THE UNIVERSITY OF
NEW SOUTH WALES

SCHOOL OF ELECTRICAL ENGINEERING
AND TELECOMMUNICATION

Massive Connectivity for Internet of Things

by

Zhongtian Tang

Master of Engineering (Telecommunications)

Submitted: October 24, 2016

Abstract

Machine Type Communication (MTC) for IoT is a significant technology for future smart city. The project aims to deal with collision problem in uplink access of MTC with the background of LTE networks. Plentiful load relief schemes (e.g. Access Class Barring (ACB), slotted access, grouping and eNB selection) have been proposed to alleviate the problem. To further improve the system, this project applies Contention Resolution Diversity Slotted ALOHA (CRDSA) schemes to current OFDMA LTE network, which could further increase throughput for given access load.

Abbreviations

IoT	Internet of Things
MTC	Machine Type Communication
OFDMA	Orthogonal Frequency Division Multiple Access
CRDSA	Contention Resolution Diversity Slotted ALOHA
eNB	evolved Node Base station
LTE	Long Term Evolution
RA	Random Access
ACB	Access Class Barring
IC	Interference Cancellation

Contents

Charpter 1

Introduction

The Internet of Things (IoT) is the network for physical objects (e.g. sensors, controllers, etc.) with minimal human intervention, which is firstly forwarded by Professor Kevin Ashton from MIT in 1991. The concept of smart city has been proposed in recent year to achieve the intelligentization of city management, which brings that the IoT should focus on not only indoor but also outdoor network construction [1] - [6]. The key technology to achieve the IoT is the Machine Type Communication (MTC) distinguished from human device (e.g. mobile phone, personal computer and tablet) communication.

In [7], the Third Generation Partnership Project (3GPP) organization proposes several service requirements for MTC, including

- *Surveillance and security*: helping police monitoring public area and auto alert;
- *e-Health*: supporting remote diagnosis and health information update;
- *Infrastructure management*: real-time interaction between infrastructures to provide better public service;
- *Smart home*: monitoring, remote control or automatic action of home machines to provide better living environment and saving energy resource.

Apparently, such smart city applications need a large number of devices (e.g. sensors, cameras, controllers, etc.) sharing information at the same time. Therefore, the MTC has the feature of frequent uplink transmission with small packet size from massive devices. The MTC devices should do random uplink access to network to initiate the uplink transmission. According to the feature of MTC, the system is easy to be overloaded during such uplink access procedure. Then several devices would contend for the same uplink access resource, which would lead to severe collision problem and system throughput performance would be catastrophic.

The aim of this project is to deal with collision problem during the uplink access of MTC devices and reduce packet loss rate to improve system throughput performance. This paper is divided into 8 chapters. MTC access networks and project system model will be introduced in Chapter 2. In Chapter 3, certain existing load relief schemes will be discussed. Chapter 4 will analyse the imperfection of current system with load relief schemes. Chapter 5 will introduce CRDSA scheme which is the key technique of the project. Chapter 6 will propose an OFDMA uplink access system applying CRDSA with signal processing details. Its simulation results and analysis will be demonstrated in Chapter 7. Chapter 8 will conclude the whole paper and state some future work.

Charpter 2

MTC networks and System model

2.1 MTC Access Networks

There are plentiful types of access networks for human device (e.g. PC, mobile phone and laptop) communication currently, so are for MTC [8]-[10]. The access network can be either wired, such as cable or optical fibre, or wireless, such as Wireless Local Area Network (WLAN), ZigBee or cellular. Wired networks possess the feature of high robust and high data rate but low mobility, low scalability and high cost in complex terrain environment with large number of access devices. As for WLAN, although its power cost is less, the small coverage range and poor outdoor performance make it not suitable for MTC network in smart city. In contrast, cellular, or Long Term Evolution (LTE), provides ubiquitous coverage, high mobility and good scalability, which make it an ideal type of main access network for IoT devices to realize MTC in smart city.

[11] gives a conceptual graph (shown in Figure 2.1) of MTC in LTE networks. In the radio access network (RAN), human devices (e.g. mobile phone or mobile broadband device) and MTC devices share the same access to one evolved Node-Base station (eNB) in one cell. In some situation, some

MTC devices, such as e-Health and camera sensor, access to eNB via MTC Gateway (MTCG) which provides local control for MTC devices through low-power WLAN.

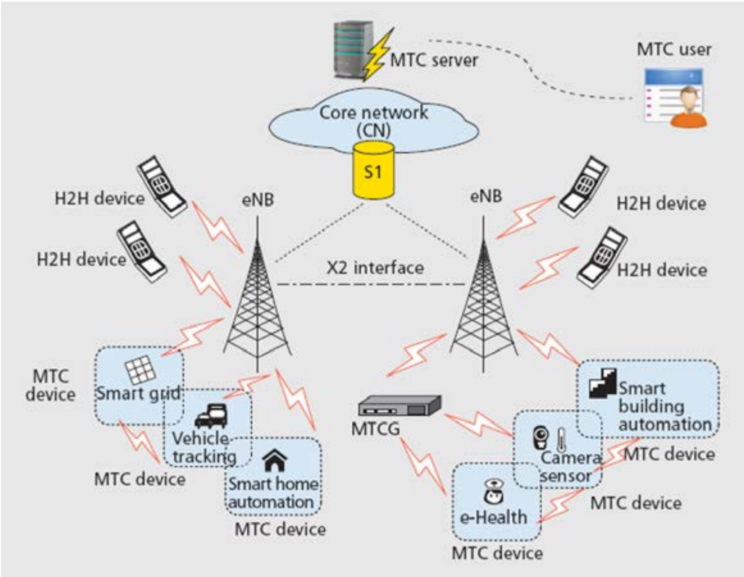

Figure 2.1 [11]

