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A Survey of Random Access Control Techniques for Machine-to-Machine Communications in LTE/LTE-A Networks

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ABSTRACT Machine-to-machine (M2M) communications refer to the autonomous interaction between connected devices without the human intervention. Recently, the Third-Generation Partnership Project (3GPP) introduced the Long-Term Evolution (LTE) and Long-Term Evolution-Advanced (LTE-A) as the improved version of the fourth-generation (4G) cellular networks. LTE/LTE-A networks have been considered an appropriate infrastructure for implementing M2M communications. However, the LTE/LTE-A networks were originally introduced for human-to-human (H2H) communications which have different characteristics from M2M communications. Thus, the LTE/LTE-A networks must be adapted to support the special characteristics of M2M communications. This work provides a comprehensive review of M2M communications over LTE networks, including M2M architectures, LTE structure, deployment challenges, and access control requirements. Moreover, this work introduces a novel classification for the current Random Access (RA) techniques that have been proposed for M2M communications in LTE networks. According to the main targeted objective, the current RA techniques are classified into three categories: massive access control techniques, energy efficiency techniques, and performance improvement techniques. Each category is further divided into two subcategories, and the relevant RA techniques are presented for each category. Furthermore, an analytical comparison has been provided among the different techniques according to the parameters for each approach. This work can be considered a good starting point for those who are interested in RA techniques for M2M communications over LTE/LTE-A networks.

INDEX TERMS LTE/LTE-A Networks, machine-to-machine, massive access, random access control.

I. INTRODUCTION

The Internet of Things (IoT) is a recent paradigm that has received much attention in the last decade due to the growing interest in the use of autonomous computing. According to the Global Standards Initiative on Internet of Things (IoT-GSI), the IoT can be defined as the infrastructure of the information society. In the IoT, physical objects are connected to the existing network infrastructure to be sensed and controlled remotely through the network. These objects are embedded with sensors, actuators and software that facilitate the sensing and controlling process, as well as the network connection which allows data to be exchanged among the connected objects [1]. Such connectivity results in smart city improvements where all systems such as transportation, lightening, power and water are managed intelligently [2]. These capabilities will give rise to incredible developments in system efficiency and reliability. To support the IoT, machine-to-machine (M2M) communications are required because billions of devices will be connected to the Internet in the near future [3]. Therefore, it is very important for researchers to investigate and improve M2M communications because they formulate the foundation capacity for the IoT. The following section describes the fundamentals of M2M communications in detail.

II. M2M ARCHITECTURES

M2M refers to the connected devices that communicate and interact autonomously without human intervention [4].

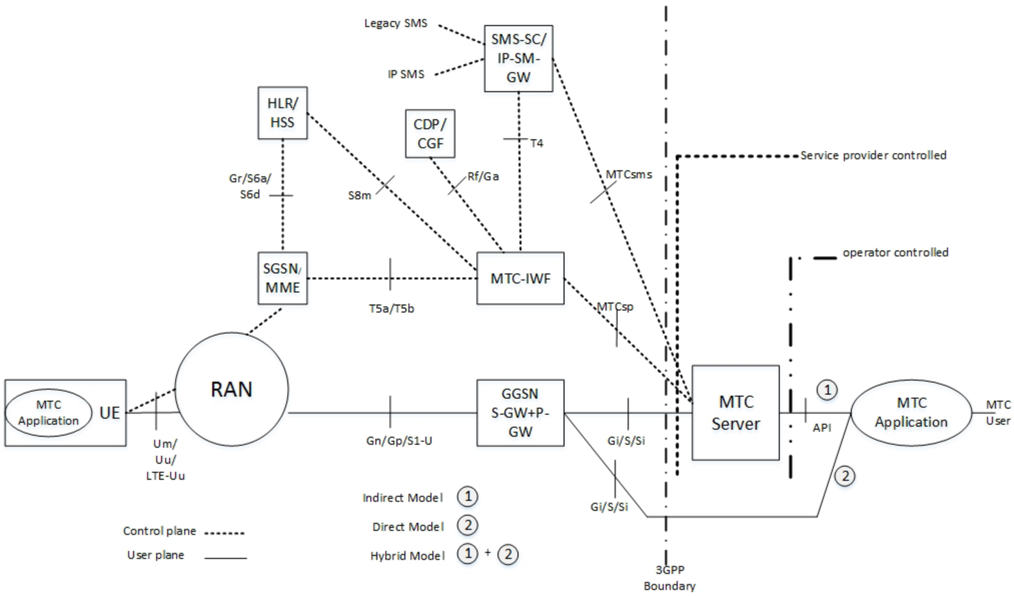

FIGURE 1. Reference Model for 3GPP MTC Architecture [9]. (©2012. 3GPP™ TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TSDSI, TTA and TTC who jointly own the copyright in them. They are subject to further modifications and are therefore provided to you "as is" for information purposes only. Further use is strictly prohibited.)

This autonomous style of communication requires M2M systems be self-deployed, self-managed, self-maintained and self-healed. M2M applications are involved in several systems such as intelligent transportation, e-health care, automated industry and remote controlling. Furthermore, M2M communications have different characteristics from human-to-human (H2H) communications [5]. For example, M2M involves a massive number of devices with lower mobility than H2H devices. Most M2M devices are battery operated which requires energy-efficient communication. Furthermore, in contrast to H2H, M2M communication traffic is higher in the uplink and lower in the downlink. Moreover, the traffic in M2M applications is mostly small and periodic which makes it more uniform than H2H traffic [6]. These unique characteristics of M2M communications have to be considered during the deployment of M2M systems.

To support the improvement of M2M systems, several standardization efforts have been released globally. Basically, two main reference architectures have been defined for M2M communications [7]. The first is defined by the Third-Generation Partnership Project (3GPP), known as 3GPP machine-type communication (MTC), and the other is defined by the European Telecommunications Standards Institute (ETSI), named ETSI M2M architecture. The 3GPP MTC architecture emphasizes the communications part while the ETSI M2M architecture focuses on applications and services [8]. The following subsections present each architecture in detail.

A. 3GPP MTC ARCHITECTURE

In Release 11, 3GPP introduced two main architecture models for communication between MTC applications and the 3GPP network [9]. The first is the direct model where the MTC application communicates directly with the user equipment (UE) through the 3GPP network as an over-the-top application. The second model is the indirect model in which the MTC application communicates with the UE using an MTC server.

To support end-to-end application, 3GPP provides transport and communication services to facilitate the communications between the MTC user equipment and the MTC application. The architectural reference model provided by 3GPP for MTC is shown in Fig. 1. This architecture covers the architectural models mentioned previously.

In Fig. 1, the UE is connected to the 3GPP network (UTRAN, E-UTRAN, GERAN or I-WLAN) via the Um/Uu/LTE-Uu interface. The MTC server entity is connected to the 3GPP network to communicate with the UE. The "MTC application" entities and the reference point API beyond the scope of the 3GPP. They are used only as abstracts to show the end-to-end view for MTC. Network elements are described in detail in the document for 3GPP Release 11 [9].

B. ETSI ARCHITECTURE

ETSI is a global organization that was established with the aim of producing global standards related to information and communication technologies (ICT) [10]. Most of these standards are conducted within the M2M technical committee (TC-M2M) which was established in 2009. ETSI defined a high-level architecture for M2M communication systems as shown in Fig. 2. This architecture includes two main domains: the device and gateway domain and the network domain [11].

The device and gateway domain contains the M2M device which runs M2M application(s) using M2M Service Capabilities. M2M devices are connected to the network domain in two ways; either a direct connection via the access

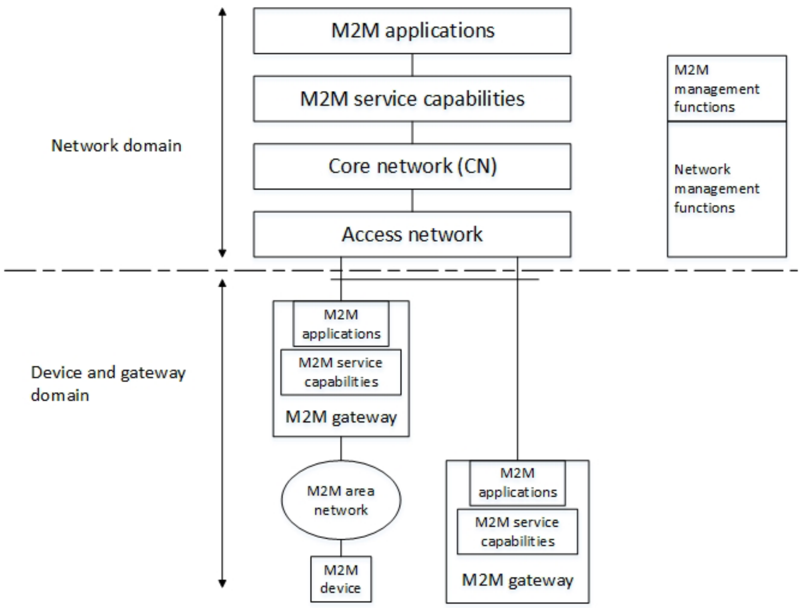

FIGURE 2. ETSI high-level architecture for M2M communications [11]. (©European Telecommunications Standards Institute 2013. Further use, modification, copy and/or distribution are strictly prohibited.)

network or a gateway that acts as a proxy for the network domain. The M2M area network provides connectivity between M2M devices and M2M gateways using personal or local area network technologies, such as Zigbee, Bluetooth and Wireless M-BUS [12]. The M2M Gateway runs M2M application(s) and performs procedures such as authorization, authentication, management and provisioning. The network domain contains the access network which includes satellite, UTRAN, W-LAN and WiMAX that allows the M2M devices and gateways to communicate with the core networks such as 3GPP core networks and the ETSI TISPAN core networks that provide connections to other networks. The core network is connected to the M2M service capabilities which provide M2M functions and simplify the development of the applications. M2M applications run the logical services and use the service capabilities that are accessible via an open interface. In addition to the connected components, the network domain contains network management functions which manage the core network, and M2M management functions that control the M2M service capabilities in the network domain. The ETSI architecture focuses on the service and application layer of M2M systems which is harmonious with the 3GPP MTC architecture that focuses on MTC communications.

