Overload Control for Machine-Type-Communications in LTE-Advanced System

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ABSTRACT

As Machine-Type-Communications (MTC) continues to burgeon rapidly, a comprehensive study on overload control approach to manage the data and signaling traffic from massive MTC devices is required. In this work, we study the problem of RACH overload, survey several types of RAN-level contention resolution methods, and introduce the current development of CN (core network) overload mechanisms in 3GPP LTE. Additionally, we simulate and compare different methods and offer further observations on the solution design.

INTRODUCTION

Machine-Type-Communications (MTC) applications are automated applications, which involve communications between machines or devices without human intervention. Such applications are widely adopted in our everyday life [1]. Though cellular mobile networks could offer MTC ubiquitous network access service with widely deployed infrastructure, they were originally designed for voice call and simple messaging for Human-to-Human (H2H), Human-to-Machine (H2M) and Machine-to-Human (M2H) applications, which are different from MTC in essence. Thus, 3rd Generation Partnership Project (3GPP) [2] standardizes the deployment of MTC applications in 3GPP networks (UMTS (Universal Mobile Telecommunications System) and LTE). As suggested in [3], deployment of massive MTC devices would generate a huge amount of signaling/data flow that congests random access network (RAN) and core network (CN). The former issue, RAN overload, is still an open problem [3] for further research since no efficient contention resolution can fairly accommodate such massive accesses of MTC devices at present.

Though various RAN level contention resolution mechanisms have been proposed in 3GPP meetings, none of them are widely acknowledged as the best solution. Even so, some methods are specified in [4] as workable solutions, and some mechanisms are interesting and informative from the view of research. Thus, in this article, we introduce different RAN overload resolution methods, and evaluate some of them by examining their performance under an agreed simulation scenario. Additionally, we also indicate the latest development of CN overload control methods in 3GPP LTE.

This article is organized as follows. We give an overview of random access procedure (RACH procedure) in LTE to serve as the preliminary knowledge for RAN overload resolution method. We describe different kinds of RAN overload control methods and the issue of CN overload control in 3GPP LTE-A. After that, we provide a concrete performance evaluation followed by a detailed introduction about simulation settings presented later, some of which have not been introduced in the 3GPP specification but essential to the system performance. Then, as an extension of our previous simulation results [5], we compare these algorithms to pave the way for further study, which is followed by the conclusion.

RACH PROCEDURE

When an idle UE (user equipment) attempts to connect to the LTE network, it must RRC connection setup procedure whose signaling flow is shown in Fig. 1 [6, 7]. The first four signaling steps of the procedure, also known as random access procedure (RACH procedure), are introduced as follows.

SIGNALING FLOW

Random-Access Preamble Transmission — The first step consists of transmission of a random-access preamble, allowing the eNB (base station) to estimate the transmission timing of the terminal. The time-frequency resource through which the random-access preamble is transmitted is known as the Physical Random

Access Channel (PRACH). The network broadcasts (i.e. in SIB-2) to indicate available PRACH resources preamble transmission, and the terminal selects one preamble sequence to transmit on the PRACH.

Random-Access Response (Msg2) — The second step consists of the network transmitting a timing advance command to adjust the terminal transmit timing, based on the timing estimation in the first step. In addition to establishing uplink synchronization, the second step also assigns uplink resources to the terminal to be used in the third step in the random access procedure.

RRC Connection Request (Msg3) — The third step consists of transmission of the mobile-terminal identity to the network using the UL-SCH similar to common scheduled data. The exact content of this signaling depends on the state of the terminal, in particular whether it is previously known to the network or not.

RRC Connection Setup (Msg4) — The fourth and final step consists of transmission of a contention-resolution message from the network to the terminal on the DL-SCH. This step also resolves contentions caused by multiple terminals using the same random-access resource to access the system.

The remaining steps belong to NAS level procedure and are not mentioned here. Now we introduce the behaviors of UE and its corresponding parameters.

