Enhanced LTE-Advanced Random-Access Mechanism for Massive Machine-to-Machine (M2M) Communications

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***Abstract*—Machine-to-Machine (M2M) communications enable one or more autonomous machines to communicate directly with one another without human intervention. M2M applications include smart grid, healthcare and intelligent Transportation System. However, past and present wireless technologies have been engineered for Human-to-Human (H2H) communications, in particular, for transmission of voice. Consequently, LTE-Advanced, which is envisaged to play a central role in M2M communications, is highly optimized for H2H communications. Distinct and unique characteristics of M2M communications create new challenges from those in H2H communications. In this article, we investigate the impact of massive M2M terminals attempting random access to LTE-Advanced all at once. We provide a comprehensive coverage on the LTE-Advance random access mechanism in order to understand the overload problem on the LTE-Advanced random access channel. We discuss and review the solutions to alleviate the overload problem by 3GPP. As a result, we propose an effective solution that can effectively eliminate the congestion on the random access channel for M2M communications without affecting H2H communications.**

***Index Terms*—Beyond 4G, LTE-Advanced, M2M, Random Access, Wireless communication**

I. Introduction

Human-to-Human (H2H) communication has been the main driving force for the development of wireless and wired communications technologies. For instance, the Global System for Mobile Communications (GSM), which is presently the most widely deployed cellular technology in the world, was engineered for transmission of voice. For the past few years, we have witnessed an increasing number of networked machines, changing the conventional perception of human-centric communication towards networks that are independent of human interaction, which is known as Machine-to-Machine (M2M) communications [1]. M2M communication is enabling a ubiquitous computing environment towards the "Internet of Things" vision. The population of M2M machines is expected to be several orders of magnitude greater than that of the H2H population. Potential and emerging use cases of M2M communications are smart power grid, healthcare monitoring, remote security surveillance, tracking and tracing, intelligent transportation system, and many more.

Beyond Fourth-Generation (4G) wireless technologies, in particular, LTE-Advanced [2], is envisaged to play a central role in interconnecting machines. Since LTE-Advanced evolves from LTE, it is still highly optimized and suitable for legacy H2H communications such as voice calls, video streaming, online gaming, social networking and web surfing. The requirements of H2H communications are high data rates, mobility, and human quality of service and experience. M2M communications desire a very different set of requirements than H2H communications because they are mainly characterized by a high device density in a cell, small amounts of payload, machine-originated communications and low traffic volumes per machine.

The Third Generation Partnership Project (3GPP) has already started working on evolving LTE-Advanced to accommodate the characteristics of M2M communications. To date, it has specified a reference architectural model [3] and identified a set of requirements [4] for M2M communications over LTE-Advanced. One of the key challenging requirements facing LTE-Advanced is in counteracting signaling and traffic load spikes caused by a sudden surge of massive numbers of M2M terminals trying to access the LTE-Advanced's base station all at once. An example is the huge number of smart metering devices becoming active almost at the same time after a period of power outage. This leads to severe overload on the LTE-Advanced Physical Random Access CHannel (PRACH). The overloaded PRACH is further aggravated if the M2M terminals try to repeat their access attempts without realizing that the unsuccessful random access attempts are due to PRACH overload. Within 3GPP, six possible remedies [5] have been identified to combat the PRACH overload problem, which include backoff scheme, slotted-access scheme, access-class barring scheme, pull-based scheme, PRACH resource separation scheme, and dynamic PRACH resource allocation scheme. Due to the traffic load dynamics on the PRACH channel, these schemes alone cannot fully alleviate the overload problem. Therefore, an effective approach would be to selectively combine those schemes which are complementary. An important issue of overload control, which has not been addressed either in 3GPP or by the wireless access research community, is PRACH overload detection and notification. Thus, we propose a self-optimizing overload control (SOOC) mechanism which can respond to sudden changing PRACH load conditions in a timely manner. The core of SOOC is an intelligent control loop that performs congestion monitoring, decision-making and adjusting PRACH resources. SOOC includes a composite overload mechanism which comprises dynamic PRACH resource allocation, PRACH resource separation, the access-class barring scheme, the slotted-access scheme and the *p*-persistent scheme.

