user group combined RACH throughput is

$$S_{\mathrm{MQ}_{\mathrm{Aloha}}} = G_{\mathrm{M2M}} e^{-G_{\mathrm{H2H}}}. \tag{13}$$

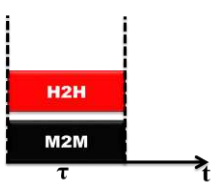

Fig. 4. Collision conditions for M2M transmission.

Finally, the overall throughput of both H2H and M2M user groups in the combined access is

$$S_{\mathrm{TQ}_{\mathrm{Aloha}}} = S_{\mathrm{HQ}_{\mathrm{Aloha}}} + S_{\mathrm{MQ}_{\mathrm{Aloha}}} = e^{-G_{\mathrm{H2H}}}(G_{\mathrm{total}} - G_{\mathrm{M2M}} G_{\mathrm{H2H}}). \tag{14}$$

B. Throughput Analysis of SA-RACH for H2H and M2M user Group Access with Retransmission

The analysis presented above does not consider retransmission of collided RACH requests. However, as discussed in the introduction, cellular network standards allow retransmission in order to limit the number of lost RACH requests. In addition, retransmissions are controlled using a cut-off strategy to limit the number of retransmissions. Retransmission is considered here and new throughput equations are obtained for the scenarios considered above. Uniform retransmission is applied, where a fixed window (number of slots) is used for the back-off, i.e., when a collision occurs, a user schedules retransmission in a random slot within the back-off window. Note that both H2H and M2M users apply the same retransmission strategy. Correlation of collided packets and their retransmissions is not considered in the analytical model. This is because (as will be shown later) the results of the simulation and analytical model prediction show an excellent match, therefore correlation of collisions cannot have a notable impact on performance.

Fig. 5 is presented to understand how different traffic is generated during a RACH request. As shown, it illustrates the retransmission cut-off strategy and also shows how aggregated traffic offered to the system increases with an increase in the number of retransmissions from both H2H and M2M users contesting for the RA slot.

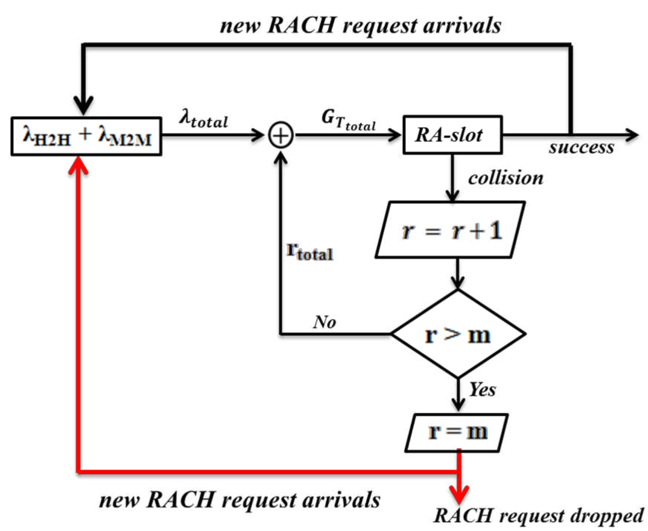

Fig. 5. Collision conditions for M2M transmission.

From Fig. 5, the total aggregated traffic from both H2H and M2M user groups ($G_{\mathrm{T}_{\mathrm{total}}}$) can be expressed as:

$$G_{\mathrm{T}_{\mathrm{total}}} = \lambda_{\mathrm{total}} + r_{\mathrm{total}} \tag{15}$$

where λ_{total} is the new request arrival rate (per RA slot) generated by both H2H and M2M users, and r_{total} is the total retransmission traffic from both H2H and M2M users.

As shown in Fig. 5, when a collision occurs, a user checks the retransmission counter, and if the counter is still within the allowed limit, the user will schedule, retransmit, and increment

r by 1. This is then compared with the number of allowed retransmissions m. If $r > m$, no further retransmission is allowed, the RACH request is dropped, and r is reset to zero; otherwise the request is sent again.

Using Fig. 5, the probablity of success and collision or failure can be redefined as

$e^{-G_{T_{\text{total}}}}$ and $1 - e^{-G_{T_{\text{total}}}}$, respectively.

The aggregated traffic can be obtained from the fraction of traffic (from the request) being retransmitted for the ith time as

$$G_{T_{\text{total}}} = \lambda \sum_{i=0}^{m} \left(1 - e^{-G_{T_{\text{total}}}}\right)^{i} \quad (16)$$

and the throughput is

$$S_{\text{retrans}} = G_{T_{\text{total}}} e^{-G_{T_{\text{total}}}} \quad (17)$$

when retransmission is considered.

Considering a single user group and $m=2$, the throughput is given by

$$\begin{aligned} S_{\text{retrans}} &= \left[\lambda + \lambda\left(1 - e^{-G_{T_{\text{total}}}}\right) + \lambda\left(1 - e^{-G_{T_{\text{total}}}}\right)^{2}\right] e^{-G_{T_{\text{total}}}} \\ &= 3\lambda e^{-G_{T_{\text{total}}}} - 3\lambda e^{-2G_{T}} + \lambda e^{-3G_{T_{\text{total}}}} \\ &= \lambda\left[1 - \left(1 - e^{-G_{T_{\text{total}}}}\right)^{3}\right]. \end{aligned} \quad (18)$$

Therefore, in general, the throughput equation of a single user group, using the SA-RACH scheme with cut-off retransmission limit m, is

$$S_{\text{Aloha}_r} = \lambda\left[1 - \left(1 - e^{-G_{T_{\text{total}}}}\right)^{m+1}\right]. \quad (19)$$