2.2 Uplink access

As mentioned in the previous section, the main challenge of massive connectivity for IoT is the uplink collision due to frequent access attempt from large amount of MTC devices. In LTE network, Random Access (RA) is an inevitable procedure for devices requesting uplink resource. Current LTE (4G) network's RA procedure is mainly for human devices, which initiates in the slotted Physical Random Access Channel (PRACH). The steps of RA procedure can be summarized as follows [11]:

1. Devices randomly choose one preamble and transmit it to eNB in slotted PRACH;

2. The eNB transmits Random Access Response (RAR), including preamble ID, cell radio network temporary identifier (C-RNTI) and information of transmission schedule;

3. According to schedule information in RAR, device transmit actual RA

message as well as C-RNTI and International Mobile Subscriber Identity (IMSI);

4. eNB sends contention resolution message (e.g. Back-off message) if the RA message is unable to decode (i.e. contention is detected).

Contention will occur if different devices choose same preamble in step 1, which will lead to RA message interference in step 3.

However, this current RA procedure may not be suitable for MTC. As a huge number of devices in one cell as well as limited available preambles, the collision probability is extremely high. For example, according to [12], assuming 1000 users in one cell with 64 available PRACH preambles, the collision probability is nearly 99.97% if the packet arrival interval is 30ms. Additionally, with frequent RA from large number of devices, coordination process (step 2) of eNB could increase system latency and power consumption. Therefore, in the future LTE networks (e.g. 5G), coordination should be given up, at least in MTC.

2.3 System Model

Coordination scheme is not suitable for MTC, so in the project model, a pure RA Orthogonal Frequency Division Multiple Access (OFDMA) is settled. OFDMA system has been widely used in LTE's access system because of its flexibility [13]-[17]. Also, OFDMA could be more energy efficient if access resources are allocated appropriately [18] - [36]. When a device attempting to access the network, it will randomly choose a Time-Frequency slot in one OFDMA frame to transmit the uplink access packet which includes not only just preamble but also payload part containing actual uplink access message.

In this model, the collision problem will happen if several devices chose the same Time-Frequency slot to transmit packets. This situation would frequently happen if the system is overloaded. Therefore, plenty of schemes have been proposed (introduced in the following section) to relieve the system load.

Charpter 3

Load Relief Schemes

Currently, plenty of papers have proposed various methods and schemes to alleviate the severe collision in RA procedure in MTC. In this part, certain good schemes will be presented.

3.1 Access Class Barring (ACB)

The original ACB scheme is proposed in [37] and [38]. The eNBs initially broadcast the access probability and access class (AC) barring time to all the devices in the cell. When a device attempts to perform RA, it randomly generates a number between 0 and 1. If the generated number is less than access probability, then the device will proceed the RA. Otherwise, it will wait for AC time to try again. Also, if the device fails the RA (e.g. collision), the back-off time will be still AC.

There are also some enhanced versions of ACB scheme. The extended access barring (EAB) is presented by 3GPP in [39]. In this scheme, ACs are different in different type of devices. For example, devices which can tolerant high delay time would possess large AC. The eNB only have to broadcasts access probability to devices according to its RA load.

Cooperative ACB [40] is an advanced ACB scheme where all the ACB parameters (access probability and AC) are dynamic, selected by eNB according to the RA load in the system and the type of devices.

The ACB schemes use parameters to control the permission and back-off time of RA among devices which are classified according to their ACs, so that can relieve the RA load of each eNB. Therefore, the collision in RA could be alleviated.

3.2 Slotted Access

In this scheme, the RA frame is built in the MAC layer, which is divided into several time slots. Each of device is allowed to transmit RA packet in one dedicated slot. The number of slots in the RA frame is first broadcast by the eNB. Then the devices can calculate its allowable packet transmission slot by the number of slot and its own ID.

The slotted access scheme spreads the all devices in the cell on several time slots, which builds several parallel RA channel, so it could alleviate the collision and increase throughput. However, collision still could happen if several devices attempting RA are allocated in the same slot. Additionally, the situation that collision happens in one slot while other slots are unused could happen, which wastes the precious time slot recourse in RA.

3.3 Grouping devices

In [41], the scheme grouping or clustering the MTC devices are proposed based on QoS requirements. The devices are grouped according to their types or locations. Then there should be a group head which could be one of the grouped devices or a gateway. The group head is as functional as a replay point communicating with eNB in LTE networks on behalf of the grouped devices.

As for the network in the group, it can be wired or WLAN. [42] introduces a WLAN standard (still in research) dedicated to MTC called IEEE 802.11ah which is firstly proposed in [43]. The IEEE 802.11ah is an improved version of conventional WLAN standard (IEEE 802.11) and aims to support cellular offloading and MTC. In comparison to conventional IEEE 802.11, the carrier frequency of IEEE 802.11ah is below than 1GHz, so the transmission range can be up to 1km. Also, it is more suitable for small data transmission and operate in low power. In downlink, it adopts bitmap and could support up to 6000 devices. As for uplink, the IEEE 802.11ah uses slotted access and in each slot it adopts Distributed Coordinate Function (DCF) and optional Point Coordination Function (PCF) which are already used in conventional IEEE 802.11 standard and can support up to 50 devices for uplink, so the number of devices the IEEE 802.11ah can support is $50 \cdot n$ where n is the number of slots in the MAC access frame. Grouping scheme is another effective method to release the RA load of the eNB. It could reduce collision rate, thus improving the throughput performance.