II. M2M Communications

Machine-to-Machine (M2M) communication can be used to create a rich set of applications, e.g., Smart Grid, Healthcare and Intelligent Transportation System.

Smart Grid – Smart grid is the next-generation electrical power system, which embraces M2M communications in order to control and optimize power generation, distribution, and consumption. Smart machines, also known as smart meters, gather utility usage information from electrical appliances and send the information to the M2M server at the utility provider for analysis by communicating directly through LTE-Advanced.

Healthcare – M2M communications facilitate remote patient monitoring and healthcare services. Thus, elderly or chronically ill patients can stay at home. One or more machines are used to send the patient's health information (e.g., blood pressure and body temperature) to the M2M server in the hospital at regularly intervals or on-demand via LTE-Advanced.

Intelligent Transportation System – M2M communications can be applied to enhance transport efficiency, security and safety. Machines onboard a vehicle's navigation system communicate status information (e.g., location and velocity) to the M2M server via LTE-Advanced. The M2M server in turn analyzes the collected information and sends up-to-date traffic information to the vehicle's navigation system through LTE-Advanced.

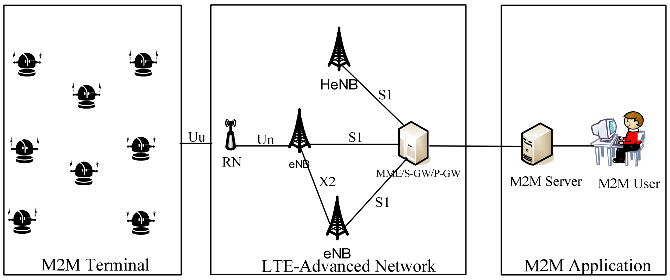

Fig. 1. M2M Communications with LTE-Advanced Cellular Networks

Fig. 1 shows a high-level M2M communications system. The communications architecture is composed of three segments, namely the M2M terminal segment, the wireless network segment and the M2M application segment. In the M2M terminal segment, the M2M terminal, usually embedded in a smart electrical device, can automatically send sensor data, and receive control and command data from the M2M user. LTE-Advanced, which is a beyond 4G wireless network, is the wireless network segment considered in this article. The M2M terminal is connected to LTE-Advanced via a conventional base station, i.e., evolved Node B (eNB), a Home eNB (HeNB), or a Relay Node (RN). The eNB and HeNB are in turn are connected to the Mobility Management Entity (MME), Serving Gateway (S-GW) and Packet data network Gateway (P-GW). The M2M server not only acts a data sink for storing all sensory data from the M2M terminals, but also provides these real-time data to a variety of M2M applications for remote monitoring and management.

TABLE I
M2M and H2H Communication Characteristics

Characteristics	M2M	H2H
Number of Devices per cell	Hundred to Thousand	Tens of Thousand
Base station Access	Massive and concurrent	Low to medium and independent
Mobility	Fixed to low	Fixed to high
Payload Size	Typically small	Small to large
Amount of Traffic per terminal	Low	Low to high
Traffic Flow	Unidirectional (typically, machine-originated)	Bidirectional, unidirectional (typically, mobile-terminated, e.g., video streaming)
Traffic Transmission Frequency	Infrequent	Infrequent to Frequent
Power Consumption	Extremely low	Low to High
Time-insensitive	Application-specific (e.g., home appliances)	Application-specific (e.g., e-mail, web browsing)
Time-sensitive	Application-specific (e.g., smart grid control data)	Application-specific (e.g., VoIP, online gaming)
Time-Controlled	Application-specific (e.g., smart metering)	No
Group Formation	Yes (e.g., smart grid)	No
Secure Connection	Required	Required