III. LTE / LTE-A OVERVIEW

Long-Term Evolution (LTE) is a recent cellular network paradigm that was developed by 3GPP under the fourth-generation (4G) standardization. Starting from Release 8, 3GPP has defined the specifications for LTE networks that provide high peak data rates and efficient management for radio resource [13]. Fig. 3 shows the overall architecture of the LTE network which consists of the EU-TRAN and the core network.

The Evolved Node B (eNodeB) is the base station component of the LTE system which is responsible for providing physical and medium access control (MAC) layer services, such as radio resource management, access traffic control, packet scheduling and routing, message transmission, roaming, authentication, and handover. Multiple eNodeBs are connected using a high-speed X2 interface which facilitates communication among them. ENodeBs are connected to the core network through an S1 interface which allows the eNodeB to access the mobility management entity (MME) and the serving gateway (S-GW). The core network components facilitate the communication between the LTE system and the Internet.

LTE was recently developed to LTE-Advanced (LTE-A) which aims to provide higher data rates and spectral efficiency [15]. Carrier aggregation (CA) is one of the main new functionalities introduced in LTE-A in addition to the use of multiple input multiple output (MIMO) and relay node (RN) [16], [17]. Furthermore, the relay node allows efficient heterogeneous network planning by using a low power base station to enhance the coverage and capacity at the cell edges [18]. These capabilities allow LTE-A networks to be more efficient in terms of coverage, data rate and spectral efficiency which makes LTE-A networks a reasonable choice for M2M deployments.

In LTE, physical channels are used to transmit and receive data in the uplink and the downlink [19]. The most common physical channels in LTE are listed below:

- Random Access Channel (RACH): this channel is used by the user equipment to request access from eNodeB.

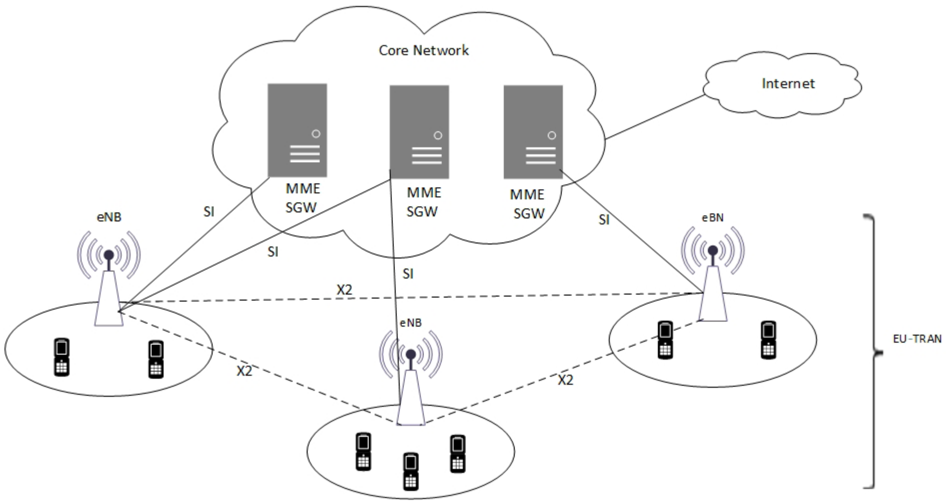

FIGURE 3. LTE overall architecture [14]. (©2018. 3GPP^{TM} TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TSDSI, TTA and TTC who jointly own the copyright in them. They are subject to further modifications and are therefore provided to you "as is" for information purposes only. Further use is strictly prohibited.)

- Downlink Shared Channel (DSCH): this channel is shared among different users and used to transmit their data.
- Downlink Control Channel (DCCH): this channel is used to transmit resource allocation information for the uplink and the downlink.
- Uplink Shared Channel (USCH): this channel is allocated by the uplink scheduler in eNodeB and used to transmit both control signal data and user data.
- Uplink Control Channel (UCCH): this channel is used by the user equipment to send control information, such as the channel quality indicator (CQI), to eNodeB.

A. RANDOM ACCESS (RA) PROCEDURE

When the user equipment is turned on for the first time, the equipment goes through a synchronisation process in which the equipment acquires the system information from a particular network operator under which the equipment subscribes [20]. After the synchronisation, the user equipment must go through a random access procedure to inform the eNodeB that the equipment requires the connection. Normally, the user equipment is required to perform the random access procedure for the following reasons [21]:

- To acquire the initial access to the network.
- To re-establish the connection after the failure of a radio link.
- To hand over from one eNodeB to another.
- To update the user equipment location.
- To make scheduling requests.

To support the previous situations, two forms of random access procedures are defined in LTE networks [22]:

1) Contention-based random access: in this form, the access process is triggered by users that compete to access the RACH. This form is more suitable for delay-tolerant applications due to the probability of collisions.
2) Contention-free random access: in which the access process is initiated by the eNodeB which allocates particular access resources to the users to allow them to transmit their access requests. This form is appropriate for delay-sensitive applications that require high success rates.

The focus of this work is the contention-based random access procedure which triggered by the user equipment and composed of four steps as shown in Fig. 4.

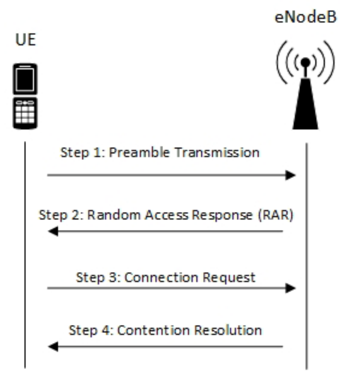

FIGURE 4. Random access procedure.

- Step 1: Random access preamble transmission: in this step, the user equipment transmits its access request to the eNodeB by randomly choosing one of the available orthogonal preambles in the next available random access slot. This preamble is used as a digital signature to define the temporary identity of the user equipment based on the time slot in which the preamble is transmitted [20]. To guarantee a successful transmission, each preamble must be used only by one user in a specific time slot.
- Step 2: Random access response: once eNodeB receives the preamble, the eNodeB sends the random-access

response (RAR) message to the user equipment which contains the identity of the detected preamble, the timing instructions, the uplink resource and the scheduling that will be used by the user equipment in step 3.

- Step 3: Connection request: in this step, the user equipment transmits its connection request message using the uplink resource guaranteed in step 2. This message contains the device identifier and the reason for the access request.
- Step 4: Contention resolution: in this step, eNodeB transmits a contention resolution message as a response to the previous message to the user equipment that guarantees access to the network. If the user equipment does not receive this message, it means that a collision occurred with another device which requires this user equipment to make a new access attempt.

IV. M2M COMMUNICATIONS OVER LTE/ LTE-A NETWORKS

Due to the extended coverage, mobility support and Quality of Service (QoS) guarantees, cellular networks are considered an adequate choice for M2M deployments [9]. LTE/ LTE-A networks are the most proper cellular networks that can be used for MTC due to their scalability, longevity, large capacity, low latency and spectral efficiency. For this reason, many deployments have been introduced for M2M communications over LTE networks. M2M systems are composed of three main domains: the device domain, the network domain and the application domain [10]. As shown in Fig. 5, the device domain contains M2M devices which perform sensing, actuating and data gathering. M2M devices communicate through personal networks. These devices are connected to the core network through an E-UTRAN network or an MTC gateway. The core network and the E-UTRAN network formulate the network domain which is connected to the M2M server in the application domain. The M2M server communicates directly with the MTC application user that could be a human or another M2M device performing system monitoring and management [23].

A. DEPLOYMENT CHALLENGES

Many challenges have to be considered to optimize LTE networks for M2M communications. These challenges are as follows [24]:

- LTE provides a higher data rate at the downlink (50 Mbps) and a lower data rate at the uplink (25 Mbps) which is not suitable for M2M that requires an increased data rate at the uplink.
- Allowing M2M communication in LTE networks creates an overhead problem that may affect the performance of H2H communications.
- Although M2M communications involve small data transmissions, congestion may occur in LTE due to the massive number of devices trying to access the network simultaneously.
- LTE transmissions and receiving consume more power which must be reduced for M2M communications to cope with limited-energy devices.

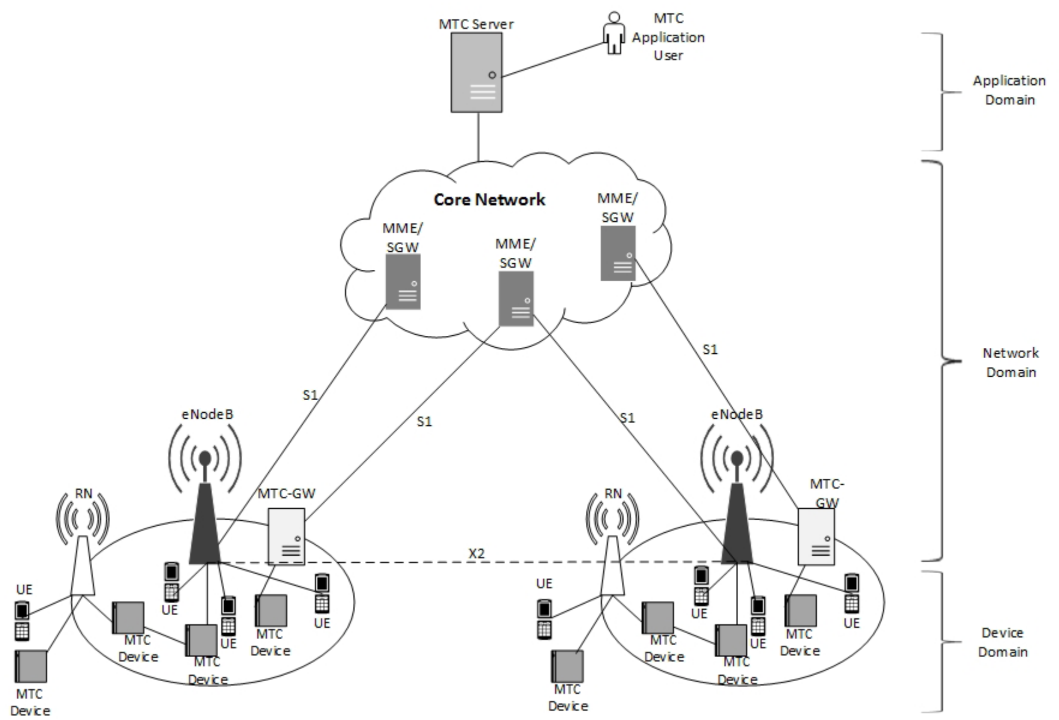

FIGURE 5. An example of LTE-based M2M system.