UE Behaviors

The random access procedure could be triggered by a request from MAC layer or a paging message. Before a UE sends a preamble to the eNB, the must-known parameters should include random access response window (RAR window), the maximum number of transmission times, the power of transmission based on the number of transmission times, resource in PRACH (have been assigned by high layer, if not, UE will randomly choose one from the preambles) and the corresponding RA-RNTI. In one sub-frame (ten milliseconds) of LTE FDD (Frequency Division Duplexing) mode, the UE has two random access opportunities (RACH slots) to send preamble. If it is not a RACH slot, the UE sends preamble at the next RACH slot comes. After sending the preamble, the UE increases the number of transmission times by one and wait for random access response (also known as Msg2 or UL grant) from the eNB.

Upon receiving the random access response in the RAR window, the UE processes TA (Timing Alignment), UL grant and temp C-RNTI and prepare for sending RRC Connection Request (also known as msg3). If the UE fails to receive random access response in the RAR window (i.e., the eNB fails to detect the preamble from the UE), he checks whether its number of preamble transmission is smaller than the maximum number of preamble transmission. If it is, the UE randomly chooses a time slot for preamble retransmission based on the value of Backoff Indicator. Otherwise, the UE is implicitly informed of RACH procedure failure and should report the random access failure to the higher layer.

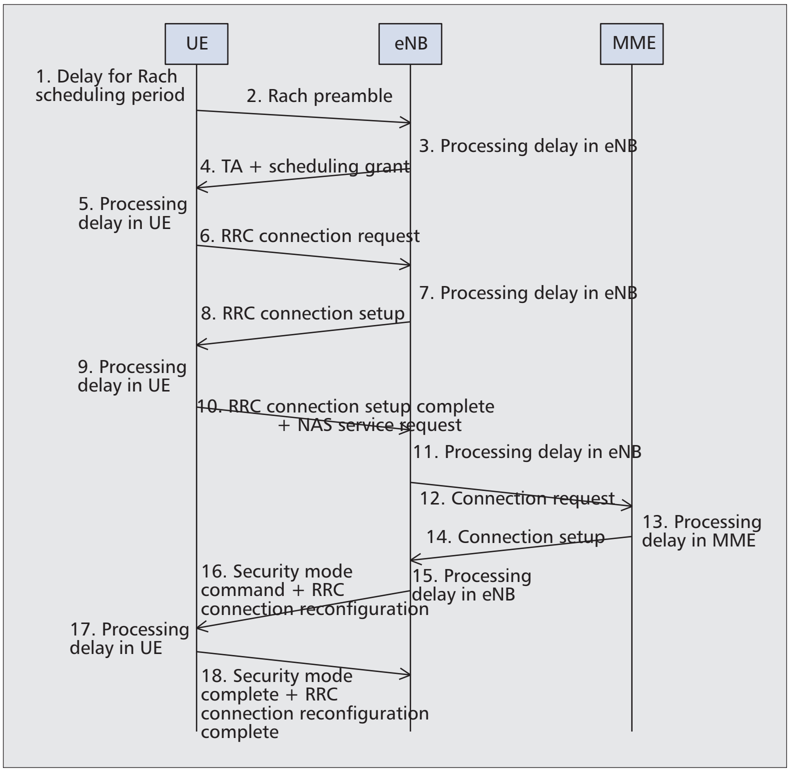

Figure 1. *Control-plane activation procedure.*

Both msg3 and msg4 adopt HARQ (Hybrid Automatic Repeat request) as an approach for retransmission of data blocks that are not received successfully at the first time, in such a way that the data from the multiple transmissions can be combined. The retransmission probability and maximum number of HARQ transmission of msg3 and msg4 for simulation are listed in Table 1 [4]. If the transmission number of msg3 or msg4 reaches the maximal number of HARQ transmission in Table 1, the UE shall restart RACH procedure from preamble transmission. Only when both msg3 and msg4 are successfully received is the RACH procedure completed.

RAN overload caused by massive MTC devices results in the shortages of RACH resources and control resources. The former leads to extremely high RACH collision probability, and the latter means that insufficient control resources are available to reply UL grant and Msg4 to all MTC devices before UE timer expiration. Both of the shortages bring about high probability of RACH procedure failure and therefore degrade the network performance severely. Since RAN overload problem is predictable and crucial to LTE and other communication systems involving with MTC, we introduce RAN overload control methods in the following section.