3.4 eNB selection

The learning-based eNB selection scheme is proposed in [11], which aims to minimize the network overload. In this scheme, the devices in the overlapped area of several eNBs covered range are allowed to choose the eNB who has the lowest load to perform RA. The selection algorithm is called Q-learning algorithm which can be summarized as follows (assuming the device is in the overlapped cover-area of n eNBs $B = \{b_1, b_2, \ldots, b_n\}$):

1. The device initializes the Q-values $Q(s,a)$ for all s and $a \in B$, where s is the current selected eNB and a is the new eNB about to choose;

2. Assume the device is currently connecting to b_x (i.e. $s = b_x$). As for parameter a, there is a small probability (e.g. 3%) that the device would randomly choose an eNB, which is called *exploration* step. Otherwise, the device will perform *exploitation* step by choosing $a = \arg\max_{a \in B} Q(b_x, a)$. Let us assume $a = b_y$ in this step;

3. The device observes the QoS performance (i.e. Delay performance) of the communication to the current eNB b_x denoted by D_{b_x};

4. The device updates the particular Q-values as

$$Q(b_x, b_y) \leftarrow (1-\kappa)Q(b_x, b_y) + \kappa(D_{b_x} + \gamma \max_{a \in B} Q(b_y, a)),$$

where κ is the learning rate and γ is the discount rate;

5. Go to step 2.

The eNB selection scheme is another effective scheme to transfer the RA load from one overloaded eNB to relatively less loaded one. Although the devices adapting to this algorithm are in the overlapping area of the eNBs cover range, which may be a small fraction of the devices in the whole cell, it still could be applied with other load relief schemes together to further control the instant RA load of each uplink access frame.

3.5 Group paging

The above schemes presented are called push-based schemes. In contrast, there is also a pull-based scheme called group paging [41] in which the eNB cyclically pages a part of the devices in the cell. Each device is allowed to proceed RA only when it receives page message. The frequency of paging and the number of devices that be paged at a time are dynamic according to the eNB RA load and the device type.

Although this scheme can alleviate the RA load thus resolving the collision, it cannot be combined to other plentiful push-based schemes to improve the whole system. Moreover, if the scheme wants to be suitable for the MTC feature of frequent uplink transmission, the frequency of paging has to be quite high, which would consume much extra channel and power resources. Therefore, this method may not be suitable for the system.

Charpter 4

System Imperfection

Most of current methods dealing with the contention of RA in LTE networks for MTC are overload control mechanisms which decrease instant number of devices attempting RA procedure with one eNB. However, for constant RA load of one eNB, the throughput is not improved at all. Therefore, the project work is decided to focus on RA procedure design to improve the system throughput without reliving the RA load, which can still add overload control mechanisms in the whole scenario.

As a basic RA model system in telecommunication, Slotted ALOHA (SA) [44], [45] system has been widely researched and evaluated. For single-channel SA, [46] analyses the capacity of SA system and computes the throughput, while [47] presents the average access delay of devices according to the throughput of the single-channel SA system. Additionally, for MTC in LTE networks, [48] focuses on the collision and success rate, applying conventional (human device) RA procedure.

The RA procedure in LTE can be considered as a multichannel SA system. The scheme first sets a RA frame in MAC layer. During the period of RA frame, each device is allowed to randomly choose only one slot to transmit a burst (physical layer packet). This is called framed SA of which a received

RA frame example with 8 slots is shown in Figure 4.2. In this example, there are 6 devices attempting to access network and 4 of them collide during RA.

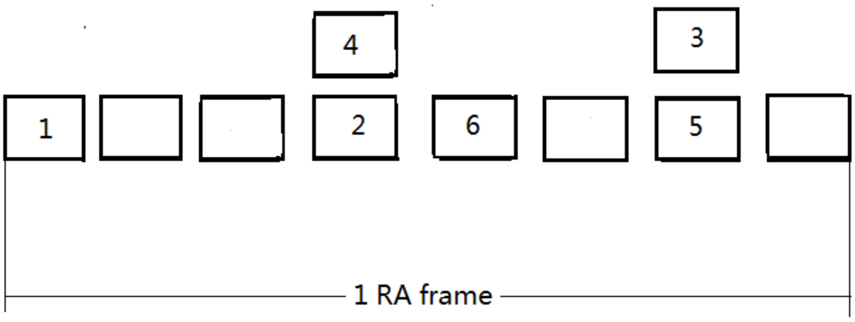

Figure 4.2

The simulation result of the framed SA is shown in Figure4.3. The blue line is perfect throughput performance with 100% throughput of the system load, while red line is the simulated framed SA throughput performance with much collision during RA. The object of the design is to increase the fraction of throughput to system load, which means making the red curve as close as possible to the blue curve in the graph.