- Transmission protocols must be optimized to consume low power to extend the lifetime of battery.
- Interferences may occur in the communications lines of LTE due to M2M communications [25].

Thus, the LTE/LTE-A network must be adapted to accommodate the unique characteristics of M2M communications. For this reason, many cellular operators have introduced LTE-M as a prospective technology to optimize LTE for M2M communications [26]. LTE-M was first introduced in EXALTED as a novel paradigm that extends LTE specifications to support M2M communications in terms of extended coverage, lower cost, energy efficiency, enhanced security and the ability to support a massive number of devices [27]. However, this version of LTE-M does not support the use of a shared spectrum which may result in some degradations in system performance. A new standard was introduced recently by 3GPP for M2M communications called Narrowband (NB) LTE-M [28]. This technology supports stand-alone and shared spectrum systems in the normal LTE network while providing low power consumption, low latency, improved coverage and low cost. However, the performance of H2H communications should be considered during the integration of NB LTE-M in the normal LTE network to avoid any performance degradation caused by M2M communications.

B. ACCESS CONTROL REQUIREMENTS

A crucial part of LTE/LTE-A networks is the access control to the shared resources which normally carried out by the MAC layer of the base station, i.e., eNodeB. The critical responsibility of MAC layer protocols is to facilitate channel access for a large number of M2M devices. Therefore, the access control protocols and methods designed for M2M communications must consider some requirements [29] that can be summarized as follows:

- Normally, the M2M system involves a massive number of connected devices. Thus, scalability is one of the most important design concerns that must be supported by MAC protocols designed for M2M communications.
- Energy saving is another key consideration for MAC protocols designed for M2M systems. As most M2M devices are battery operated, it is important that all operations involved in M2M communications are optimized to consume low power which, in turn, improves the longevity of the battery lifetime.
- The designed protocol should achieve high throughput to cope with limited spectrum resources and a large number of devices.
- The network latency must be very low especially for critical, real-time applications, such as e-health care applications, where network connections must be reliable and fast.
- The designed protocol should allow the M2M access network to coexist with other networks without causing interference or collisions.
- Finally, the M2M MAC protocols should be designed to be operated on simple, low-cost devices.

By considering these design requirements, M2M systems will be more efficient and more reliable which results in improving the IoT a great deal. In addition to the requirements, 3GPP has defined four criteria for the access method designed for M2M to reduce the adverse effect of M2M devices on LTE networks [30]:

1) Deploying M2M on cellular networks must have the least impact on H2H communications.
2) Integration of M2M on LTE must be simple to achieve the minimum impact on the current cellular networks.
3) It is essential for the network to be able to predict the behaviour of M2M devices in the RAN for those applications where the delay is not the main concern.
4) The designed access control method should support the overload control in the core network.

V. CLASSIFICATION OF RANDOM ACCESS CONTROL TECHNIQUES

According to the literature, the contention-based random access control techniques for M2M in LTE networks can be classified based on their key objective into three main types. These types are massive access control techniques, energy efficiency techniques and performance improvement techniques (Fig. 6).

Each category is described in detail in the following subsections.

A. MASSIVE ACCESS CONTROL TECHNIQUES

The first challenge for M2M communications in LTE/LTE-A networks is the massive number of devices that are trying to access the network simultaneously [31]. Due to the limited spectrum resources, the massive number of devices causes an overload in the RACH that, in turn, decreases the overall performance of the M2M systems. Furthermore, overload in the RAN and the core network causes congestion, a waste of resources and QoS degradation and in the worst case, it may cause service unavailability [32]. Thus, massive access must be controlled efficiently to allow all M2M devices to access the network fairly. For this reason, many solutions have been proposed to control the massive access of M2M devices in LTE networks. The massive access control techniques can be further classified, based on their targeted objective, into two categories: congestion control techniques and collision resolution techniques.

1) CONGESTION CONTROL TECHNIQUES

The main cause of congestion in the RACH is the massive number of M2M devices that are trying to access the network simultaneously. As the current contention-based operation of RACH is based on ALOHA access [33], in which all devices are allowed to transmit their access requests at the first available opportunity, the congestion rate can be increased rapidly especially with the large number of M2M devices. 3GPP has considered this problem and introduced several solutions to

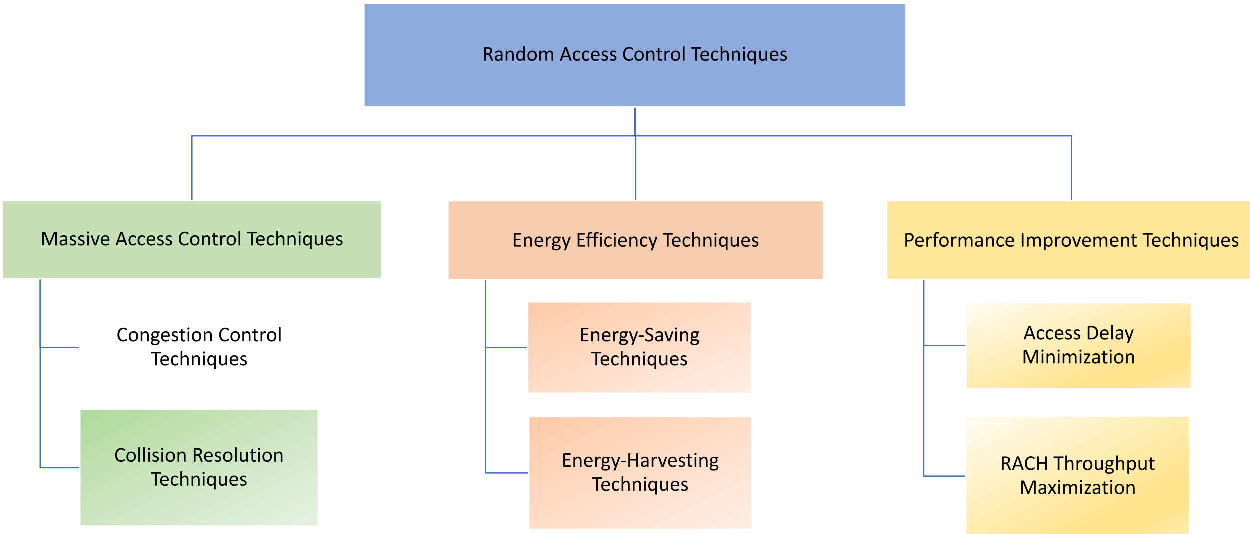

FIGURE 6. **Classification of random access control techniques for M2M in LTE/LTE-A.**

resolve congestion in the RACH. One of the well-known solutions introduced by 3GPP is the Access Class Barring (ACB) [34]. ACB controls the random access congestion by reducing the arrival rate of access requests. In this scheme, users are classified into several access classes. When a user wishes to access the network, it generates a random number between 0 and 1. This number is compared to the ACB factor broadcasted by the eNodeB. If the generated number is less than or equal to the ACB factor or named access probability parameter p, the user is allowed to access the network. Otherwise, the user is barred temporarily for a specific barring duration. The ACB technique has been studied and developed extensively, by 3GPP and other researchers, which results in different types of ACB [35]–[37].

To support massive M2M access, 3GPP has defined separate access classes for M2M devices. Individual ACB is also introduced by 3GPP where a group of M2M devices are classed together if they have the same QoS [38]. If the QoS is related to the delay, then the M2M devices can be classified into two classes: delay-sensitive devices and delay-tolerant devices [39]. QoS guarantees can be provided for different classes by the prioritized dynamic preallocation of the RACH resources. [40]. Considering the QoS requirements for each class of M2M devices is an essential concern that has been used to determine the allowable contending devices in each class which helps in reducing core network congestion while providing a reasonable QoS [41].

Another ACB approach is the extended ACB (EAB) where M2M devices with low priority are barred from accessing the network if the random access arrival rate is high [42]. Moreover, estimation-based adaptive ACB has been proposed to support M2M scalability [43]. In this scheme, the network load is estimated first. Then, two functions are used to obtain the relation between the ACB factor and the network load. According to the estimated load and the obtained functions, eNodeB changes the ACB factor dynamically to adapt to the network load. ACB factors can be optimized by estimating the total number of M2M devices competing in an RACH [33]. To estimate the total number of M2M devices, a probability distribution function (PDF) is derived from the number of preambles that are chosen by one or zero M2M devices. Moreover, the number of active devices can be estimated based on the number of idle preambles in each time slot [44]. The preambles status can be modeled using the 6D Markov chain model which results in a higher success rate and a shorter time delay [45]. The load estimation has been considered an efficient technique to allow the dynamic regulation of ACB factors which helps to cope with the changing load in M2M systems. Using the estimation method to optimize ACB factors could increase the system throughput and reduce the access delay which, in turn, supports the massive access of M2M devices a great deal.

Moreover, ACB has been improved to consider multiple classes of M2M devices [46]. In this approach, the ACB factor is not applied to all classes of M2M devices. Instead, different ACB factors are derived for different classes of M2M devices which efficiently improves the success probability and increases the radio resources utilization. The multiple-ACB technique has been extended to the adaptive multiple ACB where the ACB factors are changed according to the traffic indicator [47]. The network traffic in this approach is divided into three categories: high priority, medium priority and low priority. For each category, eNodeB estimates the traffic load and broadcasts the ACB factor to control the congestion in the next RACH slots.