Now we can obtain new throughput equations for the combined access of H2H and M2M user groups when both use the SA-RACH scheme with m allowed retransmissions as follows. Considering H2H transmission, the aggregated traffic being offered to the system will also be obtained from the fraction of failed traffic during the ith attempt as

$$\lambda_{\text{H2H}}\left(1 - e^{-G_{T_{\text{total}}}}\right)^{i}. \quad (20)$$

Therefore, from (18) and (20), the throughput of H2H users is given by

$$\begin{aligned} S_{\text{H}_{\text{Aloha}_r}} &= \lambda_{\text{H2H}} + [\lambda_{\text{H2H}} \sum_{i-1}^{m} 1 - e^{-G_{T_{\text{total}}}}]\, e^{-G_{T_{\text{total}}}} \\ &= \lambda_{\text{H2H}}\left[1 - \left(1 - e^{-G_{T_{\text{total}}}}\right)^{m+1}\right]. \end{aligned} \quad (21)$$

Similarly,

$$S_{\text{M}_{\text{Aloha}_r}} = \lambda_{\text{M2M}}\left[1 - \left(1 - e^{-G_{T_{\text{total}}}}\right)^{m+1}\right]. \quad (22)$$

C. Throughput Analysis of SA-RACH for H2H and QL-RACH for M2M User Group Access with Retransmission

A similar method is adopted to develop the throughput equation for the combined access schemes, i.e., when H2H uses SA-RACH and M2M uses QL-RACH. The only difference is the probability of success for the individual user groups. Therefore putting the probability of successful transmission shown in (11) (where the offered traffic in this case is the aggregated traffic) into (17) will give the combined access throughput of H2H as

$$\begin{aligned} S_{\text{H}_{\text{QAloha}_r}} &= \left[\lambda_{\text{H2H}} + \lambda_{\text{H2H}} \sum_{i=1}^{m} \left(1 - e^{-G_{T_{\text{total}}}}\right)^{i}\right] \\ &\times \left[e^{-G_{T_{\text{H2H}}}\left(1 - G_{T_{\text{M2M}}}\right)}\right] \end{aligned} \quad (23)$$

where $G_{T_{\text{H2H}}}$ and $G_{T_{\text{M2M}}}$ are the H2H and M2M aggregated traffic, respectively.

Equation (6) can be rewritten as; $e^{-G_{\text{total}}} = e^{-G_{T_{\text{H2H}}}} + e^{-G_{T_{\text{M2M}}}}$, and rearranging gives

$$e^{-G_{T_{\text{H2H}}}} = \frac{e^{-G_{T_{\text{total}}}}}{e^{-G_{T_{\text{M2M}}}}}. \quad (24)$$

Substituting (24) into(23) and re-arranging gives

$$\begin{aligned} S_{\text{H}_{\text{QAloha}_r}} &= \lambda_{\text{H2H}}\left[1 - \left(1 - e^{-G_{T_{\text{total}}}}\right)^{m+1}\right] \\ &\times \frac{\left(1 - G_{T_{\text{M2M}}}\right)}{e^{-G_{T_{\text{M2M}}}}}. \end{aligned} \quad (25)$$

Similarly, the throughput of the M2Muser group in the combined scheme can be obtained as

$$S_{\text{M}_{\text{QAloha}_r}} = \left[\lambda_{\text{M2M}} \sum_{i=0}^{m} \left(1 - e^{-G_{T_{\text{total}}}}\right)^{i}\right] . \, e^{-G_{T_{\text{H2H}}}}. \quad (26)$$

Substituting (24) into (26) and re-arranging then gives

$$S_{\text{M}_{\text{QAloha}_r}} = \frac{\lambda_{\text{M2M}}\left[1 - \left(1 - e^{-G_{T_{\text{total}}}}\right)^{m+1}\right]}{e^{-G_{T_{\text{M2M}}}}}. \quad (27)$$

D. Throughput Analysis for the FB-QL-RACH

Observing the throughput equations derived above shows that at high H2H traffic load, a high level of the total aggregated traffic will reduce the throughput performance. Also, as mentioned earlier, the aggregated traffic increases with an increase in retransmission as a result of collisions. This has been described in [15] as an effect due to the un-coordinated random access behaviour of H2H. This effect (which increases with an increase in H2H aggregated traffic) dominates the performance of the QL-RACH scheme. Therefore, even though the QL-RACH controls the M2M traffic, the level of disturbance due to collision from H2H users has a significant impact on the overall throughput performance (especially for the M2M user group).

This effect has been studied in [16], which introduces the FB-

QL-RACH scheme (with fixed frame size) to direct H2H retransmissions to a separate frame, and improves the throughput performance by significantly reducing collisions between H2H and M2M users, which can only occur during each user's first attempt. The throughput analysis of the FB-QL-RACH is developed in this section by extending the throughput analysis of the combined scheme developed above. In this approach, we show analytically how the FB-QL-RACH scheme improves the throughput by reducing the overall aggregated traffic, as shown below.

Two consecutive virtual frames of RA slots are designated from the main LTE PRACH resource, making a global frame. The first is the M2Mframe, which has a size equal to the number of M2M users. This frame is used by both M2M and H2H users during their first RACH request attempt, and repeats after the second frame. The second frame is the H2H back-off frame (H-B frame), which is mainly used for H2H retransmission and can also be used by H2H for a first attempt when required. M2M users are not allowed to use the H-B frame. Fig. 6 is an example of a frame structure representing the FB-QL-RACH scheme, where a steady state of three M2M users acquiring three dedicated slots is assumed. For full details on the FB-QL-RACH scheme, see [16]. On the other hand, Fig. 6 also shows how the H2H aggregated traffic is directed to the H-B frame. This process reduces the overall probability of collision as well as the total aggregated traffic, and significantly increases the overall throughput performance.