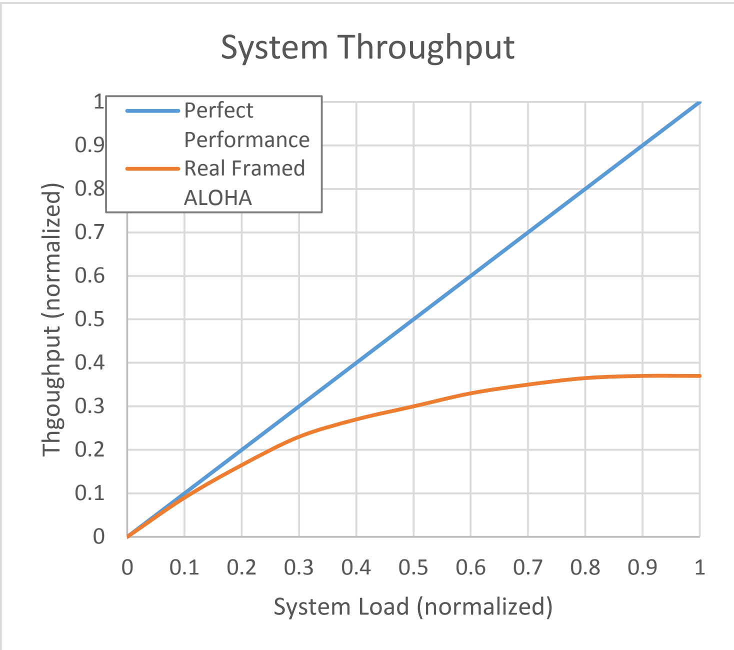

Figure 4.3

Charpter 5

Contention Resolution Diversity Slotted ALOHA (CRDSA) Scheme

Certain enhanced versions of framed SA have also been proposed. Diversity Slotted ALOHA (DSA) is introduced in [49]. The DSA allows every device to generate another replicas of the same burst which is also transmitted in a random-picked slot within the same RA frame. Therefore, in DSA scheme, the received RA frame in Figure 4.3 could be changed as shown in Figure 5.1. The throughput of DSA is slightly improved at small or medium RA load as it increases the success rate of transmission. However, the performance of DSA is worse than framed SA when RA load is high. [50] proposes Dynamic Frame Length ALOHA which is an enhanced version of framed SA. In this protocol, the frame length is dynamic according to colliding, successful and empty slots in the previous RA activities. The normalized RA load is given by $G = m/n$, where m is the number of devices attempting transmit a burst and n is the number of slots in one RA frame. Therefore, Dynamic Frame Length ALOHA can have a dynamic normalized RA load G thus be able to keep a high successful rate of transmission, which can also be helpful to DSA remaining low RA load.

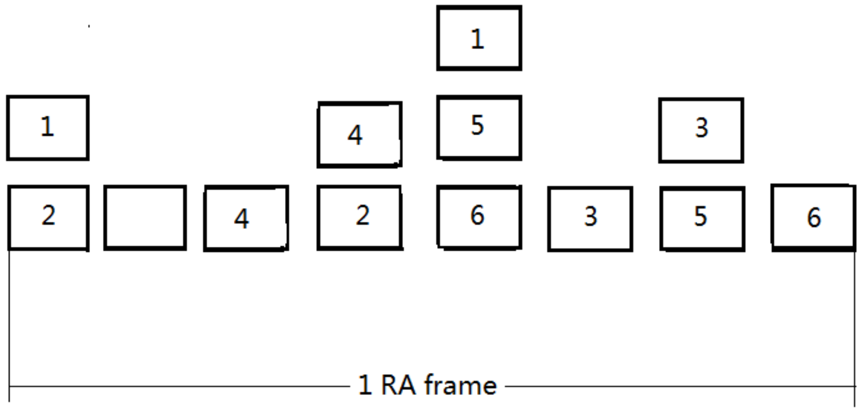

Figure 5.1

Contention Resolution Diversity Slotted ALOHA (CRDSA) is the main inspiration of the project design, which is first proposed in [51]. At transmitter side, the transmission scheme of CRDSA is similar to DSA. The MAC frame is composed of M slots. Each device randomly picks two of these M slots to transmit replica bursts when attempting RA. Each packet transmitted by device contains N_{pre} preamble symbols and N_{pay} payload symbols, while N_{guard} symbols are also needed between every two slots. We assume that there are N symbols in each slot. Therefore, we have $N \cdot M$ symbols in one frame, where $N = N_{guard} + N_{pre} + N_{pay}$.

The key novelty of CRDSA is that it applies iterated Interference Cancellation (IC) at receiver side to cancel the interference generated by the twin burst of the successfully decoded packets. The burst preamble in CRDSA is a pseudo-random sequence randomly chosen among a code family series by each device in each frame. The sequences in the family provide good auto and cross-correlation properties, which is for carrier phase estimation on the slot during the IC algorithm process. Although the real identification information is in the payload, preamble can be used to tell from each other in the one MAC frame. There is a small probability that same sequence is reused in the burst transmitted by different device in the same frame. However, according to the research in [51], the process will be sabotaged only when two packets from different devices reusing same preamble sequence are arriving within 1 symbol time of absolute differential delay. The payload is the actual RA message. In CRDSA, it also contains the slot pointer (protected by FEC) of its twin burst position in the same frame. The process of IC algorithm can be summarized as follows:

1.Initially set iteration counter $N_{iter}=1$ and maximum number of iteration $N_{iter}^{\max}$;

2.Demodulation and decode all the 'clean' bursts (bursts that can achieve preamble recognition and payload decoding and passed the CRC check);

3.Record the number of recovered bursts in current iteration $N_{recov}[N_{iter}]$ and output useful payload bits;

4.Stop if $N_{iter}=N_{iter}^{\max}$ or no clean burst in the step 2 (i.e. $N_{recov}[N_{iter}]=0$);

5.Get all information for twin burst regeneration, including:

(a) FEC encoded bits of current slot information bits and useful payload bits;

(b) Twin slot information bits;

(c) Channel Estimation;

(d) Twin burst preamble sequence;

(e) Twin slot phase estimation (position is derived from twin slot information);

6.Regenerate twin burst;

7.Repeat step 5 and 6 until all the $N_{recov}[N_{iter}]$ twin bursts are regenerated;

8.Cancel all the known bursts (regenerated and clean) in the signal

9.Get the interference canceled signal in to step 2 and $N_{iter}=N_{iter}+1$.