In the same context, an overload control mechanism has been proposed based on the adaptive ACB [48]. This mechanism is activated and deactivated according to the value of the congestion coefficient. Once the mechanism is activated, the traffic load distribution is analyzed by mapping the current traffic curve with the traffic model curve. According to the analyzed traffic, eNodeB determines the optimal value of the ACB factor for the current traffic load to control the overload accordingly. Another adaptive ACB algorithm has been proposed to control the congestion for bursty M2M traffic in LTE networks [49]. In this algorithm, the random access preambles are allocated to M2M devices dynamically to achieve better utilization of random access resources. This dynamic ACB (D-ACB) algorithm is proposed based on the dynamic preamble allocation. D-ACB aims to determine ACB factors without prior knowledge of the system backlog. This algorithm reduces the average number of random access opportunities for M2M devices which, in turn, reduces the access congestion in the RACH. Another D-ACB has been proposed to dynamically adjust the ACB factor according to the estimated number of MTDs that are in the backoff state [50]. This algorithm outperforms the static ACB in decreasing the access delay and increasing the access success probability. Furthermore, the performance of ACB has been evaluated by many researchers. For example, an accurate analytical model has been introduced to evaluate the ACB approach in LTE-A networks [51]. This model provides accurate derivations with minimal errors for several performance indices, such as success probability, collision probability, access delay and the number of preamble transmissions. The performance of ACB has also been analyzed by implementing an accurate simulation model following the 3GPP standard specifications [52]. In this work, certain configurations have been modified which result in optimal performance in terms of access success probability. Moreover, ACB has been optimized in terms of throughput under the assumption that the arrival traffic follows the Poisson distribution [53]. In this model, the throughput is defined as the number of access requests that have been transmitted successfully. This analytical model has been validated with extensive simulations that show the accuracy of the proposed model. In addition, the reliability of the RACH with ACB has been analyzed under the bursty traffic [54]. In this work, they obtain the probabilistic burst resolution time which is required by the burst MTDs to connect to eNodeB. This model can be used to assist the RACH performance for end-to-end systems. However, the ACB approach must be optimized in terms of the access delay to achieve better QoS guarantees, especially for delay-sensitive devices.

Slotted access is another mechanism proposed by 3GPP to control RACH congestion [55]. In this scheme, an M2M device is allowed to make the access request in a specific time slot in each access cycle. The access cycle contains a set of L consecutive access slots that are repeated periodically. Each access slot is allocated to a specific number of devices that belong to the same class C. These devices can find their access slots by using the system frame numbers (SFNs) which are used to identify the access slots. Thus, an M2M device from class C is allowed to send its access request in the access slot with $SFN = s$, if $C \bmod L = s$. More than one device can be served in each slot because each slot contains several resource blocks. However, the random allocation of access slots to devices may reduce the performance of this scheme, while the pre-allocation of resources can increase the system efficiency up to three times [30]. Furthermore, slotted access has been developed by several researchers. For example, multi-channel slotted ALOHA-optimal estimation (MCSA-OE) is proposed to control the access congestion in the RAN [56]. In this mechanism, the number of arrivals is estimated in each random access slot, and then the estimated number is used to optimize the access slot allocations. This approach achieves higher success probability under a high traffic load. In general, slotted access achieves better access success rates especially with the bursty traffic which means a better control for RACH overload.

Grouping M2M devices into clusters is another technique that has been suggested to control RACH congestions. In this technique, M2M devices are grouped according to their functionality or their geographic locations into clusters. Each cluster has a head node which acts as an intermediate interface between the cluster devices and eNodeB. Thus, instead of allowing M2M devices to communicate directly with eNodeB, the cluster head conducts the communication between M2M devices and the eNodeB which, in turn, allows the cluster head to control the access rate to the eNodeB [21]. A grouping-based method has been proposed to avoid congestion in LTE networks [57]. In this method, M2M devices in dense areas are grouped together. Each group contains a set of M2M devices with a leader device that is determined by the designed selection algorithm based on the communication capability. All devices in the group are allowed to send and receive information to eNodeB through the leader device only. The leader device is also responsible for aggregating the uplink traffic in its own buffer and then transfers the messages in an efficient format to eNodeB. In addition, the leader device broadcasts the information sent by the MTC server to all devices in the group. The simulation results show that this method reduces the RACH overload a great deal.

Another group-based massive access management (MAM) approach has been proposed to provide QoS guarantees for M2M communications [58]. In this approach, M2M devices are grouped into M clusters according to the QoS requirements which means that M2M devices in the same cluster have the same QoS characteristic. The main QoS metric adopted in this scheme is jitter which is defined by the difference between the departure rate and the arrival rate. Jitter is the most appropriate metric for capturing the timing performance for periodic traffic because jitter reflects the congestion rates in real-time communications. After clustering M2M devices, eNodeB must reserve the required resource blocks for each cluster to ensure the QoS guarantees for each M2M device. The experimental results indicate that this approach can provide access for a massive number of M2M devices with the required QoS guarantees. Furthermore, a coordinated random access control approach is proposed to handle the signalling process in a group of M2M devices [59]. This scheme is composed of three main parts. First, a set of

M2M devices with similar behaviour are grouped together, and the group representative is selected according to some advantages, such as the radio link quality and the device capacity. Then, eNodeB checks all signalling messages to inhibit the redundant messages. After that, radio resources are allocated for various message transmissions. Simulation results show that the grouping method increases the random access success probability which, in turn, reduces the congestion in the RACH.

In addition to the well-known solutions, several methods for controlling RACH congestion have been suggested. Dynamic RACH partition is one of the proposed methods for controlling the RACH overload for differentiated M2M services [60]. In this scheme, two types of services are considered: delay-sensitive and delay-tolerant services, which means that M2M devices are clustered into two groups. The RACH resources are then dynamically partitioned and allocated to each cluster of M2M devices. Among each cluster, the ACB mechanism is adopted to control the access to the network. The simulation results show that this scheme improves the system performance in terms of access success probability and access success delay.

Scattering the intensity of the access requests among different eNodeBs is another scheme that has been proposed to reduce the congestion in RANs [61]. This method aims to balance the random access intensity among different eNodeBs by scattering the M2M devices that are always trying to access the same base station. Scattering is achieved by the proposed selection algorithms in which eNodeB is selected to be attached to M2M devices according to the estimated random access intensity. The results show that this method improves the access success rate and reduces the access delay which, in turn, controls the congestion for massive differentiated M2M services.

A proactive access control technique is proposed for M2M devices in LTE networks with reliability guarantees [62]. The access procedure in this technique is divided into two phases. The first phase is the estimation phase in which the number of arrivals is estimated. The second phase is the serving phase in which the number of allocated resources is determined based on the estimation phase information. These resources are reserved for M2M devices to provide high-reliability guarantees. The proposed scheme is evaluated based on two types of traffic, and the results show that this method improves the RACH reliability which, in turn, supports massive access for M2M devices in LTE networks.

Virtual frame is another technique that has been introduced to control the overload of M2M access requests in the RACH [63]. In this technique, the random access time slots are grouped to form the virtual frame. M2M devices are allowed to transmit their access request at the end of each frame by sending a codeword to eNodeB. Using codewords instead of preambles expands the random access resources which results in improving the system efficiency in massive access situations. The main challenge in this technique is how to adjust the virtual-frame length according to the network load. To overcome this challenge, an online load estimation approach has been proposed to adjust the virtual-frame length based on the expected traffic load [64]. In this approach, eNodeB uses the proposed online load estimator to estimate the traffic load based on the network traffic of the previous virtual frames. This estimation process is accomplished at the end of each virtual frame to determine the length of the following virtual frame. This process allows the system to adapt dynamically to the differentiated traffic load especially under massive access traffic which, in turn, improves the RACH efficiency in controlling the access congestions.

Moreover, an adaptive RACH congestion management algorithm has been proposed to support the massive access of M2M devices in LTE networks [65]. The main objective of this algorithm is to determine the most suitable RACH control technique among different techniques according to the congestion level of the RACH. The RACH congestion level in this scheme is divided into three categories: no or less congestion scenario, moderate congestion scenario and extreme congestion scenario. For each scenario, the performance of different RACH congestion control techniques is estimated, and the technique with the best performance is chosen. The simulation results show that this method improves the RACH performance more than any single congestion control technique in terms of access success and access delay. Although these techniques perform well in controlling the massive access congestion of the RACH, this field still must be extended to consider various aspects, such as critical M2M applications which require a high-reliability RACH with low or no access congestion for massive M2M communications.

2) COLLISION RESOLUTION TECHNIQUES

The first step in random access procedure involves the transmission of a preamble that must be unique by each M2M device in a particular random access slot. For each random access slot, only 54 preambles are specified for random access procedure. When an M2M device requires access to the RACH, the device randomly selects one of the available preambles and transmits it in the first available random access slot. A collision occurs if two devices select the same preamble in the same random access slot. This is because the preamble is used by eNodeB to identify the device that has sent the access request. Thus, in the case of a collision, eNodeB will be not able to distinguish between the two devices that use the same preamble. However, both devices will receive the RAR message in the second step of the random access procedure which means that the same uplink resource is allocated to both devices. A collision is detected during the third step of RA procedure when both devices attempt to use the same uplink resource which causes the random access procedure to fail. In this case, both devices need to re-transmit a new access request until the device gets successful access.

The collision problem considered a very critical problem especially for delay-sensitive applications when the M2M device requires a reliable and fast RACH. This problem becomes more complicated with the massive number of M2M devices trying to access the network simultaneously which increases the collision probability a great deal. For this reason, many solutions have been proposed to address preamble collisions in the RACH. 3GPP introduced a MTC-specific backoff scheme to solve collisions in the RACH [66]. In this scheme, M2M devices that failed in their first access attempt are blocked from accessing the network for a specific time duration called the backoff interval. If an M2M device fails to get access for the second time, due to a collision, the device will be blocked for a longer backoff interval than the first time. Although this scheme solves the collisions in the RACH, it may increase the access delay and the access attempts because this scheme solves the collision after it has occurred.