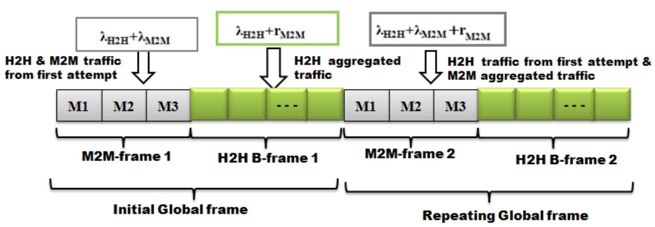

Fig. 6. Representation of FB-QL-RACH scheme.

To realise the H2H throughput equation we consider the two different frames (M2M and H-B) separately and obtain the aggregated traffic offered to each frame. In the M2M frame, the aggregated traffic is

$$G_{\mathrm{TBF\,M2M}} = \lambda_{\mathrm{total}} + r_{\mathrm{M2M}} \tag{28}$$

where $G_{\mathrm{TBF_{M2M}}}$ is the aggregated traffic offered to the M2M frame using the FB-QL-RACH scheme. Also, in the H-B frame, the aggregated traffic is

$$G_{\mathrm{TBF\,H2H}} = \lambda_{\mathrm{H2H}} + r_{\mathrm{H2H}}. \tag{29}$$

where $G_{\mathrm{TBF_{H2H}}}$ is the aggregated traffic offered to the H-B frame using the FB-QL-RACH scheme. Therefore, combining (28) and (29) and using Fig. 5 gives the total aggregated traffic for the FB-QL-RACH scheme as

$$G_{\mathrm{TBF\,total}} = G_{\mathrm{Ttotal}} + \lambda_{\mathrm{H2H}}. \tag{30}$$

Hence, the new aggregated traffic will be used to determine a new probability of successful transmission and a throughput equations, that is similar to (21) with only a difference in the aggregated traffic:

$$S_{\mathrm{H_{Aloha_{FB}}}} = \lambda_{\mathrm{H2H}}\left[1-\left(1-e^{-G_{\mathrm{TBF\,total}}}\right)^{m+1}\right]. \tag{31}$$

For the M2M user group, since there are no collisions between M2M users (QL-RACH scheme) and collisions between H2H and M2M users occur only during the first access, the condition for the M2M user group here is similar to that of Section V.A. The equation is similar to (13) with a little modification to the M2M user group proportion of traffic, which is now a total aggregated traffic shown as

$$G_{\mathrm{T_{M2M}}} = \lambda_{\mathrm{M2M}} + r_{\mathrm{M2M}}. \tag{32}$$

The throughput equation is therefore given by

$$S_{\mathrm{M_{Aloha_{FB}}}} = G_{\mathrm{T_{M2M}}} e^{-\lambda_{\mathrm{H2H}}}. \tag{33}$$

VI. Performance Evaluation

A. Simulation Scenario

An event-based simulation is used to evaluate the performance with interaction between the H2H and M2M user groups. A Monte-Carlo simulation is utilised, where it is assumed that users are deployed randomly within a cell coverage area with a single preamble sequence. All users share and access the channel randomly with equal rights. Similar to the analytical model, here we also assume that RACH request generation for each user group follows a Poisson distribution with average inter-arrival time (τ_{ia}) determined by the desired traffic load as

$$\tau_{\mathrm{ia}} = \frac{\tau N}{GR} \tag{34}$$

where τ is the packet length in bits, N is the number of users in the system, G is the desired traffic load in Erlangs, and R is the transmission data rate in bits/s. Since H2H is the existing user group in the network, we predict and fix its traffic load based on the capacity of s-ALOHA (the existing RACH access scheme).

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Consider a fixed traffic load for the H2H users that is either close to the 0.3 E throughput capability of the s-ALOHA channel or a more lightly loaded channel of 0.1 E. Then consider a variable amount of additional M2M traffic to complete the desired traffic load. For example, at 0.3 E fixed H2H traffic, M2M users will generate 0.7 E of traffic if the desired total traffic is 1 E, and so on. In the resulting figures, we refer to the situation with 0.1 E of H2H traffic as the *lower limit* and the situation with 0.3 E of H2H traffic as the *upper limit*.

B. Simulation Parameters

Table 1 details the parameters used in this simulation, based on the LTE standard.

Table I
Simulation Parameters

Parameter	Value
PRACH configuration index	12
Number of preamble sequences	1
RA-slot period	1ms
Conventional frame period	10ms
Number of M2M users	100
M2M frame period	0.1s
RAO	5 per frame
Back-off period	14 RA slots
Maximum retransmission limit	7
Learning rate	0.01
Minimum blocking probability of RACH request	0.05

C. Results – Analysis and Discussion

Firstly, we compare the throughput performance of the two s-ALOHA (SA-RACH) and Q-learning (QL-RACH) schemes for a single user group. Secondly, to demonstrate the instability of the SA-RACH scheme, we compare the performance with retransmissions (typical of the LTE standard) and without retransmissions. A steady state is assumed for the QL-RACH scheme and therefore the access is contentionless, similar to the traditional TDMA scheme. Hence the analytical results can be described by the s-ALOHA and TDMA throughput chracteristic equations.