The numerical results shown in [51] and [52] proved that the CRDSA performs much better than framed SA and DSA, even at high normalized load. [52] proposed an improved version of CRDSA called Irregular Repetition Slotted ALOHA (IRSA). In the MAC frame of IRSA, the number of burst replicas of each device are different and settable according to the regular and irregular graphs defined by the author, which can improve the throughput further. However, the designs and algorithms in [51] and [52] are based on the Multi-Frequency Time Division Multiple Access (MF-TDMA) system in satellite communication networks which is quite different from the MTC in LTE networks, although both MTC and satellite communication possess the feature of small-sized and frequent uplink burst. Therefore, much details should be designed in both transmitter and receiver scenario if applying CRDSA/IRSA to MTC in LTE networks.

Charpter 6

Applying CRDSA in OFDMA LTE Network

6.1 Transmitter

The conceptual system diagram of applying CRDSA in OFDMA LTE network at transmitter side (device) is shown in Figure 6.1.

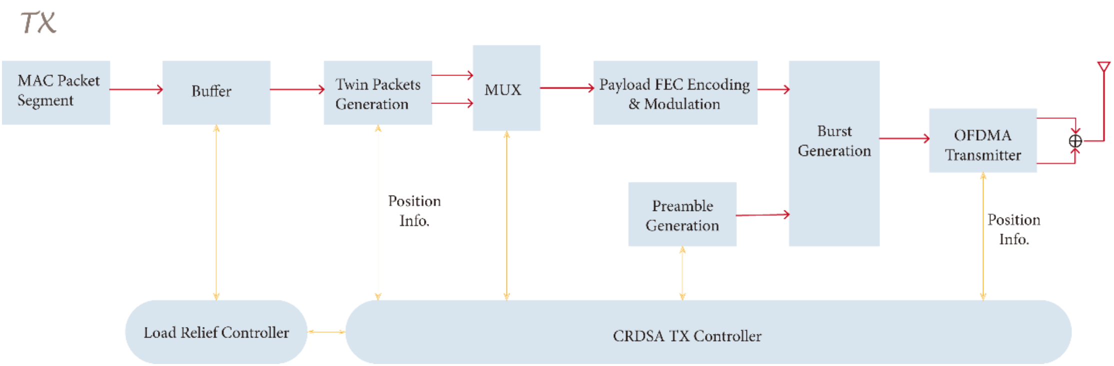

Figure 6.1

Access packets on the MAC layer would be first stored in a buffer which is controlled by a Load Relief Controller. Multiple Load Relief Schemes mentioned in Chapter 3 are applied on this controller, such as ACB schemes, Slotted Access, Grouping Devices and eNB selection. Once the packet is permitted to transmit, the CRDSA controller will start processing transmission. Two time-frequency slots will be randomly picked by the controller. Then the Twin Packets Generator will copy the incoming packets and add pointer bits among them according to position information from controller. After that, packets bit will be encoded and modulated then added preambles to form into bursts. The bursts will be fed into OFDMA transmitter and ready to be transmitted in the next frame time.

Briefly, the state diagram of CRDSA controller and system is shown in Figure 6.2. There are only 4 states overall. The first number indicates the number of processing packet, the second number indicates the number of packets in OFDMA transmitter buffer (ready and waiting to be transmitted in the next frame time) and the third tag is the state of the controller.

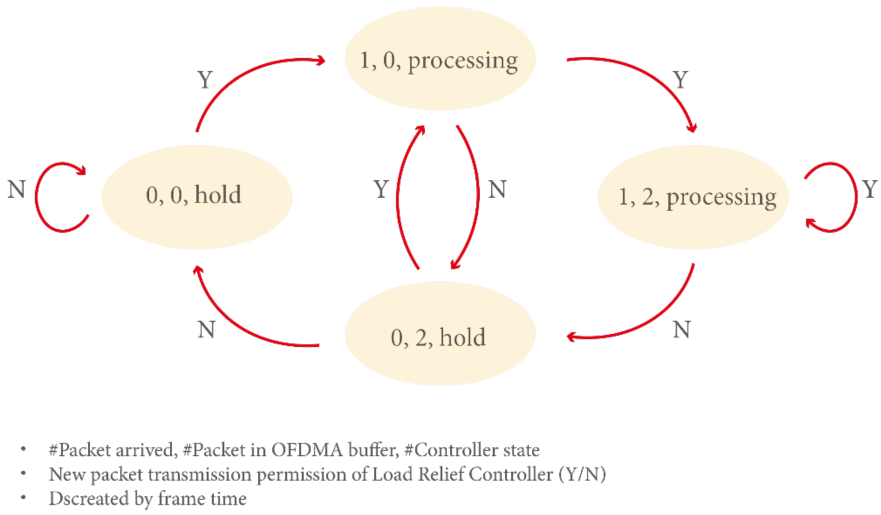

Figure 6.2

6.2 Receiver

At receiver side, the system diagram is shown in Figure 6.3.