A separate backoff scheme was proposed by 3GPP to prevent excessive delays for delay-sensitive applications [67]. In this method, machine devices are divided into two classes: The first class contains H2H devices with delay-sensitive M2M devices, and the second class contains delay-insensitive M2M devices. In the case of a collision, devices in the second class are blocked for a longer backoff interval than the devices in the first class which means that access priority is given to the first class of devices. The simulation results for this scheme show that it effectively reduces the access delay for delay-sensitive M2M devices.

Carrier sense multiple access (CSMA) is another mechanism that has been proposed to reduce the collisions caused by ALOHA-based communications [68]. However, this mechanism causes throughput degradation due to hidden terminal problems [29]. For this reason, CSMA is extended to the CSMA with collision avoidance (CSMA/CA) which is used by the IEEE 802.11 protocol [69]. This mechanism allows two devices to communicate without the central control node (eNodeB) using the physical infrastructure. The device that attempts to transmit a frame must listen first to the medium and transmit its data only if the medium is idle. Thus, no collision occurs which increases the access success and reduces the access delay. However, the performance of this mechanism is degraded by the massive number of M2M devices.

To solve the RACH collisions for massive M2M devices, efficient access with collision resolution mechanism has been proposed [70]. This mechanism is activated upon the detection of RACH overload and uses the basic concepts of LTE preambles. The main idea of this technique is to use the q-ary tree splitting algorithm to define a set of preambles to be used by the conflicting devices. In the case of a collision, which normally is detected in the third step of the random access procedure, eNodeB informs the colliding device about the collision and determines the details for the next access attempt. Precisely, eNodeB informs this device about a set of preambles that can be used for the second access attempt. The simulation results indicate that this mechanism provides a reliable service for a massive number of M2M devices by reducing the RACH collisions.

Preamble grouping based on distributed queuing is another solution that has been proposed to resolve RACH collisions [71]. Distributed queuing is an efficient algorithm that has been used to resolve contention because this algorithm reduces the average access delay even for massive access arrivals. In the case of a collision, the collided preambles are divided into several groups with a particular size. The devices that use the preambles of the same group are queued together for the next preamble transmission. Thus, for each group of collided preambles, there is a corresponding queue of M2M devices. The splitting concept of the collided M2M devices results in lower collision probability and a higher success rate. However, an over-division problem may occur when the number of collisions is large. To overcome this issue, a novel distributed queuing-based access protocol has been proposed [72]. In this protocol, a load estimation strategy is used to control the number of groups. The unsuccessful MTDs are divided randomly into a number of groups based on the output of the estimation strategy. These groups then are pushed to the end of the logical access queue to try another access attempt. This protocol has decreased the average access delay for massive simultaneous arrivals compared to the normal distributed queuing access and the ACB protocol.

Moreover, distributed queuing algorithm has been used together with MIMO functionality to design an efficient random access and data transmission system [73]. This system contains two main parts: collision resolution and data transmission. A distributed queuing-based algorithm is used to solve preamble collisions while the MIMO technique is utilised to transmit data efficiently. The frame structure of this system is composed of four segments; access request, access feedback, data transmission and data feedback. When an M2M device attempts to access the network, the device randomly selects one of the access request slots to send a preamble to eNodeB which then responds by sending a feedback message using the corresponding access feedback slot. The feedback message indicates the status of the access request slot which can be one of three: "I" (idle) if no preamble is detected, "S" (success) if the preamble is successfully detected or "C" (collision) if multiple devices are using the same access request preamble. The collided device then has to move to the tail of the random-access queue together with its competitor before they can start a new access request attempt, and the successful devices are moved to the data transmission queue to wait for packet transmission. The analytical results show that this scheme efficiently improves the system performance in terms of throughput and average delay. Furthermore, the distributed queuing performance has been analysed using a low-complexity analytical model [74]. This model aims to estimate the access delay and preamble transmissions for distributed queuing-based random access. The numerical results of the proposed model accurately matched the simulation results which validates the correctness of this model. However, other performance metrics such as energy consumption and RACH throughput should be analysed for the proposed model.

In addition to the solutions that are presented to solve RACH collisions, several methods for avoiding collisions have been proposed. The virtual preambles mechanism is one of the most efficient solutions that have been proposed to support massive access for low-cost MTC (LC-MTC) [75]. The idea behind virtual preambles is to increase the number of available preambles in the RACH which, in turn, increases the opportunity for massive M2M devices to choose a unique preamble without collisions with other devices. Virtual preambles are created by combining the existing preambles with the RACH indexes that are used to transmit preambles. Each M2M device determines its identifier according to the selected preamble together with the RACH index which allows eNodeB to distinguish between M2M devices even if they use the same preamble. The analytical and simulation results demonstrate that this scheme efficiently reduces the collision probability and access delay for LC-MTC while increasing the successful access rate.

Separate resource allocation is another technique that has been proposed for avoiding RACH collisions [76]. In this scheme, preambles are separated between H2H devices and M2M devices to avoid the complexity of the four steps of the random access procedure. The proposed scheme eliminates the unnecessary messages in the second and fourth steps of the random access procedure to reduce the congestion in the RACH. Moreover, this scheme uses an efficient CSMA/CA MAC protocol which is more suitable for M2M characteristics. The analysis results show that this method increases the probability of success access for M2M and H2H devices while reducing the interference between them.

Furthermore, an auction-based random access technique has been introduced for efficient control of preamble transmissions [77]. This scheme is composed of two stages. The first stage is the RACH attempt estimation which is used to estimate the number of M2M devices that are trying to access the network. The second stage is the auction-based preamble transmission control which aims to balance the traffic load among different periods according to the results obtained from the estimation stage. The auction stage uses two payment methods: One is paid by each M2M application, and the other is paid by M2M users for preamble transmission. Simulation results show that this method efficiently controls the preamble transmission which, in turn, reduces the collision rate in RACH.

A hybrid random access protocol for RACH collisions is proposed to utilize the advantages of collision resolution and collision avoidance techniques [78]. In this protocol, the collision avoidance techniques such as backoff are combined with the tree-based collision resolution technique. Specifically, the collision avoidance technique is implemented first to solve the load estimation problem. After the collision avoidance, the tree resolution method is used to process the access requests on a given number of preambles. This hybrid technique ensures efficient random access with a high reliable RACH. The simulation results indicate that this approach improves the RACH performance in terms of throughput and delay. However, the hybrid random access protocols need to be investigated and improved by researchers to achieve a reliable RACH with fewer or no collisions for massive M2M devices.

B. ENERGY EFFICIENCY TECHNIQUES

Energy consumption is considered one of the critical issues for M2M communication because most M2M devices are battery operated with no recharging ability. Thus, increasing battery lifetime is a significant concern that must be considered throughout the design process of M2M systems. This objective could be achieved by reducing the communication overhead and signalling which is the main cause that consumes battery lifetime [79]. To overcome this matter, several solutions have been proposed to reduce energy consumption for M2M devices during the random access procedure and the data transmission process. However, there is a lack of studies that investigate the performance of the RACH from the energy efficiency perspective. This section classifies the current random access techniques from the energy perspective into two categories: energy-saving techniques and energy-harvesting techniques.

1) ENERGY-SAVING TECHNIQUES

The performance of the LTE RACH has been investigated in terms of energy efficiency to understand how the random access procedure affects energy consumption in M2M devices [22]. This work modelled the RACH with a different configuration index based on the FDD mode and ALOHA-type access using an NS-3 simulator with more than 1,000 M2M devices accessing the network simultaneously. For energy efficiency, if an M2M device reaches the maximum number of access attempts, i.e., preamble transmissions, the device is blocked by eNodeB immediately. The simulation results show that as the number of simultaneous arrivals increases, the energy consumed by the RACH increases as well. It is also shown that the RACH with different random access slots per frame tends to a common limit even if the number of simultaneous arrivals is increased. This is because the number of maximum preamble transmissions is limited which results in a better control of energy consumption for M2M devices. Moreover, as the value of the maximum preamble transmissions is increased, the energy consumption is increased as well. Thus, with fewer maximum transmission attempts, M2M devices consume less energy compared with the higher number of maximum transmission attempts.

Similarly, the performance of the standard random access procedure is investigated under the massive arrivals from an energy point of view [80]. This study aims to quantify the RACH limitations in terms of energy consumption and access delay to determine whether the standard random access is suitable for M2M communications or not. The authors developed a new module to simulate the random access procedure in LTE using NS-3 with 30,000 M2M devices. A limited time beta distribution is used to simulate the arrivals traffic. Results show that the standard RA procedure is not able to handle the access requests from thousands of M2M devices in time-constrained applications. Moreover, developing the random access procedure by increasing the number of preamble retransmissions will increase the energy consumption as well which is a non-preferable choice for M2M. Thus, the random access procedure must be improved to support energy saving for M2M devices. Furthermore, an analytical model for M2M communications has been introduced to evaluate the energy consumption for M2M devices during the random access procedure and data transmission process [81]. In this study, transmission time T_t is used as an indicator to identify the overall power consumption and defined as follows:

$$T_t = T_p + T_d + T_m, \tag{1}$$

where T_p, T_d, T_m, are the time required to transmit the preamble, control data and message, respectively. To evaluate the RACH performance for M2M devices in LTE, energy per bit has been calculated according to the following equation [81]:

$$E_b = \frac{P \cdot T_t}{N_b} \cdot L, \tag{2}$$

where P is the transmission power, T_t is the overall transmission time, L is the path loss and N_b is the number of payload bits. The energy consumption of LTE-based transmissions is then compared to an ideal transmission system. The numerical results show that the LTE M2M system requires almost ten times more energy than the ideal system. Thus, the random access procedure must be developed concerning energy efficiency to be adapted with the energy constraints of M2M devices.