M2M communication exhibits traffic characteristics that differ from H2H communication. Table I summarizes and compares the key characteristics of M2M and H2H communications. Unlike H2H, M2M communication involves very low-power and a potentially huge number of devices in the world (in the order of billions to trillions). Some or all of these M2M terminals may attempt to access wireless network's base station simultaneously or almost simultaneously. An example is when a single event is detected by multiple sensors and triggers all of them to report to the M2M server, such as a bridge monitoring with a massive number of sensors. When a train passes through the bridge, all sensors simultaneously transmit the sensory data to the same or different M2M server. An M2M terminal infrequently generates a small amount of traffic. Similar to H2H, the M2M traffic types can be classified into time-sensitive and time-insensitive. In addition, there is time-controlled traffic which is only transmitted and received during certain time periods that are defined in advance. For many M2M use cases, the M2M terminals are stationary or move infrequently over a long period of time. A number of M2M terminals can be managed by the wireless network as a group if these M2M terminals share a common set of requirements such as subscription and Quality of Service (QoS) policy.

III. LTE-ADVANCED RANDOM ACCESS PROCEDURE

Random access procedure [6][7] is a process that is initiated by an idle mobile terminal that does not have uplink radio resources allocated in which to send user data or control data (e.g., a channel measurement report) to the base station. In addition, it is also used by a mobile terminal in connected state in order to perform handover from one cell to another, or to recover from radio link failure. The Random Access (RA) procedure can be classified into two operational modes, namely uncoordinated RA and coordinated RA. The former is applied to mobile terminals in idle state while the latter is used in connected state. In coordinated RA, the base station has explicit control over which and when a mobile terminal can initiate random access. Hence, it is collision-free and mainly used for handover. In this article, the term mobile terminal refers to an LTE-Advanced-enabled device which can be an H2H terminal or an M2M terminal.

A. Protocol Operation

The uncoordinated RA operation comprises four steps which are as follows.

Step 1: The mobile terminal transmits a randomly selected RA preamble sequence on PRACH to the base station.

Step 2: The base station transmits an RA response on the Physical Downlink Shared Channel (PDSCH) in respond to the detected preamble sequence.

Step 3: The mobile terminal transmits its identity (which includes the Temporary C-RNTI (Cell Radio Network Temporary Identifier) that received in Step 2 and the C-RNTI if it already has one else its unique address), and other messages (e.g., scheduling request) to the base station using the Physical Uplink Shared Channel (PUSCH) resources assigned in the RA response in the second step.

Step 4: The base station echoes the mobile terminal identity it received in the third step on PDSCH.

The preamble sequences used by the mobile terminals in Step 1 are known as Zadoff-Chu sequence, which have low Peak-to-Average Power Ratio (PAPR). In LTE-Advanced and LTE, each cell is assigned 64 preamble sequences, some of which are reserved for coordinated RA. The remaining preamble sequences are for uncoordinated RA, which are further subdivided into two subgroups. By selecting a proper subgroup, the mobile terminal can indicate to the base station the amount of uplink resources it desires to transmit the Step-3 message. The broadcast system information indicates which preamble sequences are available in each of the two subgroups. The mobile terminal randomly selects a preamble sequence from the subgroup corresponding to the size of the Step-3 message. All of the 64 sequences can be derived from a single Zadoff-Chu sequence by cyclically shifting the root sequence. These cyclically shifted sequences are orthogonal to each other. In other words, the cross-correlation between the cyclically shifted versions is zero. As a result, no RA collisions will occur if two or more terminals simultaneously transmit a different preamble sequence on the same PRACH resources. However, a collision will occur if two or more mobile terminals have randomly selected the same preamble sequence. The cyclic shift is configured according to the maximum round-trip propagation delay in the cell and the maximum delay spread of the channel in order to ensure the orthogonal property. For a finite preamble sequence length, the number of cyclically shifted sequences decreases with increasing cell size. Consequently, multiple root sequences are needed to generate the 64 sequences. The sequences derived from different root sequences are not orthogonal, but the cross-correlation is low. Thus, the probability of concurrent detection of preamble sequences from different roots by the base station is lower than when using two or more preamble sequences from the same root.