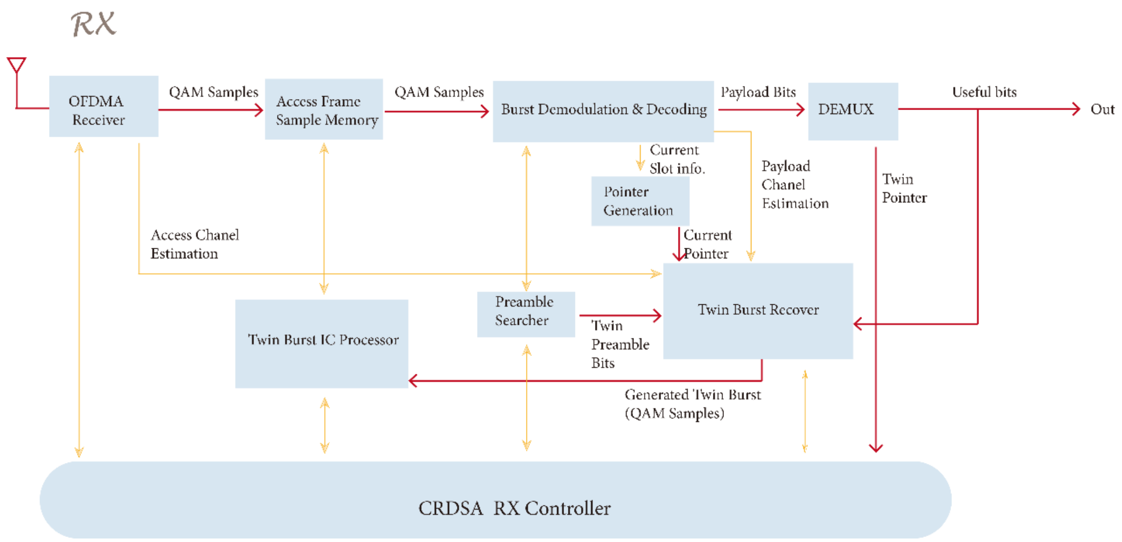

Figure 6.3

When received an OFDMA frame, the OFDMA receiver will demodulate received OFDM blocks into samples of basic modulation (e.g. BPSK, QPSK or QAM) and send its Access Channel Estimation parameter (e.g. frequency shift of OFDM sub-channels) to Twin Burst Recover. Then payload bits will be decoded from clean packets, which includes pointer bits and useful bits. Twin Burst Recover will integrate useful bits, current pointer bits and twin preamble bits and re-modulate them into basic modulation samples then shift them according to twin position information, Access Channel Estimation (frequency shift) and Payload Channel Estimation (time, phase and carrier). The Twin Burst IC Processor will cancel the twin packets according to recovered packets.

The state diagram of receiver applying CRDSA is shown in Figure 6.4 which could briefly demonstrate the system.

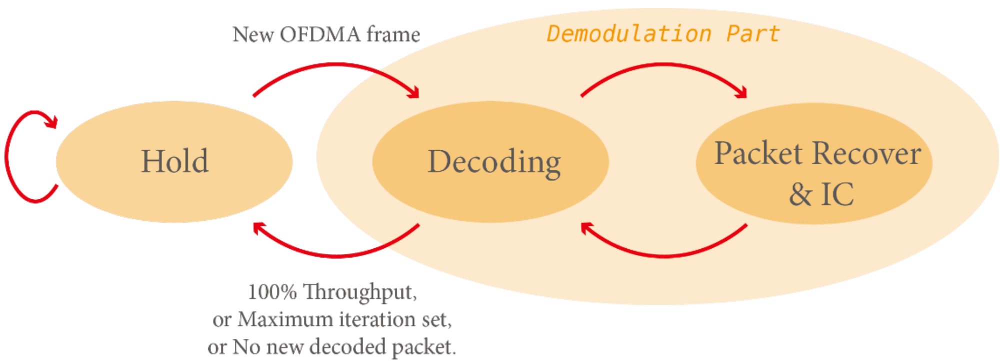

Figure 6.4

The receiver system mainly includes two states – 'Hold' and 'Demodulate'. When receiving new OFDMA frame, the system state will be changed from 'Hold' to 'Demodulation'. Specifically, the demodulate state includes two sub-states – 'Decoding' and 'Packet Recover and IC'. The system will keep decoding and doing packet recover and IC iteratively until the system achieves 100% throughput, meet maximum iteration set or there is no longer clean packet in the sample memory.

Charpter 7

Simulation Results and Analysis

The above CRDSA-applied OFDMA LTE system (Figure 6.1 ~ 6.4) is simulated in Matlab. The simulation stays on the MAC layer and the Matlab code is shown in the Appendix. For OFDMA access frame setting, number time slots is set as 64 and number of frequency slot is set as 32, so there are 2048 time-frequency slots in one OFDMA uplink frame. Because it is a random access simulation, each result is taken from the mean of 500 test results.

7.1 Performance

Figure 7.1 shows the throughput performance of 3 schemes, which is indicated by packet loss rate versus normalized load. The blue curve represents original Frame ALOHA, while the green curve is the CRDSA scheme with maximum iteration set as 1. Red curve represents CRDSA scheme without any maximum iteration set, which means the iteration will stop if system achieves 100% throughput or no clean packet in the sample memory. From Figure 7.1, we can see that original Frame ALOHA already start losing packet, while CRDSA (red curve) only starts losing packets when load is larger than 45%. Also, we can see that CRDSA packet loss rate increase significantly after 60% load, but it is still better than Frame ALOHA. CRDSA with 1 iteration maximum set could save more time and power than non-maximum-set CRDSA, but the performance is much worse. However, its packet loss rate is still lower than Frame ALOHA before 75% load.