Another analytical model has been proposed to evaluate the RACH performance under the disjoint allocation method in which the available preambles are divided into two separate groups: one for M2M devices, and one for H2H devices [82]. Then, a joint allocation method is proposed in which H2H devices are allowed to access the preambles set of M2M devices. In this model, it is assumed that the H2H random access arrivals follow the Poisson distribution while the M2M arrivals follow the beta distribution. Based on the previous assumptions, analytical expressions are derived and presented for collision probability, access success probability, idle probability and throughput. Then, the energy consumption is evaluated for both schemes. The simulation results demonstrate that the new joint allocation method can improve the energy savings of M2M devices up to 4%.

To improve the energy efficiency in the RACH, a dynamic backoff random access technique has been proposed for M2M devices in LTE networks [83]. In this scheme, the backoff time division between M2M devices and H2H devices is modelled as a bankruptcy problem. Then, two solutions are provided for this problem. The first one is a game theory framework in which the bankruptcy problem is formulated as a transferable utility game. The second solution uses an axiomatic strategy in which some characteristics are persistent during the decision of which amount should be received by each player in the bankruptcy problem. The simulation results illustrate that these methods improve the energy efficiency of M2M devices and controls the impact of M2M devices on H2H devices in LTE networks.

Several solutions have been introduced as alternatives to the random access procedure with the objective of energy saving for M2M devices. Grouping M2M devices into clusters is one of the solutions that has been used to improve energy efficiency in M2M communications [84]. In this approach, M2M devices communicate with the group representative instead of communicating directly with the base station. This style of communication increases the network lifetime, as well as the lifetime of the battery. To support group management policies, cooperative communications are introduced to achieve persistent transmission rates in low power-networks [85]. A multi-radio cooperative retransmission approach has been proposed to support multi-casting in M2M communication [86]. This scheme aims to reduce control signalling which, in turn, improves energy efficiency by carrying out all the retransmissions upon collisions in the main cellular link, therefore, reducing the traffic load on the main link and improving energy saving for M2M devices. The simulation results demonstrate that the cooperative retransmission scheme efficiently reduces the energy consumption for M2M devices compared to non-cooperative transmission techniques.

Data aggregation is a well-known method that has been used to improve the energy efficiency of M2M devices in cellular networks [85] [87]. Instead of being transmitted to the base station directly, the data is aggregated in an M2M gateway which is operated as a local supervisor that receives the collected data from M2M devices and then forwards this data to the base station. The data aggregation could be implemented in different deployments, such as the line- and grid-based models that achieve a significant improvement in reducing energy consumption for M2M devices [88]. The analytical and simulation results show that a major decrement in energy consumption is observed when M2M devices use the data aggregation mechanism.

2) ENERGY-HARVESTING TECHNIQUES

Energy-harvesting is an efficient technique that has been introduced to improve the energy efficiency of cellular networks. This technique aims to provide unlimited and green energy for M2M devices by using renewable energy resources, such as solar, thermal and wind. However, harvesting energy requires some time to be performed which, in turn, increases the transmission time. For this reason, several works have been conducted to balance the trade-off between energy-harvesting and the data transmission rate. For example, an adaptive MAC protocol has been introduced to support energy-harvesting for M2M devices efficiently [89]. Moreover, the energy-harvesting technique has been used together with the relay technique to support cooperative transmissions and to improve energy efficiency for M2M devices [90]. The relay is a low-power base station used to extend the coverage of the main base station, i.e., eNodeB. This technique is also being used to improve the RACH efficiency for energy-constrained M2M devices by uniformly installing a small number of relays in each cell [91]. Thus, M2M devices communicate with the relay node instead of communicating directly with eNodeB which helps reduce access congestion and collisions in the base station which, in turn, reduces the energy consumption of M2M devices.

Energy harvesting of uplink communications in cellular networks has been studied for different random access techniques [92]. In this study, the authors investigate pull-based and push-based random access techniques in terms of energy consumption, collision probability, throughput and packet delay. They found that the energy control technique in push-based schemes is not enough as the number of M2M devices increases. However, there is no scheduling cost for push-based random access techniques.

Furthermore, the authors found that pull-based schemes are more reliable in terms of throughput and energy efficiency but with an increasing scheduling cost and delay. For this reason, they proposed a hybrid random access scheme to avoid the high collision probability in push-based schemes and the extensive delay in pull-based schemes [92]. According to the proposed hybrid scheme, eNodeB first estimates the expected number of M2M devices that are ready to send their access requests. Then, according to the estimated number of devices, eNodeB calculates the RACH resources required for the push-based random access process. If the number of resources consumed by the push-based scheme is smaller than the resources consumed by the pull-based scheme, eNodeB applies push-based random access. Otherwise, it applies the pull-based random access process. The results show that the hybrid random access scheme performs better than using a single push-based or pull-based scheme in terms of delay and energy consumption. Although all these techniques perform well in saving energy for M2M devices, this field must still receive significant attention from researchers to improve the random access techniques from an energy perspective.

C. PERFORMANCE IMPROVEMENT TECHNIQUES

The overall performance of M2M systems is affected by the random access technique [93]. If the RACH is not efficient enough to handle the congestion and collision situations, then the performance of the M2M systems will degrade which may result in unforeseen problems. Thus, it is significant to adopt efficient random access techniques that increase the overall performance of M2M systems. For this reason, several techniques have been suggested to improve the performance of the RACH. In this work, we classify these techniques according to the targeted metric into two categories: access delay minimization techniques and throughput maximization techniques. The following subsections discuss the proposed solutions for both techniques.

1) ACCESS DELAY MINIMIZATION

Access delay refers to the time required for an M2M device to complete the random access process successfully. To minimize the average access delay for M2M devices, it is significant to avoid RACH congestion and collisions that are considered the two main causes that increase the access delay. Several improvements have been composed to enhance the RACH performance with the objective of reducing the average access delay for M2M devices. For example, a simplified random access procedure is proposed to reduce access delay in the RACH by using stable random access attempts [94]. This scheme aims to distribute the RACH traffic using multichannel slotted ALOHA. By using the stable RA attempts, the authors prove that the number of access attempts follows the truncated geometric distribution. The numerical results show that the access delay is decreased as the number of available preambles increases. However, the packet loss ratio must be considered due to the trade-off between the access delay and the packet loss ratio.

A dynamic ACB approach has been proposed to efficiently reduce the access delay in the RACH [95]. This work provides an analytical model to estimate the total access delay for all M2M devices. This estimation is used to determine the optimal value of the ACB factor for the ideal case. However, it is not easy to estimate the total access delay for practical scenarios. For this reason, the authors proposed a heuristic algorithm to adapt the ACB factor without knowledge of the backlogged users. The simulation results demonstrate that this algorithm is nearly optimal in minimizing the access delay.

The dynamic allocation of RACH resources is an efficient method for reducing the access delay by reducing the overload and congestion in the RACH. In this scheme, the resources are dynamically allocated to M2M devices and H2H devices according to the state of the traffic load. This method makes the resource allocation process smoother and improves the resource utilization [21]. The dynamic resource allocation becomes more efficient when it is used with a clustering scheme [96]. In this approach, M2M devices are divided according to their delay requirements into two clusters: delay-sensitive and delay-tolerant. Then, the available number of preambles is divided between the two clusters under the condition of guaranteeing the maximum number of successful devices. After that, the devices in each cluster apply the ACB mechanism to access the RACH. The simulation results indicate that the dynamic allocation of RACH resources is efficient in improving the access success which, in turn, reduces the access delay as well.

Using signature instead of preambles for an access request is an efficient solution for reducing the average access delay. The signature could be constructed using the Bloom filtering algorithm [97]. The signature is more efficient than the preamble as the signature contains information about the device identity and the cause of the access establishment. By using the signature mechanism, the random procedure is simplified to contain only two steps instead of four steps.

The RAR message and the connection request message are eliminated as the signature provides the functionality of these two steps. The simulation results show that signature-based random access is more efficient in reducing access delay compared with preamble-based random access and the code expanded scheme.

Access delay can also be reduced by controlling the arrival rate in the RACH [98]. In this method, the number of active M2M devices is divided into multiple intervals according to the derived boundary of the traffic load. The RACH resources are allocated to different M2M devices according to the resources that are allocated to each interval. In addition, the arrival rate is controlled using access barring to reduce the access delay. The numerical results show that this improved random access procedure reduces the access delay efficiently compared with hybrid schemes.

However, with the rapid increase in M2M devices, it is significant to improve the massive access control techniques to keep reducing access delay, especially for delay-sensitive applications where access delay is a critical parameter to achieve reliable systems.

2) RACH THROUGHPUT MAXIMIZATION

The throughput of the RACH can be defined as the number of successful preambles in a particular random access slot [99]. The number of successful preambles is affected by the performance of the chosen random access technique. Thus, it is essential to design an efficient random access technique in terms of throughput maximization especially for critical M2M systems that require high success rates. For this reason, numerous solutions to increase the RACH throughput have been proposed. The cooperative communications technique is one of the most efficient solutions that aims to increase the throughput in wireless networks [100]. The idea behind cooperative communications is to allow multiple base stations to cooperate to reduce the congestion in a given area of cellular networks. This idea has been used to control RACH congestion by using cooperative access class barring (CACB) [36]. In this scheme, multiple eNodeBs cooperate with each other to obtain a set of ACB factors to reduce the congestion in the RACH for M2M devices. However, this scheme has been improved to the cooperative ACB with load balancing (CACB-LB) [101]. In this scheme, M2M devices are allocated to a specific eNodeB according to the criterion of the percentage of devices that can access only one eNodeB among two adjacent eNodeBs. The simulation results show that the CACB-LB achieved 20% higher throughput than the CACB scheme. Furthermore, to ensure load balancing for the RACH, an auction-based RA mechanism has been proposed [77]. This scheme aims to control preamble transmission in multiple time slots using a two-stage scheme. In the first stage, an auction-based method is used to balance and allocate RACH preambles for multiple periods. To control the preamble transmission rate, an estimation method is used in the second stage to determine the maximum number of the allowed RACH attempts. It is demonstrated with numerical results that this scheme increases the RACH throughput a great deal and supports the massive random access request transmitted by different M2M applications.