RAN Overload Control Method

The essence of RAN overload control methods is to disperse the load of random access to different time slots, to limit and distinguish the random access behaviors, and to tune system parameters for different MTC access traffic.

PUSH BASE METHODS

In a push based MTC network, it is the MTC device that autonomously initiates the RACH procedure. Three subclasses of mechanism have been proposed: *randomized access dispersion*, *differentiated services provision*, and *dedicated resource allocation*.

Randomized Access Dispersion — In this category, MTC devices apply randomization to decide their preamble transmission slots so that massive accesses can be spread onto a long period of time and thus RACH contention can be resolved. This subclass includes:

Backoff Indicator Adjustment: Apply a backoff indicator much larger than the maximum value (960ms) specified in [8], as suggested in [9]. The corresponding simulation result is shown later.

P-persistent approach: In this method each MTC device is assigned a predefined value *p*. Each time when a MTC device attempts to start the random access procedure, it first randomly generates a random number between 0 and 1. If the generated number is smaller than the device's P-persistent value, it can transmit RACH preamble. Otherwise, the device needs to backoff and waits for the next interval to try again. The interval is specified by backoff indicator in Table 1 [4].

Wait timer adjustment: For this alternative, we add a new parameter called "wait timer." Note that the wait timer here is different from the extended wait timer defined in RRC level. Here, we refer the wait timer to be the length of period that a MTC device has to wait for after it fails to receive RAR, msg3 and msg4. In this period, UE stops sending information to the eNB, enabling itself to optionally switch to sleep mode to save power.

Differentiated Services Provision — In this subclass of method, the UE is classified into several categories and/or are prioritized according to their service type or QoS requirement.

- Access Class Barring: As introduced in [2], a UE could not send RACH preambles if it belongs to the forbidden access class (AC).
- UE/MTC prioritization: An MTC device with lower priority would be assigned with larger (MTC specific) backoff indicator, lower preamble transmission probability, or worse RACH resource (with larger collision probability compared with that of a UE).

Dedicated Resource Allocation — Allocating dedicated resource to the MTC devices can reduce the severe impact on the random access of UE.

- Slotted access: as specified in [4], each MTC device can access the network only in its own dedicated time slot.
- Separated RACH resource allocation: As suggested in [4], H2H traffic and MTC are assigned with different resources to prevent MTC traffic from competing with H2H traffic. For resource usage efficiency, resource allocation of MTC devices could be dynamically adjusted according to the immediate traffic change.

PULL BASE METHODS

In a pull based MTC network, it is the eNB that initiates the RACH procedure. In other words, by polling-based medium access control, RAN overload problem could be resolved. From the network's point of view, pull based approach can be sorted for centralized RAN overload control methods.

Paging Method — Only when the paging message includes the ID of the MTC devices should the paged ones start their random access procedures. In this centralized control method, extra control channel resources are required to page massive MTC devices, which would be evaluated in the next section.

Contention-Free RACH Procedure — Besides the aforementioned contention-based RACH procedure, 3GPP [6] specifies contention-free RACH procedure, in which the eNB can apply reserved RACH resources for RACH procedure initialization. In this procedure, the eNB first

Parameter	Setting
Number of MTC devices	5000, 10000, 30000
MTC devices arrival distribution	Uniform distribution over 60s, Beta distribution over 10s
Cell bandwidth	5MHz
PRACH Configuration	6
Total number of preambles	54
Maximum number of preamble transmission	10
Number of UL grants per RAR	3
Number of CCEs allocated for PDCCH	16
Number of CCEs per PDCCH	4
Preamble detection probability (in case of no collision)	$1-1/e^{i}$, where i indicates the i-th preamble transmission
ra-ResponseWindowSize	5 subframes (5 ms)
mac-ContentionResolutionTimer	48 subframes (48 ms)
Backoff Indicator	20ms
HARQ retransmission probability for Msg3 and Msg4 (non-adaptive HARQ)	10%
Maximum number of HARQ TX for Msg3 and Msg4 (non-adaptive HARQ)	5
Maximum number of UE in Paging List	16

Table 1. *Parameter settings.*

sends UE a RA-assignment including dedicated RACH preamble. After receiving the message, the UE initializes its RACH procedure by sending the indicated RACH preamble. At present, the utilization of contention-free RACH procedure is not yet addressed, and we think it is a potential method for centralized overload control.