The first results presented in Fig. 7 represent the running throughput peformance of the H2H and M2M user groups obtained during the learning process. Running throughput represents the throughput achieved from the beginning of the simulation up to a particular point in time. The end points of the curves represent the times at which complete convergence is obtained and the throughput reaches its maximum value. The purpose of these results is to show that the system still offers useful throughput prior to convergence, and to illustrate the difference in the convergence time between the upper and lower limits (0.1E of H2H traffic and 0.3E of H2H traffic). The H2H throughput is therefore higher at the upper limit, but there is less scope to accommodate M2M traffic, so the M2M throughput is lower at the upper limit, and vice versa at the lower limit.

Since there is less disturbance from the uncontrolled H2H traffic at the lower limit, the system converges more quickly than at the upper limit. The upper limit takes a longer learning period due to the higher level of interference from the non-learning H2H users. Fig. 7(a) represents the learning performance of 100 M2M users. As shown, the running throughput trend is the same as that obtained with 200 M2M users in Fig. 7(b), but the convergence time is longer because the M2Mframe size for 200 M2M users is larger since it is fixed to the number of M2M users. More importantly, the results in both Figs. 7(a) and 7(b) show that the throughput rises very quickly to a level close to the theoretical converged throughput value. In other words, the learning process is sufficiently effective to provide high throughput in a short space of time long before complete convergence is obtained (the end points of each line). The time to complete convergence is therefore not critical.

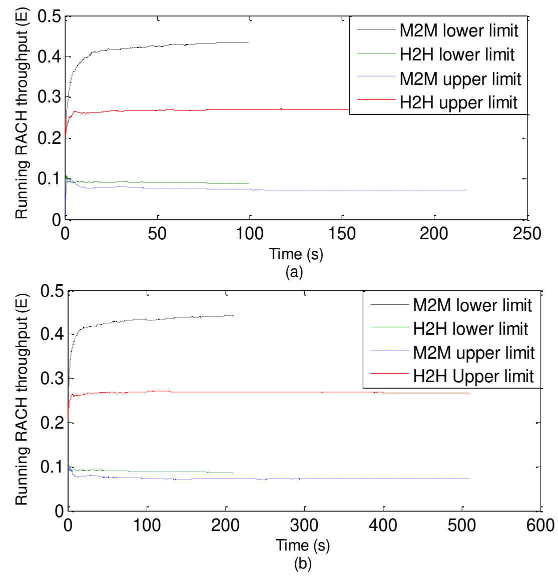

Fig. 7. Running throughput. (a) 100 M2M users. (b) 200 M2M users.

Note also that the convergence time would have been shorter if retransmissions were not allowed during the learning process, however, that would have been at the expence of lower running throughput, especially for H2H users.

Although convergence time in a QL-RACH scheme is not an issue of concern, sending important M2M information (after convergence) through the RACH could be considered. This will save transmission time better than the conventional cellular process. However, using the RACH as medium of transmission by M2M will of course depend on the area of application as well as the packet size of M2M information. For example, in a situation where the M2M devices generate a short message (e.g., single packet), reflecting RFID, sensor readings, etc. The remaining results are analysed based on the system user group and are categorised as follows:

1. Single user group: Fig. 8 represents the single-user-group performance, where the analytical results of (6), (10), and (19) are compared with the simulation. The solid lines and markers represent analytical and simulation results, respectively. SA-RACH_r and SA-RACH represent the results with and without retransmissions, repectively. It can be seen that the SA-RACH throughput increases with an increase in the generated traffic, and the maximum throughput achieved is approximately 37%, which is the maximum throughput that s-ALOHA can offer at 1E generated traffic. In addition, the result of SA-RACH shows that the channel is stable since the offered traffic does not exceed the s-ALOHA channel capacity. When retransmission is applied, SA-RACH-r performs better up to the s-ALOHA limit (0.37E). This happens because the scheme reduces the packet loss due to retransmission, and almost all the packets generated get through. However, immediately after the channel throughput limit is reached, the aggregated traffic increases to the point where the s-ALOHA scheme can no longer support the traffic. This is why we see throughput degredation, which increases with an increase in traffic, to the extent that the channel becomes unstable. On the other hand, in a steady state, the QL-RACH scheme offers up to 100% throughput (assuming no overhead). This is because there are no collisions since the scheme is contention free. Finally, both results in Fig. 8 illustrate good agreement between the analysis and simulation.

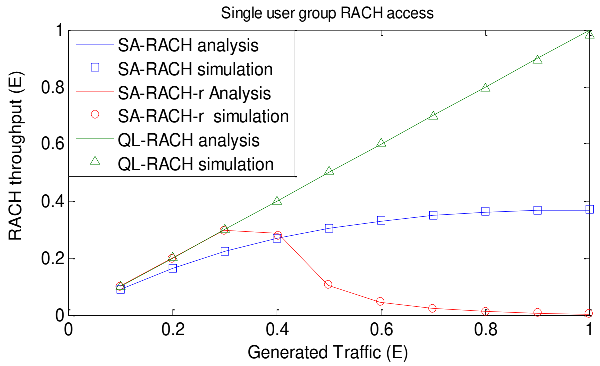

Fig. 8. Comparison of SA-RACH and QL-RACH throughput for a single user group.