A dynamic backoff random access scheme has been proposed to improve the RACH throughput under various traffic loads [102]. If an M2M device fails in the first access attempts, it performs preamble retransmission after a backoff period with a random window size chosen from $0, 1, \ldots, W$, where W is the backoff indicator that is dynamically changed according to the RACH overload status. Precisely, the eNodeB first must estimate the number of M2M devices that attempt to send access requests and then determine the window size accordingly. By using this method, the RACH throughput is improved without the need to determine the optimal value of W. The analytical and simulation results show that the dynamic backoff random access technique increases the RACH throughput up to 98% of the RACH capacity.

Q-learning-based random access is another scheme that has been used to improve RACH throughput [103]. In this approach, a frame ALOHA with Q-learning is proposed to eliminate RACH collisions between M2M devices and H2H devices. Separate frames are allocated to each group of devices to allow them to access eNodeB without sharing the frames. The simulation results show that this scheme achieves 100% of performance in terms of throughput compared to the slotted-ALOHA scheme. This is due to the use of the designed separate frames which eliminate collisions between M2M and H2H devices by 100%. However, this scheme does not consider the massive simultaneous arrivals which require higher RACH capacity to avoid throughput degradations.

Moreover, the coded random access technique has been used to increase RACH throughput [104]. This mechanism was originally proposed to improve the performance of slotted-ALOHA [105]. In coded random access, M2M devices are classified into multiple classes according to their channel conditions with the same packet length. If an M2M device wishes to access the channel, the device randomly selects a slot to start transmitting a packet. This packet is duplicated and transmitted over N slots. If eNodeB has successfully received, then the device ID can be derived, and the position of the other copy can be extracted. Thus, the collisions among different devices are resolved, and the RACH throughput is improved. The simulation results demonstrate that the coded random access has achieved higher throughput compared to the slotted-ALOHA technique.

Furthermore, the RACH throughput is affected by the number of preambles that are allocated for the random access procedure. Thus, the number of allocated preambles must be changed dynamically to adapt to different traffic load scenarios. For this reason, an adaptive approach has been suggested to determine the number of preambles required to maximize the RACH throughput [106]. This scheme adopts the fast retrial mechanism for preamble retransmission in the case of collisions. The number of required preambles is determined according to the estimated number of active devices which is derived from the number of collided preambles. Thus, it is possible to maximize the RACH throughput by dynamically changing the number of allocated preambles without prior knowledge about the total number of devices. The simulation experiments show that this scheme achieves the maximum average throughput with different access probabilities.

Early detection of collisions is another approach that has been used to improve the RACH throughput [107]. In this approach, the eNodeB detects preamble collisions in the first message of the random access procedure. The eNodeB then informs the collided devices to retransmit a new access request after adjusting their access probability to grant successful access. This approach has improved the throughput of the RACH especially with massive access requests. The RACH throughput has a direct impact on the overall network throughput. This issue has been studied by [108]. In this work, they proposed a new double-queue model: One queue is for the random access procedure, and the other is for data transmission. The RACH throughput is optimized by tuning the ACB factor and the backoff time based on the arrival traffic rate and the number of MTDs. The results show that the network throughput remains high only if the ACB parameters are optimally tuned. This model can be considered an efficient network design for massive M2M communications. However, it must be analyzed considering the access delay and QoS requirements.

Although these solutions have increased the RACH throughput, there is a demand to improve such methods that consider the coexistence of H2H devices and heterogeneous M2M devices with different QoS requirements.

VI. COMPARATIVE ANALYSIS AND FUTURE DIRECTIONS

This work provides a comprehensive review of the current random access techniques according to the proposed classification. In this section, the performance of these techniques is analyzed and compared according to the results provided in each work.

A. COMPARATIVE ANALYSIS

According to the proposed classification, the essential random access schemes are summarized for each category in tables 1, 2, 3 and 4. To make a clear comparison of the different techniques, we highlight the main objective, the technique, the performance enhancements and the limitations of each approach. In Table 1, the congestion control techniques have been summarized. Most of these techniques improve the access success probability and reduce the access delay. We notice that ACB techniques improve the access success rate during massive access while the slotted access technique achieves a better access success rate with bursty traffic. However, these techniques must consider the QoS requirements and the impact on H2H communications. In Table 2, we highlight the collision control techniques, such as backoff and CSMA techniques. These techniques have reduced the collision probability and increased the access success rate in the RACH. The collision resolution technique provides a reliable service while the distributed queueing technique reduces access delay even for massive access situations. The virtual preambles technique increases the number of the available preambles which, in turn, increase the access success probability. However, these techniques require consideration of the throughput performance and the prioritized access. Table 3 summarizes the energy efficiency techniques that aim to save the device energy during the random access procedure. For example, the disjoint allocation and dynamic backoff techniques improve energy saving for M2M devices and control the impact of M2M communications on H2H devices. The clustering scheme increases the battery and the network lifetime while the adaptive MAC achieves a greater throughput and less transmission delay. However, these techniques must consider the QoS requirements and the access delay. Furthermore, Table 4 shows the performance improvement techniques which aim either to minimize the access delay or to maximize the throughput of the RACH. For instance, the signature-based random access reduces the access delay compared to the standard random access which is preamble-based. Moreover, the cooperative communication technique increases the RACH throughput while the CACB-LB technique achieves 20% higher throughput than the cooperative communication technique. The dynamic backoff technique increases the RACH throughput up to 98% of the RACH capacity while the Q-learning technique achieves 100% higher throughput compared to the slotted-ALOHA technique. However, these techniques must consider several aspects, such as the access success probability and the QoS requirements. It is unfair to state that one approach is better than another because different approaches have different circumstances. However, some techniques achieve specific enhancements in certain performance indices while getting some degradations in other metrics. This is because of the trade-offs among different performance metrics. Thus, each technique may be perfect for a certain system and not for another. Consequently, the chosen random access technique must fulfil the system criteria and QoS requirements that have been imposed by the client. Moreover, the highlighted limitations in each table can be used as research problems to extend the current approaches and to improve their performance.

Table 5 shows a compound view for the performance metrics that are considered by each technique. The performance indices included in this comparison are access delay, success rate, throughput, energy efficiency, QoS guarantees and coexistence of H2H devices. It is clearly seen in table 5 that most of the proposed random access techniques focus on solving the congestion/overload problem of the RACH. Although these techniques have efficiently addressed the overload problem for M2M devices, they may have a negative impact on H2H devices. This parameter has to be considered while designing random access techniques as M2M devices and H2H devices share the same cellular networks. The designed random access technique must have the least impact on H2H devices to achieve higher satisfaction for users which is more critical for network operators. However, there is a lack

TABLE 1. Category #1: massive access (congestion control techniques).

Proposed scheme	Reference	Objective	Technique	Performance	Limitations
ACB	[34]	To reduce the arrival rate of access requests.	1. eNodeB determines an ACB factor p. 2. UE generates a random number r 3.UE gets access if $r \leq p$	Improving the access success rate + reducing the access delay.	Not considering Prioritised access and QoS requirements
Adaptive ACB	[43]	To support M2M scalability	1. Network load is estimated. 2. eNodeB changes the ACB factor dynamically according to the estimated load.	Improving the access success rate + supporting the massive access	Not considering the coexistence of H2H devices.
Multiple Access ACB	[46]	To support the prioritized access	Different ACB factors are derived for different classes of M2M devices	Improving the success probability and increasing the radio resources utilization	Not considering the massive number of devices.
Slotted Access	[55]	To control the RACH congestions	M2M device is allowed to make the access request in a specific time slot in each access cycle	Achieving better access success rates especially with the bursty traffic	QoS requirements are not considered.
Multi-channel S-ALOHA	[49]	To control the access congestions in RAN	1. The number of arrivals is estimated in each RA slot. 2. The estimated number is used to optimize the access slots allocations.	Achieving higher success probability under the high traffic load	Prioritized access is not considered.
Grouping schemes	[21] , [57] , [58]	To control RACH congestions	1. M2M devices are grouped into clusters. 2. Each cluster has a head node which conducts the communications between M2M devices and eNodeB	increasing the RA success probability + reducing the congestions in RACH	Higher access delay+ signaling overhead.
Coordinated RA	[59]	To handle the signaling process in a group of M2M devices	The group representative is selected according to some advantages such as the radio link quality and the device capacity	Increasing the RA success probability	Not considering the heterogeneous M2M devices.
Dynamic Partition	[60]	To control RACH overload for differentiated M2M services	The RACH resources are dynamically partitioned between the delay-sensitive and delay tolerant devices	Improving the access success probability + reducing access success delay	Not considering the massive number of M2M devices.
Scattering Approach	[61]	To balance the RA intensity among eNodeBs	Scattering the M2M devices that are always trying to access the same base station using the proposed selection algorithms	Improving the access success rate and reduces the access delay	Not considering the massive number of M2M devices.
Proactive RA	[62]	To provide reliability guarantees	1. The number of arrivals is estimated. 2. The number of allocated resources is determined based on the estimation phase.	Improving the RACH reliability + supporting the massive access for M2M devices	Higher access delay.
Virtual Frames	[63], [64]	To control the overload of M2M access requests in RACH	1. RA slots are grouped together to form the virtual frame. 2. M2M devices are allowed to transmit AR at the end of each frame only.	Supporting massive access traffic.	Lower access success probability.

TABLE 2. Category #1: massive access (collision control techniques).