SYSTEM PARAMETER TUNING

Since optimized packet success rate and resource utilization are subject to the change of MTC traffic, contention may be released with an appropriate system parameter change. The following parameters, as listed in Table 1, may be dynamically tuned with the MTC traffic change. For example, we could lower the maximum number of preamble transmission to avoid collision when the network encounters serious congestion.

- Maximum number of preamble transmission
- Maximal HARQ Retransmission Times
- Ra-ResponseWindowSize
- mac-ContentionResolutionTimer

Since eNB is unable to distinguish that the RACH preamble is initiated from a UE or a MTC device, we address the issue of identifying the initiator of the RACH procedure. Crucially, identifying the source of RRC connection setup during RACH procedure enables the eNB to immediately reject or release the connection setup request from low priority users(by sending RRCConnectionReject/RRCConnectionRelease message) to reduce the wasted resource. As suggested in [10], a new establishment cause or indicator can be added to Msg3 / Msg4 so the eNB can identify the source of connection request. However, the current 3GPP specification is mainly used to add indication to Msg3/Msg4 for low priority users, not for the identification of MTC applications.

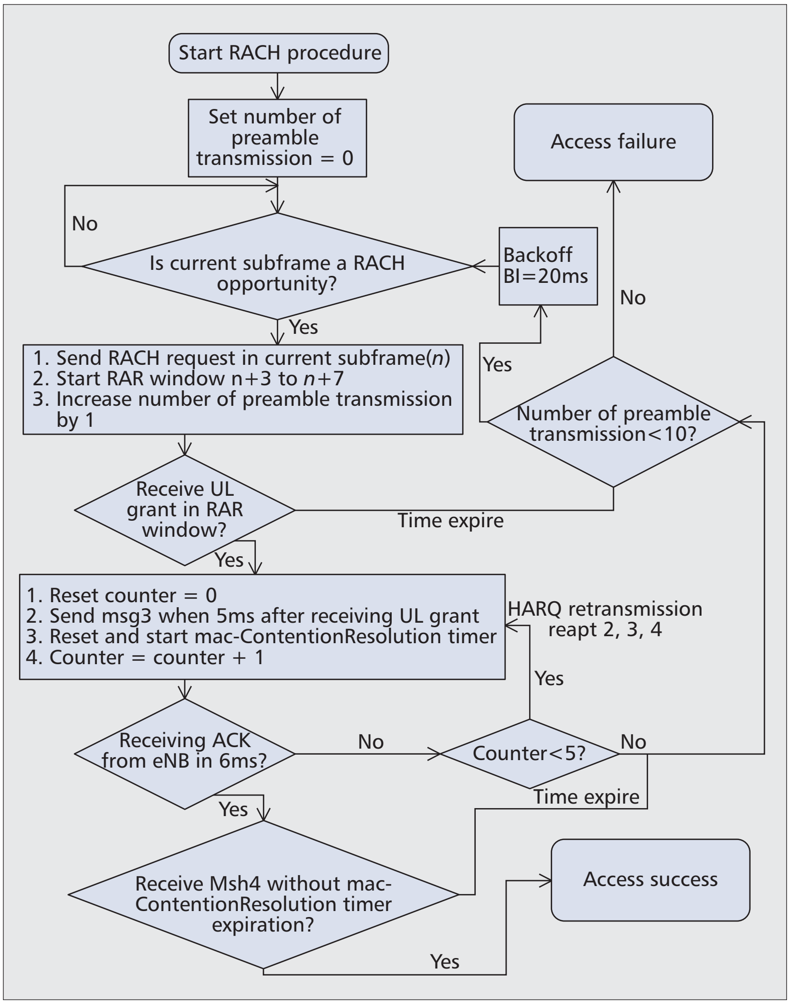

Figure 2. *UE behaviors.*

CN (CORE NETWORK) OVERLOAD RESOLUTION MECHANISM

After introducing the RAN-level overload resolution methods, we then give a brief introduction to some CN overload resolution mechanisms. Currently, the following three mechanisms are agreed by 3GPP but the detailed specification is still under discussion.