2. Dual user groups: The results shown in Figs. 9 -11 represent the performance of dual user groups, i.e., when H2H and M2M users coexist in the RACH. The analytical results are compared with simulation for the QL-RACH (25) and (27), SA-RACH (21) and (22), and FB-QL-RACH (31) and (33) schemes. Solid lines and markers are used to repesent the analysis and simulation results, respectively. The following definitions are useful in interpreting the legends of the results:

- **QL-RACH:** This represents the results when M2M users use QL-RACH with exponential back-off and H2H users use s-ALOHA with a fixed back-off window.
- **FB-QL-RACH (FBQL in graph):**This is when M2M users use QL-RACH with no back-off, and H2H users use s-ALOHA with a separate frame for back-off, and a fixed window.
- **SA-RACH:**This is when both M2M and H2H users use s-ALOHA with a fixed back-off window.
- **ana** stands for analysis and **sim** stands for simulation.

Fig. 9 compares the RACH throughput performance of the three different schemes at the upper limit. We separate the M2M and H2H user group results in Fig. 9 (a) and Fig. 9 (b), respectively. All the results illustrate a good match between the analysis and the simulation.

Fig. 9(a) illustrates the M2M user group performance in the combined access scheme where SA-RACH exhibits the worst RACH throughput performance. This indicates instability from the impact of an M2M load that renders the scheme useless. The impact is significant here because the H2H load is close to the s-ALOHA capacity, which leads to a high probability of collision, and the aggregated traffic increases due to retransmissions. QL-RACH exhibits better performance, which shows that the scheme has reduced the impact of M2M traffic to some extent. However, due to the disturbance from random uncontrolled H2H traffic (especially at this upper limit), the performance is still poor. The FB-QL-RACH can offer the best performance, depending on the value of BFZ used. As shown, the lower the BFZ, the better the M2M user group performance. It can be seen from Fig. 9(a) that BFZ = 50 gives up to about 56% of M2M user group throughput at 0.7E, which is more than five times better than the 10% obtained at the same load using QL-RACH.

Fig. 9(b) illustrates the H2H performance in a similar arrangement, with SA-RACH giving the worst performance due to the same reason mentioned above. On the other hand, the higher the BFZ value, the better the H2H performance. Since H2H is using s-ALOHA with fixed back-off, a high BFZ means thet there are enough slots within the H2H for retransmision and therefore the higher the BFZ, the better the H2H performance. A BFZ of 350 has similar performance to that of QL-RACH.

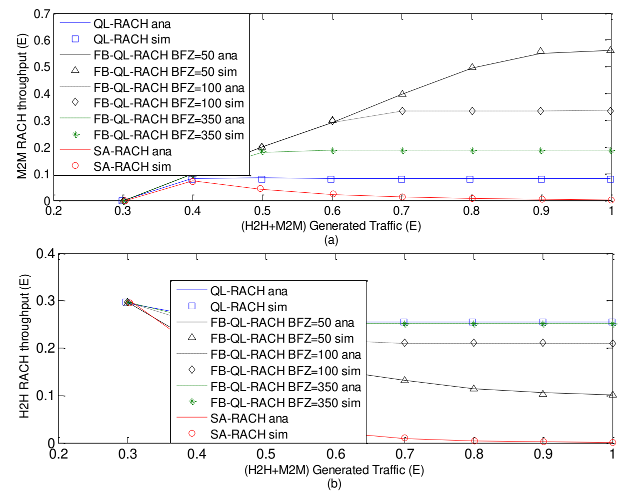

Fig. 9. Comparison of upper limit RACH throughput for H2H and M2M user groups for single and combined scheme with H2H traffic fixed at 0.3 E. (a) M2M. (b) H2H..

Fig. 10 shows that the performance at the lower limit, i.e., when the H2H traffic load is 0.1 E, is much lower than the s-ALOHA capacity. Similar to the upper limit results presented in Fig. 9, all the results representing the three schemes show good agreement between the analysis and simulation. As can be seen in both the M2M and H2H user group results, the SA-RACH scheme has the worst throughput performance. QL-RACH improves the performance here better than in the upper limit, as presented in Fig. 9. Also, for the FB-QL-RACH scheme, a high BFZ value is not required here since the H2H load is at the lower limit (0.1E), which is far away from the s-ALOHA capacity. From the M2M user group performance shown in Fig. 10 (a), it can be seen that changing the BFZ value over the range of traffic from 0 to 0.5 E, has no effect on the performance. However, above 0.5 E, the M2M user group performance increases with a decrease in BFZ, and H2H exhibits the converse in terms of performance and BFZ value. Therefore, it is clear that the FB-QL-RACH scheme works better at the lower limit (light H2H load). Up to 100% throughput is obtained by H2H for a BFZ of 50 and 100,with a significant increase in the M2M user group performance at a BFZ value of 50.

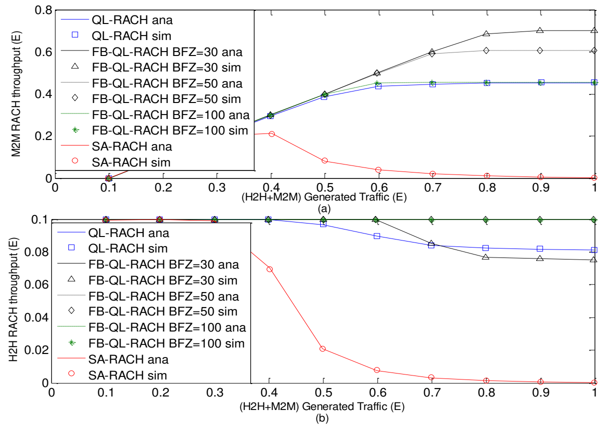

Fig. 10. Comparison of lower limit RACH throughput for H2H and M2M user groups for single and combined scheme fixed at 0.1 E. (a) M2M. (b) H2H.