In Step 2, all mobile terminals, which have transmitted a preamble sequence, expect to receive an RA response within a time window that is configured by the base station. The RA response time-window configuration is broadcast as part of the cell-specific system information. If the mobile terminal does not receive an RA response within the configured time window, the mobile terminal increases the preamble transmission attempt number (which is a variable in the MAC protocol called TRANSMISSION_PRE-AMBLE_COUNTER [7]), increases the PRACH transmit power by a power ramping step, and repeats the first step unless the maximum number of attempts has been reached. The minimum delay before repeating Step 1 after the end of the RA response time-window is 3 ms. In the event of an RA collision, the collided preamble sequence can still be detected by the base station due to the low cross-correlation of the preamble sequences. The base station, however, is not aware of the collision and responds with an RA response. Then each of the colliding terminals transmits its own Step-3 message, which will again result in a collision at the base station. If none of the Step-3 messages are successfully decoded, the colliding terminals will repeat the first step after the expiration of the contention resolution time-window which is started as soon as the Step-3 message is transmitted. If the base station manages to decode one of the collided Step-3 messages then it replies with the terminal identity in the fourth step. Only the terminal which detects a match between the identity received in the fourth step and the identity transmitted in Step 3 can feed back a Hybrid Automatic Repeat Request (HARQ) positive acknowledgement to the base station. The other colliding terminals should discard the received message.

B. Physical Random-Access Channel (PRACH)

The Physical Random Access Channel (PRACH) is defined by the time-frequency resources, referred to as RA-slots, which are dedicated for transmission of RA preamble sequences. The RA-slots for PRACH are time- and frequency-multiplexed with the Physical Uplink Shared Channel (PUSCH) and the Physical Uplink Control Channel (PUCCH) as illustrated in Fig. 2. The RA-slots are semi-statically allocated within the PUSCH region, and repeated periodically. In the frequency domain, the bandwidth of the RA-slot is 1.08 MHz. In the time domain, the duration of the RA-slot depends on the configured preamble format. Four preamble formats are defined for LTE-Advanced. Each format comprises the preamble sequence field, the Cyclic

Prefix (CP) field and the Guard Period (GP) field. The GP is used to avoid interference with subsequent subframes of PUSCH. The interference is due to the fact that RA terminals are not uplink time synchronized. The CP is used to absorb the maximum delay spread in a cell. Each preamble format has different CP and GP lengths. The first preamble format, which is shown in Fig. 2, is the shortest among the preamble formats with a duration of 1 ms and the length of the preamble sequence is 0.8 ms. The CP and the GP are both 0.1-ms long. The duration of the RA-slot for the second and third formats is 2 ms, which spans two consecutive subframes. The length of the RA-slot for the fourth preamble format occupies three consecutive subframes (a duration of 3 ms). The RA-slot can be configured to occur once every other radio frame up to once every subframe. Thus, a total of 16 RA-slot configurations are defined in the time domain. Fig. 2 shows the RA configuration index 12 for the first preamble format. For this configuration index, there are five RA-slots per radio frame and only the even subframes in each radio frame contain the RA-slot.