Extended Access Barring (EAB): When EAB is triggered, the UE configured with EAB would be restricted to access the network. The mechanism is used to bar those MTC devices to avoid the overload of access network and/or the CN.

Extended Wait Timer (eWaitTimer): If Msg3 identifies that the RACH procedure is from a MTC device, the IE (information element) eWaitTimer may be included in RRCConnectionReject/RRCConnectionRelease to bar this MTC device. On the other hand, if a MTC device is identified in the RRC complete message, RRCConnectionRelease could be used to bar it until the eWaitTimer timeouts.

"Delay tolerant" indicator: The indicator could be used to specify whether a UE is delay tolerant. Currently, the indicator can either be a new cause in Msg3 or an indicator in RRC setup complete.

Further discussion about the three mechanisms is provided in [11]. Another purpose of CN overload control is to reduce the signaling from MTC applications or small data transmission. See [12] for detailed description.

DISCUSSION OF OVERLOAD CONTROL MECHANISM

In this subsection, we address the advantages and disadvantages of these methods. Although no extra signaling is needed, pull based methods, as suggested in [3], could not efficiently resolve RAN overload when the number of MTC devices is large. As shown in our simulation results, contention resolution is always accompanied by a large delay. In fact, the tradeoff between success probability and delay is unavoidable as the RACH resource is very limited to accommodate such a massive number of MTC devices. Push based method, on the other hand, prevents the possible contention in RAN level and thus improves the resource efficiency. However, in a mobile originated (MO) case, the UE's intention of sending data is unknown to the eNB, which means that the eNB may page a UE but the UE has no data to send. Coupled with the limited number of UE to be paged on paging occasions, the MO case takes a long average waiting time for paging. System parameter tuning has the

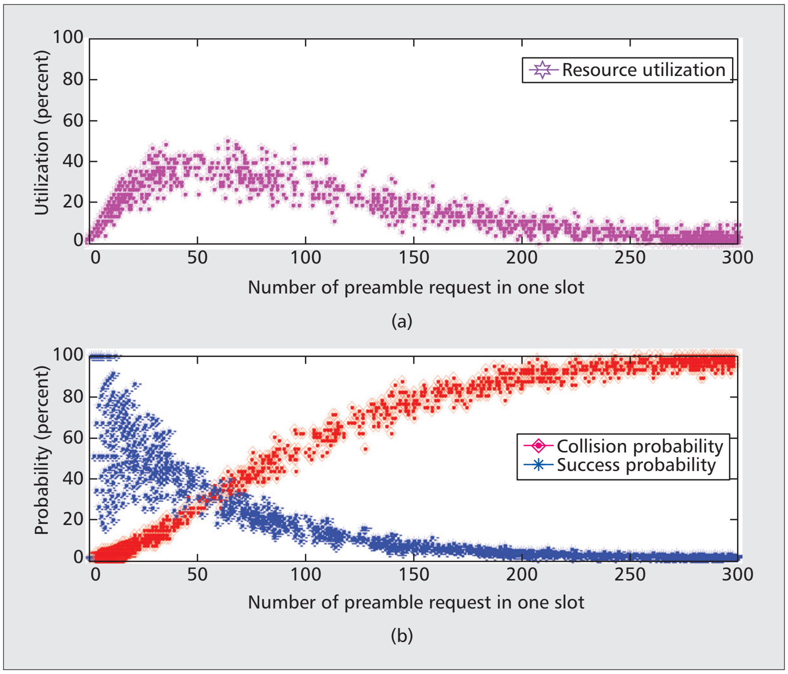

Figure 3. *Resource utilization, collision and success probability for PRACH.*

advantage of keeping the current 3GPP specification unchanged, but is not adaptive to the dynamic change of MTC traffic because it takes time for UE to receive and apply updated parameters broadcasted by the eNB (i.e. through SIB, system information block).