Fig. 11 compares the performance of the schemes at different H2H load levels from the lower to upper limit. This is to see how the performance of the different schemes varies over different traffic load combinations of H2H and M2M users. The idea here is that when the H2H load is known, we can determine (from the performance of the scheme) how much M2M traffic load the system can support on top of the existing H2H traffic. Looking at the results shown in Fig. 11(a), QL-RACH performs better from the start (i.e., from 0 to about 0.05 E of H2H traffic) when H2H generates a small amount of traffic and M2M users have a high traffic load. The performance indicates that at this H2H load, the QL-RACH scheme can control M2M traffic that is much higher, and the uncontrolled H2H load has no effect on the QL-RACH scheme. Over the range of H2H traffic load above 0.05E, the FB-QL-RACH scheme performs better than QL-RACH, depending on the BFZ value used. For example, from 0.05 to 0.1 E, only a BFZ of 30 is better than the QL-RACH, which shows that a lower BFZ value is required since H2H generates low load and collisions. In addition, at a H2H load of 0.1 E to 0.23 E and 0.23 E to 0.35 E, FB-QL-RACH with BFZ=100 and 350, respectively, outperforms QL-RACH. Also, as presented earlier, the lower the BFZ value, the better the M2M user group performance. However, the performance of the H2H user group shown in Fig.11(b) presents a contrary result, where for the FB-QL-RACH scheme (at higher H2H load), the higher the BFZ value, the better the performance. For example, BFZ values of 30 and 100 perform worse than the QL-RACH scheme, and also with a BFZ of 350 at higher H2H load.

On the other hand,the 30 and 100 BFZ values perform worse than the QL-RACH scheme with a BFZ of 350 at higher H2H load. The BFZ value of 350 has similar performance to that of the QL-RACH scheme, with a slight difference at low and high H2H load.

VII. FB-QL-RACH Scheme with Dynamic BFZ

A. Dynamic BFZ Implementation

As shown from the results of the FB-QL-RACH performance presented above, the BFZ value used plays a significant role in the throughput performance of both H2H and M2M user groups. It was observed that the best BFZ value increases directly with an increase in the H2H traffic. Therefore, making the BFZ a fixed value irrespective of the H2H traffic load will not provide optimum performance of the FB-QL-RACH scheme. Hence, a dynamic frame size is introduced here to optimise the performance of the FB-QL-RACH scheme.

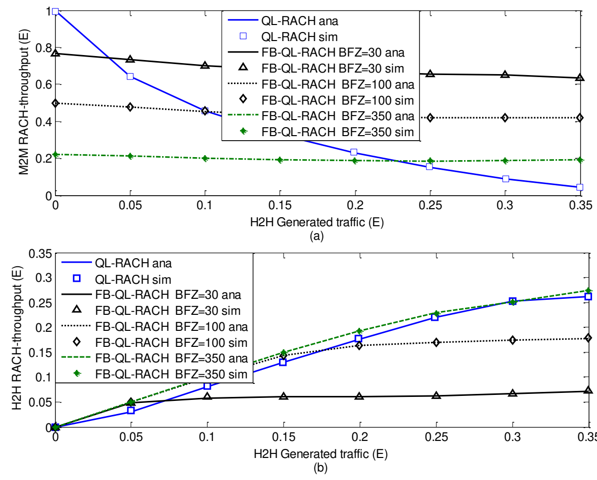

Fig. 11. Analytical and simulated RACH throughput comparison for different schemes with total traffic fixed at 1 E and H2H traffic varies from 0 to 0.3 E. (a) M2M. (b) H2H.

Dynamic frame size is implemented by an eNB with the help of prior information from H2H users, as presented below. We propose to use Message 3 of the RACH request procedure for a H2H user to send (in addition to the resource request) information of parameters needed to obtain blocking probability. Each H2H user sends its cumulative number of blocked and successful transmissions (which can be used to compute the current system blocking probability) to the eNB in a given window period. A window comprises a number of conventional frames within which the H2H blocking probability is checked and compared with a threshold. If the blocking probability is higher than the threshold, then the H2H BFZ will be increased by an integer number, say ***j***; otherwise the BFZ value remains as is. The frame duration is 10 ms, as presented in Table 1, and 1000 conventional frames are used as a window, which is equivalent to 10 s in time. The eNB uses the information from all the active H2H users within the window period to calculate the H2H system blocking probability ($H2H_{BP}$), which is compared with a defined threshold (BP_{thr}). Note that the value of BP_{thr} depends on the acceptable system blocking probability, and therefore different applications may have different BP_{thr} values. We choose 5% (as shown in Table 1) here to demonstrate the performance of our scheme. A decision on the BFZ value is made (by the eNB) from the above comparison using the following routine:

If $H2H_{BP} > BP_{thr}$
    BFZ=BFZ+j
else
    BZF=BFZ
end

where *j* is an integer value.

The blocking probability here is defined as the probability of blocking a RACH request after a user's retransmission limit has been reached (see Fig. 5). Blocking probability is chosen because it directly depends on the probability of collision, which is controlled by the BFZ value.