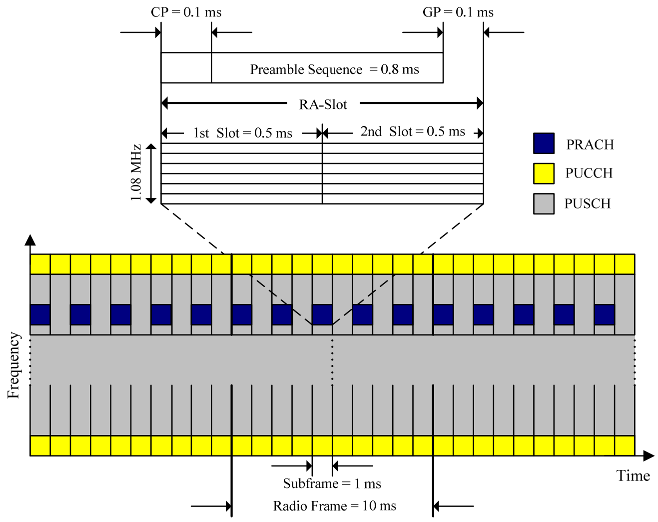

Fig. 2. PRACH Time-Frequency Resources

IV. IMPACT OF M2M ON RANDOM-ACCESS CHANNEL

As mentioned in Section II, M2M communication is characterized by a massive number of M2M terminals located in a cell. Consequently, some or all of these M2M terminals may attempt to access LTE-Advanced's base station using uncoordinated RA simultaneously. Thus, RA preamble collisions are eminent. The RA success probability, which is the probability that a terminal's preamble sequence does not collide with another preamble sequence, is determined by the number of available preamble sequences and the terminal density in a cell. Figs. 3 and 4 show the theoretical RA success probability and the RA mean delay for one mobile terminal as a function of different number of available preamble sequences and varying number of terminals competing for the same RA resources. Preamble Format 0 and RA configuration index 12 were used. For the RA mean delay, both the RA response and the contention resolution time-windows were set to 8 ms, which are defined in [8]. As observed in Figs. 3 and 4, the performance of RA deteriorates when the number of mobile terminals performing uncoordinated RA attempts increases and the number of available preambles decreases. For H2H communications, the RA success probability is expected to be 99%, which means that no more than two mobile terminals are performing the uncoordinated RA at the same time. This assumption, however, is not valid for M2M communications due to a massive number of M2M terminals.