Since no RAN-level solutions can work efficiently without significantly changing the current specification, the current 3GPP standard then turns to methods that guarantees the service quality of H2H traffic. The basic idea is to distinguish UE from MTC/low priority/delay tolerant users, reduce the loading from the latter when RAN and/or CN are overloaded, and reduce signaling overhead for MTC and small data transmission.

SIMULATION

ASSUMPTIONS AND PARAMETERS

To provide insight of RAN different overload methods, we conduct simulations following the parameters settings of the LTE FDD mode in Table 1[4]. Note that in each cell, 64 preamble sequences are available, but ten of them are dedicated for other purposes. Thus, 54 preambles are applied as shown in Table 1.

Since downlink control resources are relatively insufficient compared with numerous MTC devices, we study the downlink resource allocation for Msg2 and Msg4. In each subframe, there is only one RAR which consumes 8 CCEs in PDCCH and can grant up to 3 UEs. The total resources in PDCCH (Physical Downlink Control Channel) in a subframe are 16 CCEs (Control Channel Elements). Besides, msg4 consumes 4 CCEs for one UE and paging message consumes 4CCEs to page a UE. Thus, 16 CCEs could be used by several different combinations. For example, one of these combinations is 8 CCEs for UL grant, 4 CCEs for msg4, and 4 CCEs for paging.

The preamble detection probability, defined as the probability that the eNB detects the signal of the preamble, correlates to the transmission power of UE. In each preamble retransmission, the UE gradually increase its transmission power (follow the power ramping function [8]) to increase the detection probability. Besides, for preamble transmission, we follow the assumption in [4] that if more than two UEs choose the same preamble sequence, these collided UEs cannot receive RAR due to preamble collision (In reality, if more than two UEs choose the same preamble, it is possible for the eNB to distinguish the preamble with larger transmission power from the collided signal, which is known as the capture effect.) Simply speaking on mac-ContentionResolutionTimer, it is the window size for msg3 and will be started by a UE when it has successful received random-access response from eNB. In our simulation, we further include voice call traffic which follows Poisson distribution with average 7 calls per second. Maximum number of UE in paging list is the maximum UE ID included in a paging message.

STEPS BY STEPS ANALYSIS

The baseline results without applying overload control method [6] show that for a uniform MTC arrival distribution case, all devices achieve 100 percent success probability. Thus, we focus on beta distribution (burst arrival) with device number greater than 10,000. In this subsection, we analyze the UL and the DL part respectively.

Random-Access Preamble Transmission Analysis — In RACH preamble transmission, we classify the preamble usage into three categories: First, no UE use this preamble, called "empty." Second, only one UE use this preamble, called success "used." Third, more than two UEs use the same preamble, defined as "collided" preamble. The following three performance metrics are then defined:

- Success probability for preamble: The success probability is defined as the number of preamble successfully received by the eNB divided by the total number of RACH preamble transmission in that time slot. In other words, the total number of request RACH preamble is the number of UEs sending preamble at that time slot.
- Preamble resource utilization: The preamble resource utilization is defined as the number of "used" preamble divided by the total number of preambles (i.e., 54 preambles).
- Collision probability of preamble: The preamble collision probability is defined as the number of "collided" preamble divided by the total number of preambles.

From Fig. 3, we can see that preamble resource utilization has a maximum near the total number of preamble sequences. Besides, low utilization in high/low amount of preamble access is due to high collision probability and few number of preamble transmission respectively. In other words, when the number of preamble access is small, UEs failing in preamble transmission is mainly due to insufficient transmission power to be detected by the eNB, rather than preamble collision with other UEs.

Downlink Resource Consumption Analysis — All the UEs need to monitor PDCCH for receiving RAR and msg4. The resource consumption has been described in the previous section. The RAR has the highest priority to use CCEs, but only consume up to 8CCEs. Msg4 has the second priority to use CCEs, and paging message has the lowest priority. In Table 2, we calculate the CCEs consumed in each message, total consumption, and average CCEs for each success UE.