Proposed scheme	Reference	Objective	Technique	Performance	Limitations
Backoff	[66]	To solve the collisions in the RACH	M2M devices which are failed in their first access attempt are blocked from accessing the network for a specific time duration called back-off interval (BI)	Reducing the collisions in RACH	Increasing the access delay and the access attempts.
CSMA	[68]	To reduce the collisions caused by ALOHA-based communications	UE verifies the absence of other traffic before transmitting the access request	Increasing the access success rates	Throughput degradation.
CSMA/CA	[69]	To avoid RACH collisions	The device which attempts to transmit a frame must listen first to the medium and transmits its data only if the medium is idle	Increasing the access success and reducing the access delay	Degraded performance with the massive number of M2M devices.
Collision Resolution	[70]	To solve the RACH collisions for massive M2M devices	Using the q-ary tree splitting algorithm to define a set of preambles to be used by the collide devices	Providing a reliable and timely service for the massive M2M devices	High complexity.
Distributed Queueing	[71]	To solve RACH collisions	1. The collided preambles are divided into several groups. 2. The devices that are using the preambles of the same group are queued together for the next preamble transmission.	Reducing the average access delay even for massive number of access arrivals	Prioritized access is not considered.
Virtual Preambles	[75]	To increase the number of available preambles in RACH	Virtual preambles are created by combining the existing preambles with the RACH indexes that are used for preambles transmission	Reducing the collision probability and access delay	Massive arrivals are not considered.

TABLE 3. Category #2: energy efficiency techniques.

Proposed scheme	Reference	Objective	Technique	Performance	Limitations
Disjoint Allocation	[82]	To evaluate the RACH performance under the disjoint allocation (DA)	Available preambles are divided into two separate groups one for M2M devices and the other is for H2H devices	Improving the energy saving of M2M devices up to 4%	Massive access is not considered.
Dynamic Backoff	[83]	To improve the energy efficiency in RACH	A game theory framework An axiomatic strategy	Improving energy efficiency for M2M devices and controlling the impact of M2M devices on H2H devices	QoS requirements need to be considered
Clustering	[84]	To improve energy efficiency in M2M communications	M2M devices are communicating with the group representative instead of communicating directly with the base station	Increasing the network lifetime and the lifetime of devices' battery	Higher access delay.
Adaptive MAC	[89]	To support energy-harvesting for M2M devices	Different devices harvest energy adaptively and then contend the transmission opportunities with energy level related priorities	Greater throughput and less transmission delay	Impact on H2H communication is not considered.
Relay-based EH	[90]	To support cooperative transmissions	M2M devices communicate with the relay node instead of communicating directly with the eNodeB	Reducing the access congestions and collisions in the base station and Reducing the energy consumption for M2M devices	Higher access delay.

of random access techniques that consider energy efficiency which is a critical aspect of M2M communications. As most M2M devices are battery-operated, it is significant to reduce the energy consumption required by the random access process. Providing collision-free random access techniques could improve the energy efficiency for M2M devices a great

TABLE 4. Category #3: performance improvement techniques.

Proposed scheme	Reference	Objective	Technique	Performance	Limitations
Simplified RA	[94]	To reduce the access delay in RACH	Distributing the RACH traffic by using multichannel slotted ALOHA and stable RA attempts	Access delay is decreased as the number of the available preamble is increased	Packet loss ratio must be considered.
Dynamic ACB	[95]	To efficiently reduce the access delay in RACH	1. The total access delay for all M2M devices is estimated. 2. This estimation is used to determine the optimal value of ACB factor.	Achieving near optimal in minimizing the access delay	Impact on H2H communication is not considered.
Dynamic Allocation	[21]	To reduce the overload and congestions in RACH	The resources are dynamically allocated to M2M devices and H2H devices according to the state of the traffic load	Improving the resource utilization + reducing the access delay	QoS requirements are not considered.
Signature-based RA	[97]	To reduce the average access delay	A signature is used instead of preamble. The RA procedure is simplified to contain only two steps instead of four steps	Reducing the access delay compared to the preamble-based RA	Access success probability is not considered.
Cooperative Communication(CC)	[100]	To increase the throughput in wireless networks	Allowing multiple base stations to cooperate together to reduce the congestions in a given area of cellular networks	Increasing the RACH throughput	QoS requirements are not considerd.
CACB-LB	[101]	To increase the RACH throughput	M2M devices are allocated to a specific eNodeB according to the criterion of the percentage of devices that can only access one eNodeB among two adjacent eNodeBs	Achieving 20% higher throughput than CC	Prioritized access is not considered.
Auction-based RA	[77]	To ensure the load balancing for RACH	An auction-based method is used to balance and allocate RACH preambles for multiple periods	Increasing the RACH throughput and supporting the massive RA request	Impact on H2H is not considered.
Dynamic Backoff	[102]	To improve the RACH throughput under various traffic loads	The failed M2M device performs a preamble retransmission after a backoff period with a random window size	Increasing the RACH throughput up to 98% of the RACH capacity	QoS requirements are not considered.
Q-learning	[103]	To improve RACH throughput	Separate frames are allocated to each group of devices to allow them to access the eNodeB without sharing the frame	Achieving 100% of throughput compared to the slotted-ALOHA scheme	Access success probability is not considered.
Coded RA	[104]	To increase RACH throughput	M2M devices are classified into multiple classes according to their channel conditions with the same packet length	Achieving higher throughput compared to the slotted-ALOHA technique	Higher access delay.
Adaptive Preamble Allocation	[105]	To determine the number of preambles required to maximize the RACH throughput	The number of required preambles is determined according to the estimated number of active devices	Achieving the maximum average throughput with different access probabilities	Impact on H2H is not considered.

deal. Moreover, the performance improvement techniques perform properly in terms of RACH throughput and access delay. However, the QoS guarantees have not been considered for most of the proposed techniques. Thus, it is important to consider the QoS requirements for different M2M applications while designing random access techniques.

TABLE 5. Performance comparison of RA techniques.

Category	Sub-category	Proposed Technique	Considered Performance Indices					
			Access delay	Success rate	Throughput	Energy efficiency	QoS guarantees	Coexistence of H2H
Massive Access Control Techniques	Congestion Control	ACB	✓	✓				✓
		Adaptive ACB	✓	✓				
		Multiple Access ACB		✓				
		Slotted Access		✓				
		Multi-channel S-ALOHA		✓				
		Grouping	✓	✓			✓	
		Coordinated RA		✓				
		Dynamic Partition	✓	✓				
		Scattering	✓	✓				
		Proactive RA	✓					
		Virtual Frames	✓	✓				
	Collision Avoidance	Backoff		✓	✓			
		CSMA	✓	✓	✓	✓		
		CSMA/CA		✓				✓
		Collision Resolution	✓	✓				
		Distributed Queueing	✓	✓	✓			✓
		Virtual Preambles	✓	✓				
Energy Efficiency Techniques	Energy-Saving	Disjoint Allocation			✓	✓		✓
		Dynamic Backoff		✓		✓		✓
		Clustering				✓		
	Energy-Harvesting	Adaptive MAC	✓		✓	✓		
		Relay-based EH		✓		✓		
Performance Improvement Techniques	Access Delay Minimization	Simplified RA	✓					✓
		Dynamic ACB	✓					
		Dynamic Allocation	✓	✓				
		Signature-based RA	✓	✓				
	Throughput Maximization	Cooperative Communication	✓	✓	✓			
		CACB-LB	✓	✓	✓			
		Auction-based RA	✓	✓	✓			
		Dynamic Backoff	✓	✓	✓			
		Q-learning	✓		✓			✓
		Coded RA			✓			

B. FUTURE DIRECTIONS

Although all the previous random access techniques have achieved good improvements in different aspects, more efficient random access techniques that support the special characteristics of M2M traffic, such as bursty and periodic traffic, as well as the heterogeneity of M2M devices, must be introduced. It is desirable to consider multiple performance parameters, such as access delay, access success probability, collision probability and RACH throughput, with awareness of the QoS requirements and the impact on H2H devices. M2M communications must be efficient while having the least impact on H2H communications. Moreover, reliable random access techniques must be considered for critical M2M applications such as e-healthcare and emergency systems. Such techniques should give access priority to these systems while providing a reasonable service for other systems. Furthermore, random access techniques should consider the scalability of M2M systems to accommodate the increased number of M2M devices that will be connected to the networks in the near future. Such techniques should support massive access while providing the required QoS guarantees, such as delay constraints, throughput and reliability. Moreover, the energy consumption for random access techniques should be low to support the limited power of M2M devices. Thus, introducing a multi-objective random access technique could be a suitable solution to address as many aspects as possible. The multi-objective random access could target several performance parameters with awareness of the QoS requirements and the coexistence of H2H devices. Other future directions include the security of M2M communications [109]. Although that there are several works that consider the security of M2M communications [110], [111], it is desirable to design more robust protocols to ensure the resistance of M2M communications against internal and external attacks. Finally, the proposed random access techniques should consider the new updates of cellular networks technologies such as 5G which may be a promising infrastructure for M2M communications.

VII. CONCLUSION

Machine-to-machine communication is an emerging technology that allows devices to communicate without human intervention. M2M formulates the foundation of the IoT as billions of devices will be connected to the Internet in the near future. LTE/LTE-A networks have been considered a promising technology for M2M deployments due to the extended coverage, low latency and spectral efficiency of LTE networks. For this reason, many deployments have been introduced for M2M in LTE networks. M2M devices have to go through the random access procedure as the first step to gain access to network resources. Several techniques for solving the RACH problems for M2M devices have been introduced. This work provides a new classification for the current RA techniques. According to the targeted objective, we classify the current RA techniques into three categories: massive access control techniques, energy efficiency techniques and performance improvement techniques. Each category is further divided into two subcategories, and the proposed solutions have been reviewed for each subcategory. After that, we analyze and compare the performance of the current random access techniques. The analysis shows that most of the proposed solutions address the problem of RACH overload while there is a lack of random access techniques that consider the energy efficiency and QoS guarantees. Thus, it is suggested that researchers introduce multi-objective random access techniques with awareness of the QoS requirements and the coexistence of H2H devices to find the optimal random access technique for M2M devices in LTE/LTE-A networks.

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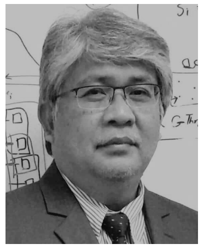

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