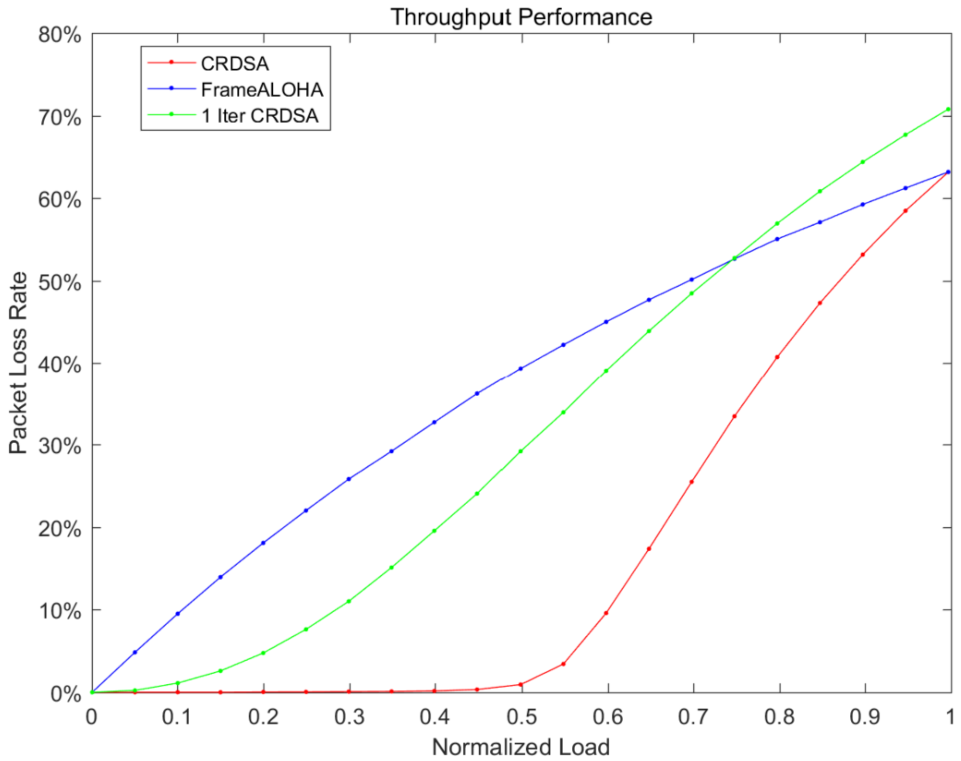

Figure 7.1

Figure 7.2 shows the frame utilization of 3 schemes mentioned above with increase of normalized load. For Frame ALOHA, it achieves its maximum utilization of 37% when load is full. In comparison, CRDSA achieves maximum frame utilization when load is nearly 0.6. For CRDSA without maximum iteration set, throughput is able to achieve 53% of the frame slots.

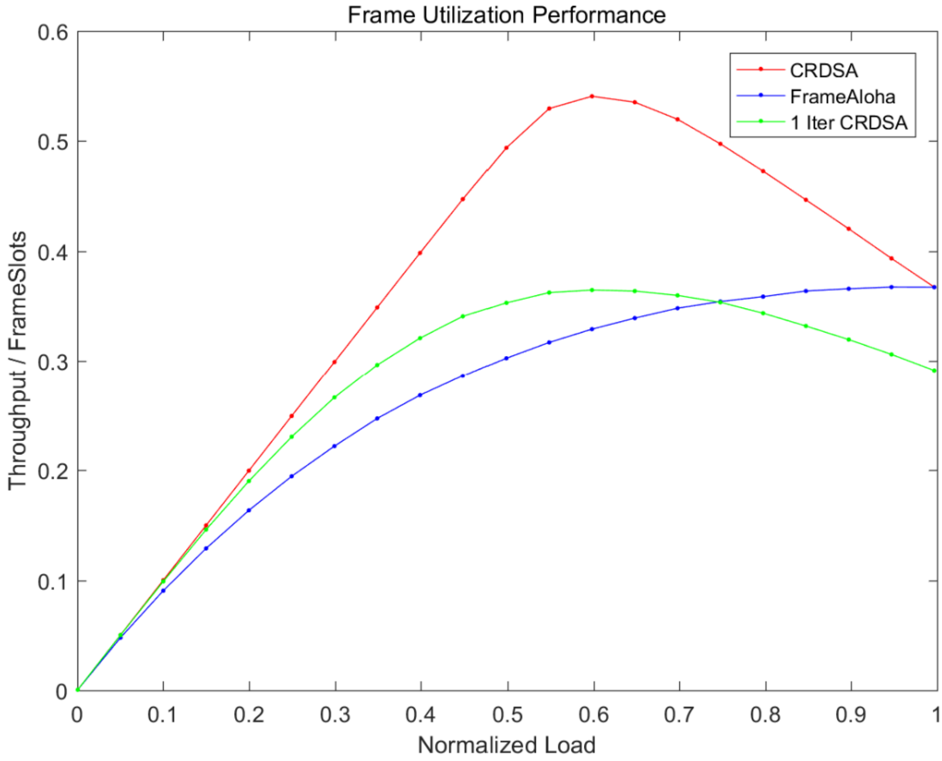

Figure 7.2

Figure 7.1 and 7.2 proves that CRDSA is able to achieve much lower packet loss rate and higher frame utilization than original Frame ALOHA. Additionally, they also provide configuration suggestions for Load Relief schemes and frame size setting. For example, if frame resource is quite precious, frame size could be set as a relatively small number and Load Relief schemes should control the normalized load no more than 0.6 at most of time. On the other hand, if throughput performance is primary, frame size could be slightly increased, combined with Load Relief schemes control, to make normalized load no more than 0.4.

However, the cost of CRDSA scheme is the uncertainty of time delay and power consumption caused from increasing iteration. Therefore, actual operation iteration should be limited. However, over-small iteration limitation would sabotage CRDSA performance like 1-iter CRDSA in Figure 7.1 and 7.2. The following analysis suitable maximum iteration set of CRDSA.

7.2 Trade-offs

Figure 7.3 shows the actual operation iteration of CRDSA scheme without maximum iteration set with increase of normalized load. We can see that the iteration increase sharply after 0.4 normalized load and peak at nearly 14 at load of 0.55. The reason why it decreases after is because collision is getting high and no clean packet could be detected after certain iteration.