From Table 2, we see that paging method consumes the most CCEs among all methods due to the paging message. For BI method in randomized access dispersion category, if we increase the value of backoff indicator, the consumption in msg2 will decrease due to less waste in the random access response. The consumption in msg4 increase is because that the success probability has increased and needs to send msg4 more frequently. Similar results can be found in both p-persistent method and wait timer method. For the maximum number of preamble transmission adjustment, though the total consumption in CCEs appears to be the same, the value of CCEs consumed per success UE is higher than other methods due to its small amount of success devices. All the push base methods have roughly the same resource consumption, and for these methods, higher success probability accompanies with lower CCEs consumption per success UE.

Units	(CCEs)	Msg2	Msg4	Paging	Total	Per success UE
Paging	343110	134180	26150	503440	16.7813	
BI	20	442300	37220	0	479520	57.8518
	800	406980	75330	0	482310	29.5215
	3840	351020	133770	0	484790	16.1793
p-Persistent	0.005	350260	134650	0	484910	16.1647
	0.04	414470	66890	0	481360	32.9907
	0.15	438830	41270	0	480100	52.4564
	0.50	441880	37680	0	479560	57.1606
	0.95	442230	37290	0	479520	57.7318
preamble	10	442300	37220	0	479520	57.8518
	13	450450	28810	0	479260	74.5159
Wait timer	60	439790	40240	0	480030	53.6047
	780	376020	109720	0	487540	20.4948
	1660	351030	133770	0	484800	16.1682

Table 2. *PDCCH resource consumption for different methods.*

Overall Analysis

In this subsection, we define some metrics to evaluate the performance of random access procedure.

- *Average Access Success Probability*, defined as the probability to successfully complete the random access procedure within the maximum number of preamble transmissions.
- *Average Access Delay*, defined as the time between the data generated and the completion of the random access procedure, for the successfully accessed MTC devices. (The definition here is a little different from which defined in [13].)

Figure 4a illustrates the statistics of the baseline scenario without applied any control method. During the period with numerous preamble accesses, the voice call is in a poor condition (i.e., no phone calls can be made at that time.) In Fig. 4b, we can see that the access peak with larger maximal preamble transmission times is much higher than the baseline one, leading to an even lower H2H success rate. This is because redundant preamble retransmissions aggravate the situation of RACH collision. However, if the traffic load is not heavy, increasing the number of preamble transmission may incur a higher success probability because the power ramping increases the transmission power, causing a higher detection probability. Thus, the optimal number of maximal preamble transmission is subject to the traffic conditions and cannot always be achieved by decreasing the maximal number of preamble transmission.

As mentioned earlier, the p-persistent and backoff method have a relationship described in [14]. Figure 4c and Fig. 4d show that both methods can lower the peak and disperse the traffic load in time to achieve higher H2H success rate. Wait timer method, on the other hand, makes similar impact on access dispersion, as shown in Fig. 4e. The distinction between the two is that wait timer method reshapes the original access traffic into several smaller access peaks in the time scale. Finally, Fig. 4f illustrates that the paging method can reshape the original traffic load into uniform distribution, which is in the premise that all paged devices have data to send. From Fig. 4, we summarize that a better contention resolution includes conditions like a lower p-value, a larger backoff indicator, and a larger wait timer. As the optimal value always depends on the access traffic, changing the maximum number of preamble transmission cannot guarantee a constant better performance.

Additionally, dispersing the traffic load in time leads to higher success probability for both H2H and MTC traffic, but is with the tradeoff of an increasing delay. Three things can be observed from our simulations: first, for all push based methods, access delay grows linearly with the increase of desired success probability. Second, these push methods share the same tradeoff between success probability and access delay. And third, the success probability for paging method (i.e., pull base method) is always 100 percent, but come with the price of more control resources consumption. Due to the limit of figure number, we omit the tradeoff result here.