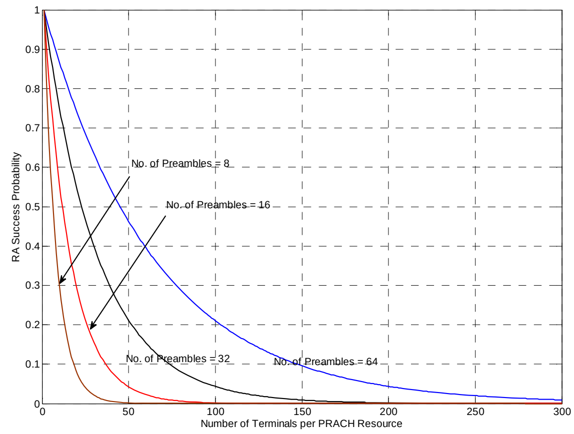

Fig. 3. RA Success Probability

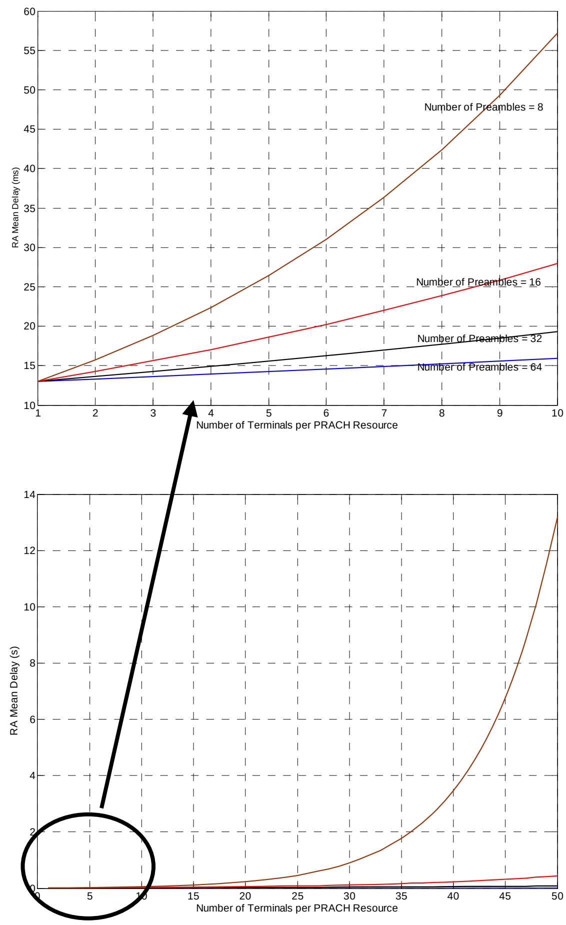

Fig. 4. RA Mean Delay

V. 3GPP RANDOM-ACCESS CHANNEL OVERLOAD CONTROL MECHANISMS

As shown in Section IV, massive simultaneous uncoordinated RA attempts lead to an extremely low RA success rate and cause PRACH channel overload. The overloaded channel is further aggravated by the M2M terminals trying to repeat their access attempts and increase their access probes. As a result, some terminals may not achieve RA successfully even after several attempts. Excessive PRACH channel overload should be prevented because every unsuccessful attempt wastes radio resources and battery energy which is a precious resource of the M2M terminals. An M2M terminal can be instructed by the base station to back off for a period of time before repeating the RA attempt. The backoff indicator is transmitted as part of RA response message in Step 2. Even though this backoff mechanism can be employed to reduce PRACH channel overload, it is not scalable because all the M2M terminals back off for the same period of time. Consequently, 3GPP has proposed six solutions [5], which are described here.

A. Backoff Scheme

The backoff scheme counteracts the PRACH overload by delaying RA attempts for M2M terminals and H2H terminals separately. This scheme is effective under normal load conditions, but it is less effective when a massive number of terminals initiating RA at once.

B. Slotted-Access Scheme

In this scheme, each M2M terminal is only allowed to transmit the preamble sequence at specific RA-slots within specific radio frames. At other times, the M2M terminals are in sleep mode. The mechanism, which is used by the M2M terminal to calculate which radio frames and RA-slots, is based on the M2M identity and the RA cycle. The base station broadcasts the RA cycle which is an integer multiple of radio frames. The number of unique RA-slots is proportional to the RA cycle length and the number of RA-slots within a radio frame. PRACH will be overloaded when the number of M2M terminals in a cell is greater than the total number of unique RA-slots. In this case, several M2M terminals share the same RA-slot and preamble collisions are unavoidable. A long RA cycle can be configured to reduce preamble collisions but it leads to unacceptably large latency in delivering RA requests.

C. Access Class Barring (ACB) Scheme

In this scheme, the existing LTE-Advanced ACB mechanism is extended to include new access classes for M2M terminals. The base station can bar or delay an M2M terminal from initiating RA. The ACB scheme deals with excessive PRACH overload by reducing the number of M2M attempting RA. This means longer RA delays for some M2M terminals.

D. Pull-based Scheme

The pull-based scheme is a centralized control mechanism whereby the M2M server triggers LTE-Advanced's base station to paging the intended M2M terminals. Upon receiving the paging signal, the M2M terminal will initiate RA. The base station could control the number of M2M terminals to be paged by taking into account the PRACH load condition and resources available.

E. PRACH Resource Separation Scheme

In this scheme, M2M terminals and H2H terminals are allocated orthogonal PRACH resources. If the M2M terminals share the same PRACH resources as H2H terminals, then PRACH overload could significantly degrade the RA quality of H2H terminals. The base station can identify if the source of overload is due to M2M or H2H RA activities. PRACH resources are preamble sequences and RA-slots, which can be divided in two ways. Firstly, M2M communications can be provided with RA-slots that are orthogonal to those used for H2H. Secondly, a subset of the preamble sequences from a common pool is assigned for M2M use.

F. Dynamic PRACH Resource Allocation Scheme

In this scheme, the base station dynamically allocates additional PRACH resources based on the PRACH load condition and overall traffic load. The dynamic RACH resource allocation scheme can effectively mitigate PRACH overload provided the base station employs an algorithm that can respond at the onset of high load conditions. In Section VI, we describe such an algorithm.

VI. Self-Optimizing Overload Control (SOOC) Scheme

A self-optimizing algorithm continuously adapts network resources and/or network parameters in order to meet specified high-level goals. Current LTE-advanced RA procedure only includes a simple algorithm for adjusting the PRACH transmit power for each unsuccessful RA attempt. The other resources are not adapted according to the PRACH channel load condition. In this section, we describe a self-optimizing overload control (SOOC) mechanism for M2M communications, which enables the base station to automatically add or reduce PRACH resources when it detects an increase or decrease in PRACH load, respectively. In order to completely prevent PRACH from overloading, SOOC also includes the RACH resource separation scheme, the access class barring scheme, the slotted-access scheme, and the p-persistent scheme.