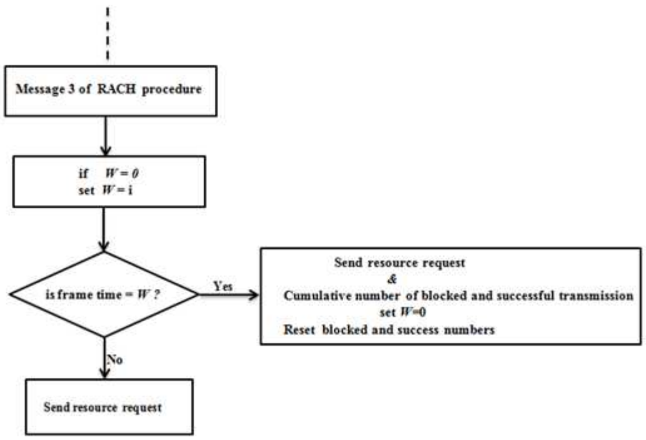

Fig. 12. UE flow chart for sending blocking probability parameters to the eNB.

Fig. 12 describes how an H2H user checks and increases the value of BFZ using Message 3 (of the existing LTE standard). If the current value of window size (*W*) is equal to a set frame time, a resource request and the parameters (cumulative number of blocked and successful transmissions) used to obtain blocking probability are subsequently sent, and then the value of *W* is reset to zero. On the other hand, if the value of *W* has not yet been reached, the H2H user only sends a resource request as a conventional Message 3.

B. Results – Analysis and Discussion

The first result presented here (Fig. 13) represents the dynamic BFZ convergence time taken to achieve the optimum BFZ value. Two separate total traffic loads are provided. In Fig. 13(a), the total traffic is at 1E with M2M traffic generating 0.9 E. The result shows that the BFZ increases with the number of global frames used, and that the system converges to a BFZ value of about 60. On the other hand, Fig. 13(b) considers a total traffic of 0.5 E with the M2M traffic generating 0.4 E. It can be seen that, even though the H2H traffic here is the same as in Fig. 13(a), the BFZ converges to a value of 30. This is because the M2M traffic load is lower here, which reduces collisions between H2H and M2M user groups. This indicates that the required value of BFZ depends on the level of collisions between the two user groups.

As discussed earlier, 100% H2H throughput is achieved at a fixed BFZ value of 50 in Fig. 10(b). Since the same load is used in Fig. 13(a), this shows that the converged dynamic BFZ value of 60 is not optimal. We check this situation by varying the increments of increasing the BFZ in the dynamic BFZ process implementation, and the results are presented in Fig. 14. The lower limit (H2H traffic at 0.1E) is used here and integer values 14, 5, 2, and 1 are used as the increment values (*j*) of the BFZ when required. As shown, from 0 to 0.2 E of M2M-generated traffic, the increment at which BFZ increases is immaterial because the total traffic is below the s-ALOHA capacity, so collisions are minimal, and a lower BFZ value is required. However, from 0.2E to 0.5E of M2M traffic, an increment of 14 exhibits different behaviour from the other values, where the BFZ increases and levels out at 30. From 0.5 E to 0.7 E of M2M traffic, a value of 14 has a little lower BFZ and finally converges at around a BFZ value of 60, similar to what is obtained in Fig. 13(a). On the other hand, integer values of 5, 2, and 1 have similar effects on the BFZ with 5 having the optimum effect at higher M2M loads, where it converges to a BFZ value around 48.

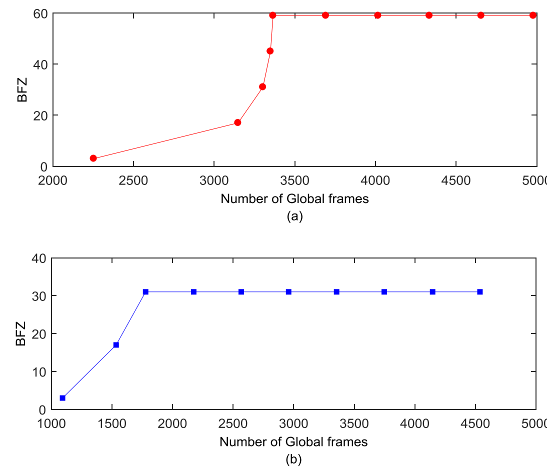

Fig. 13. BFZ convergence time at H2H lower limit with fixed total traffic. (a) Total load = 1 E. (b) Total load = 0.5 E

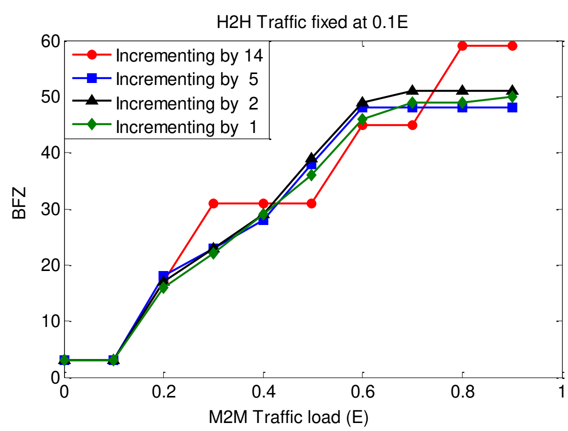

Fig. 14. Impact of various increment values on BFZ.

Fig. 15 (a) and (b) present running throughput at the upper and lower H2H limit, respectively. This shows that the system is still useful during the process of obtaining the optimum BFZ value. In addition, both results also agree with the fixed BFZ results presented earlier, where the M2M-user-group RACH throughput decreases with an increase in the BFZ, and the converse is obtained for the H2H-user-group RACH throughput. Finally, the results also confirm the converged BFZ value.