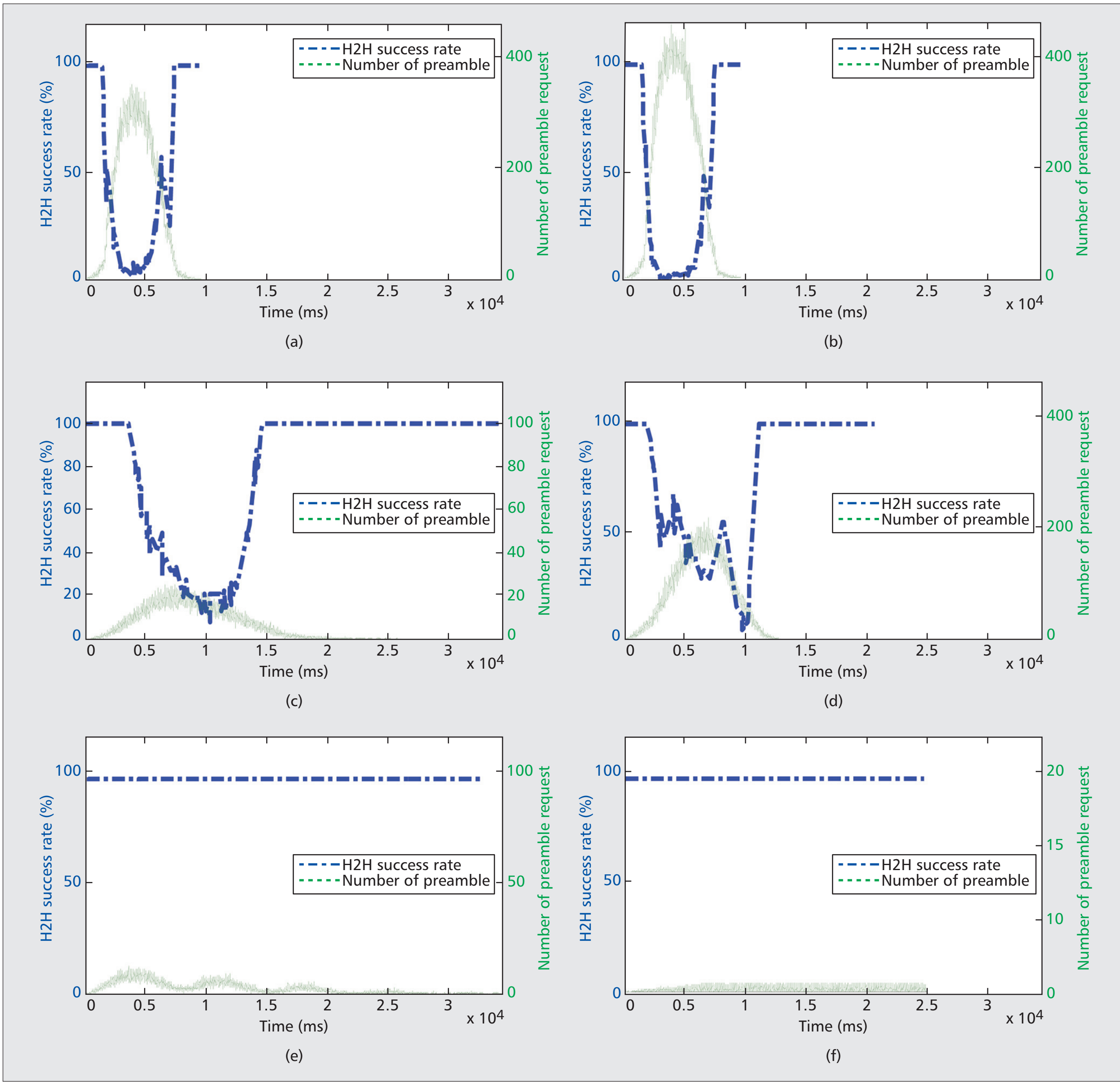

Figure 4. *H2H success rate under different methods.*

Conclusion

This article provides an overview of RAN/CN overload problem/solutions in 3GPP LTE-A. We first introduce the preliminary knowledge of RACH procedure. Then we classify different types of RAN-level contention resolution mechanism and address their advantages and disadvantages. Since CN overload control methods are promising in resolving RAN-level overload, we further introduce the development of CN overload mechanism that is under discussion of 3GPP currently. To conduct a comprehensive study to different RAN-overload resolution methods, a comparison between the performances of different mechanisms is also provided. We conclude that RAN/CN resources are insufficient to meet the needs of all users and MTC devices, and the promising solution is to discriminate UE/MTC devices, protect H2H traffic from server service degradation, and reduce signaling overload from MTC devices.

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BIOGRAPHIES

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