PRACH overload detection and notification mechanisms are not part of LTE-Advanced. SOOC implements an intelligent control loop which collects information for overload monitoring, makes decisions and then adjusts PRACH resources.

In the first part of the control loop, the monitor function is responsible for collecting information related to the PRACH load condition. A terminal can detect an overloaded PRACH channel when it fails to receive a response from the base station in the fourth step of the four-step RA process. Thus, the terminal declares the RA attempt as failed and enters the overloaded control mode before retrying RA again. In the overloaded control mode, the terminal will not randomly select and send the preamble sequence in the RA-slot in the next RA cycle. Instead, it randomly draws a value q, $0 \le q \le 1$. If $q \le p$, then the terminal proceeds to transmit the preamble sequence in the RA-slot. Otherwise, the terminal will repeat the same process in the next RA cycle. Since the collided terminals would collide again in the next RA-slot, the p-persistent algorithm is used to minimize the chance of collision among the collided terminals. The parameter *p* is the access probability which is set according to the access class of the terminal. A small *p* means a long RA access delay. Two new access classes are added to the LTE-Advanced ACB scheme for M2M terminals. The reason for defining new access classes is that M2M communication can be controlled without affecting the legacy H2H communications. The new access classes are low access priority and high access priority. For example, *p* could be set to 0.8 and 0.2 for high priority access M2M terminals and low access priority M2M terminals, respectively. Time-controlled M2M and time-tolerant M2M terminals are classified as low access priority, while time-sensitive M2M terminals (e.g., smart grid control and earthquake monitoring sensors) as high priority access. When the terminal receives an RA response in Step 2, it includes a PRACH overload indicator in the Step-3 message. The overload indicator signals to the base station the number of RA retries attempted by the terminal. The values of the overload indicator range from 0 to *raRetryCounter*. An overload indicator of *raRetryCounter* means that the terminal has repeated the RA procedure *raRetryCounter* times. It also means that the congestion level of the PRACH channel is rising. The overload indicator value can be derived from the MAC parameter preamble transmission attempt counter (i.e., TRANSMISSION_PREAMBLE_COUNTER) which is incremented for every RA attempt made by the terminal.

In the second part of the control loop, the base station reacts to the overload indicator by dynamically increasing or decreasing the number of RA-slots for PRACH. Depending on the PRACH congestion level and the available uplink radio resources, the base station can decide to increase the number of PRACH RA-slots in the frequency domain, time domain or both. In the frequency domain, the base station will allocate an additional 1.08-MHz frequency band. In the time domain, it adds extra RA-slots in a radio frame. If we double the number of RA-slots in both frequency and time domains then the total number of RA-slots is increased by a factor of four. The amount of RA-slots required can be determined by

$$B = -L \ln(1 - P_c) \quad (1)$$

where P_c is the RA collision probability in a cell or sector, B is the number of RA attempts per second per cell, and L is the total number of RA resources per second, which is the product of the number of RA-slots per second, the number of RA-frequency bands, and the number of preamble sequences in the cell for M2M communications with a maximum of 64. The value of L is calculated by the base station for every RA cycle. Fig. 5 depicts the details of SOOC. The base station only needs to estimate P_c by summing the received overload indicator value of each M2M terminal in one RA cycle and divide it by the total number of RA attempts in one RA cycle. Using the estimated P_c and L at the *n*th RA cycle, we can determine B. Then, L is calculated from B and the target P_c which is set for M2M communications. Therefore, the PRACH resources are adjusted in every RA cycle. If the number of RA-slots could not be increased due to insufficient uplink radio resources, then the base station can prevent access to low access priority M2M terminals for an indefinite period until the PRACH overload condition is brought under control. The period of RA cycle determines how often the PRACH resources are adjusted. This means, a short RA cycle period can quickly respond to the PRACH load changes while a long one is sluggish. On the other hand, a short RA cycle period incurs high signaling overhead. The RA cycle period can be configured from 1 ms (one radio frame) to a few hundred or thousand radio frames (e.g., 512 radio frames which are equal to 5.12 seconds). It is likely that the target P_c can be specified by the mobile network operator or M2M service provider, e.g., P_c = 5%. Then SOOC can tune PRACH resources in order to maintain the specified target P_c using Equation (1).