The results presented in Fig. 16 compare the throughput performance of the different schemes to analyse the effect of the dynamic BFZ on the FB-QL-RACH performance. The dynamic BFZ shows better M2M-user-group RACH throughput performance from 0 to 0.1 E of H2H traffic load compared to other schemes, as presented in Fig. 16(a). This is because a lower BFZ is required here since the uncontrolled traffic (H2H) is generating lower load, making collisions minimal. Above 0.1E of H2H-generated traffic, the dynamic BFZ scheme still offers better M2M-user-group RACH throughput than the other two schemes, with the exception of FB-QL-RACH at a BFZ value of 50. Therefore, this shows that the FB-QL-RACH scheme can be implemented with a dynamic BFZ, which has been shown to provide much better M2M-user-group RACH throughput performance than the QL-RACH scheme. On the other hand, the dynamic BFZ scheme shows good H2H RACH throughput, where up to 100% performance is achieved at the lower H2H-generated traffic limit, as shown in Fig. 16(b), and performs worse than the other two schemes at the upper limit of H2H-generated traffic.

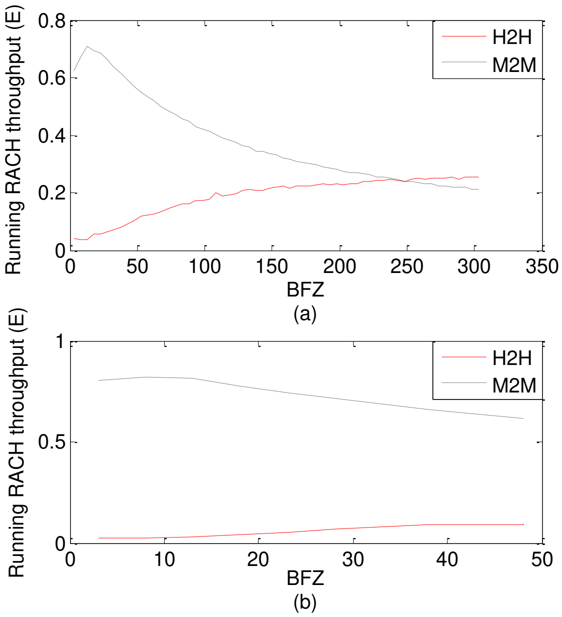

Fig. 15. Running throughput with dynamic BFZ. (a) Upper limt H2H traffic fixed ar 0.3 E and M2M traffic at 0.7 E. (b) Lower limit H2H traffic fixed ar 0.1 E, and M2M traffic at 0.9 E.

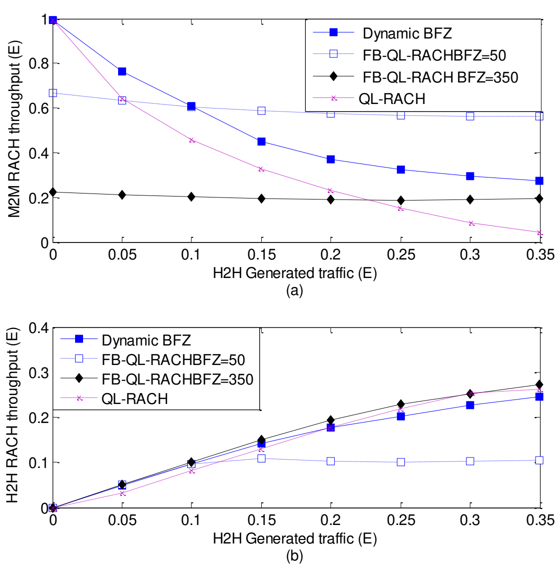

Fig. 16. RACH throughput comparison of dynamic BFZ to different static schemes with total traffic fixed at 1 E and varying H2H and M2M traffic. (a) M2M. (b) H2H.

The QL-RACH schemes have been designed to maximise the throughput of the access channel for M2M traffic, to effectively support additional load from M2M users whilst minimising the impact on existing H2H users. The results presented in this paper focus on this design goal and show the effectiveness of the QL-RACH schemes in this respect.

Other performance criteria should not be neglected, however, such as delay. An earlier paper [15] evaluated the delay performance of the QL-RACH approach and showed that it is reasonable for typical M2M applications. It is important to note however, that a large number of M2M users will lead to long access delay due to the need for a long frame. In one sense, this is a necessity and the delay associated with the interval between successive transmission slots for a particular user simply reflects the available capacity to each user. That said, if the traffic load at each user is low, then the access delay will be excessive compared with other approaches (such as the standard ALOHA scheme) but they would not permit a high channel utilisation/throughput should the load in the network rise. In contrast with a large number of users, the traffic load at each user will be very low and the queuing delay will be minimised. In situations where a small number of nodes contribute to a higher individual traffic load to the channel, queues will experience greater short term build up and queuing delay will rise.

VIII. CONCLUSION

The work in this paper has considered the coexistence of H2H and M2M users in sharing the RACH of a cellular network. An analytical model has been provided in this paper that analyses the impact of additional M2M load on the RACH and the inefficiency of the s-ALOHA scheme to support the additional load. The model also predicts the throughput performance of the QL-RACH and FB-QL-RACH schemes. High aggregated traffic resulting from H2H and M2M collisions and retransmissions has been shown by the analytical model to be the main factor that renders the s-ALOHA channel useless, especially at high traffic loads. However, the QL-RACH and FB-QL-RACH schemes are able to improve the performance by reducing collisions amongst the M2M users and between H2H and M2M users. Therefore, the reduction in total collisions reduces the aggregated traffic, which improves the throughput performance, as established by the analytical model.

In addition, the paper has also introduced a new scheme that enables the eNB to automatically update the back-off frame size (BFZ) for H2H retransmission based on a threshold of RACH-access-blocking. This makes the scheme more practical and improves the performance, especially at lower traffic loads where fewer collisions occur and a lower BFZ value is required.

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