In the last part of the control loop, the base station broadcasts the modification to PRACH resources as an integral part of the cell-specific system information.

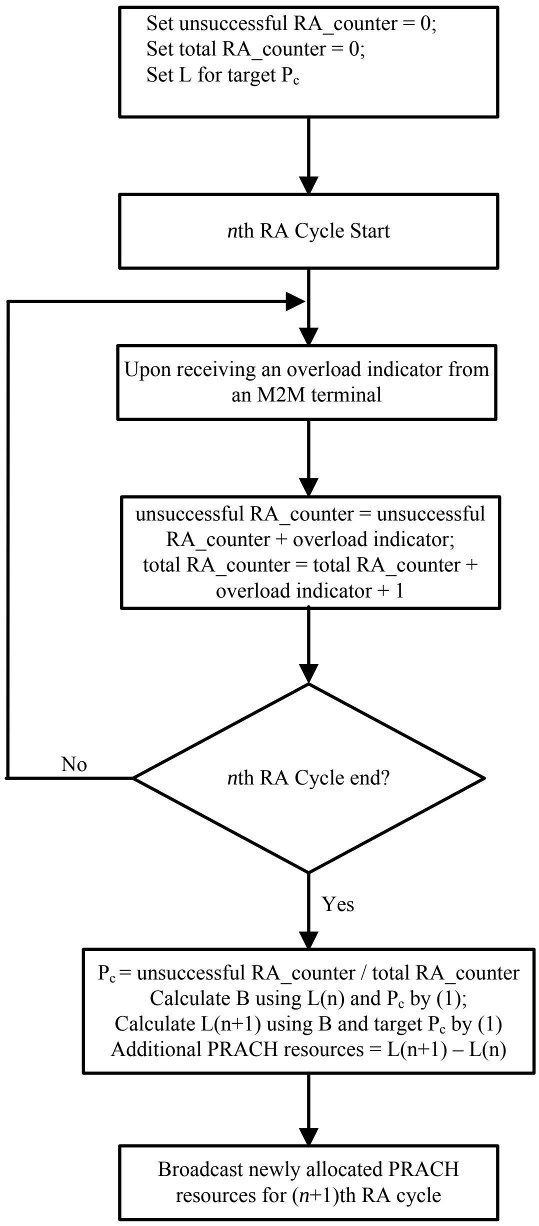

Fig. 5. Self-Optimizing Algorithm

VII. Conclusion

Modern communication is evolving towards M2M communications that require little or no human intervention. Unlike H2H, M2M communications are characterized by high machine density per cell, small amounts of payload, machine-originated communications, time-tolerant and low traffic volume per machine. These characteristics pose new challenges to LTE-Advanced which is designed for human-centric communication. One of the key challenges facing LTE-Advanced is the large number of machines initiating random access to LTE-Advanced's base station all at once. This could lead to severe overload on LTE-Advanced RACH and we have used theoretical results to show the full scale of the overload problem as the number of machines increases. Prior to unveiling the RACH overload problem, we have provided a comprehensive tutorial on LTE-Advanced random access procedure. We have provided a complete review on 3GPP proposals to alleviate the RACH overload problem. Due to the RACH load dynamics, the 3GPP proposals alone cannot complete eliminate the overload problem. As a result, we have proposed a self-optimizing overload control mechanism that can tune RACH resources according to the RACH load condition in a timely manner. The mechanism comprises a composite scheme which includes RACH resource separation, the access class barring scheme, the slotted-access scheme, and the *p*-persistent scheme.

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