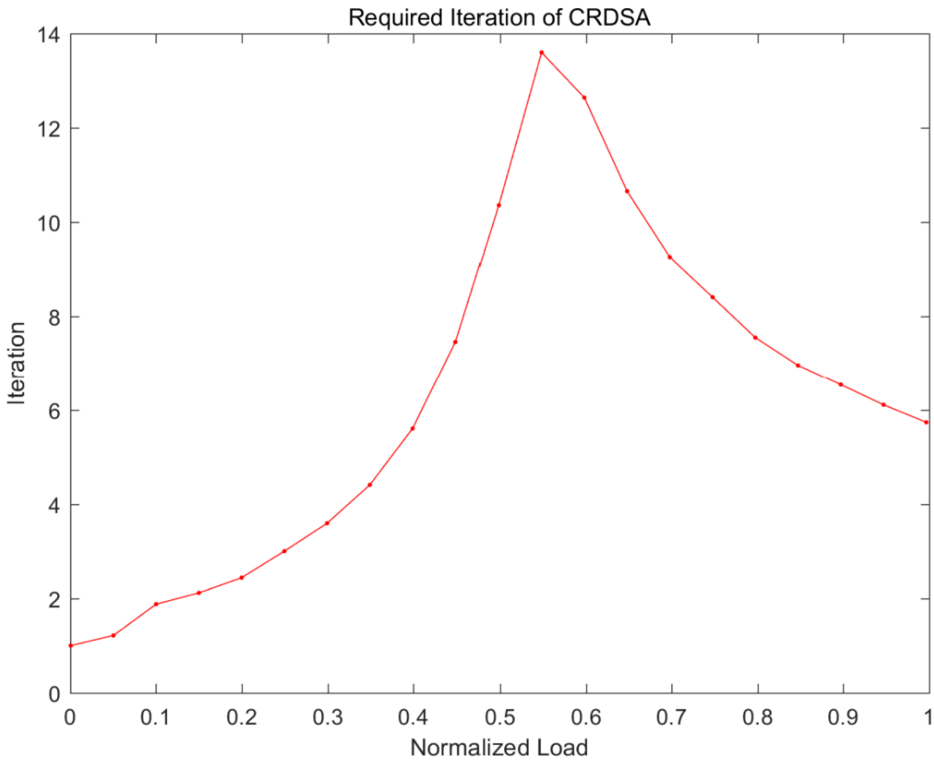

Figure 7.3

Figure 7.4 show the iteration efficiency of CRDSA without iteration limit. Specifically, iteration efficiency is defined as decreased loss rate from Frame ALOHA over the cost of total iteration. We can see that iteration efficiency is high between 0.1 and 0.4 load but quite low at 0.55 load. Combined with Figure 7.3, this means that the 2nd to 6th iterations decrease much more packet loss rate than the subsequent iterations. Therefore, in consideration of delay and power efficiency, the maximum iteration is suggested to be set as 6.

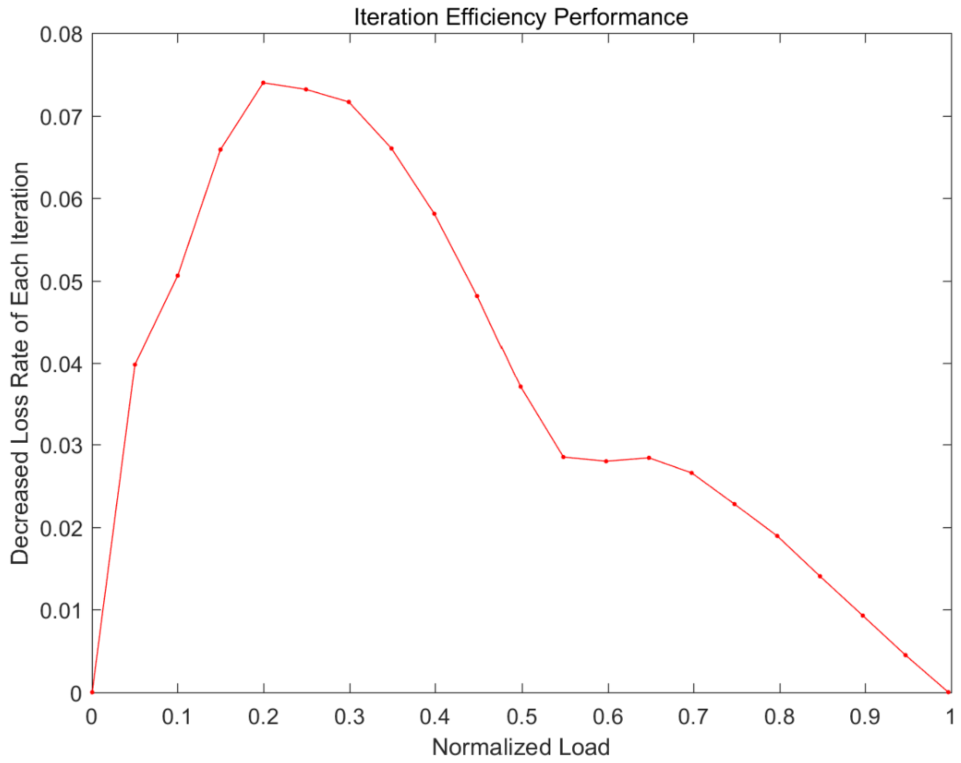

Figure 7.4

7.3 Reliability

In practical, unstable channels could lead to inaccurate access and payload channel estimation, which could sabotage the accuracy of packet recover, thus decreasing the success rate of IC.

Figure 7.5 shows the throughput performance of 6-iter-CRDSA and Frame ALOHA at different IC success rate with normalized load set as 0.5. Although packet loss rate increases with drop of IC success rate, it still performs better than Frame ALOHA until IC success rate drops to around only 3%. Therefore, CRDSA is a feasible and reliable approach to be applied on OFDMA LTE network to reduce uplink packet loss rate (increase throughput for given frame load).

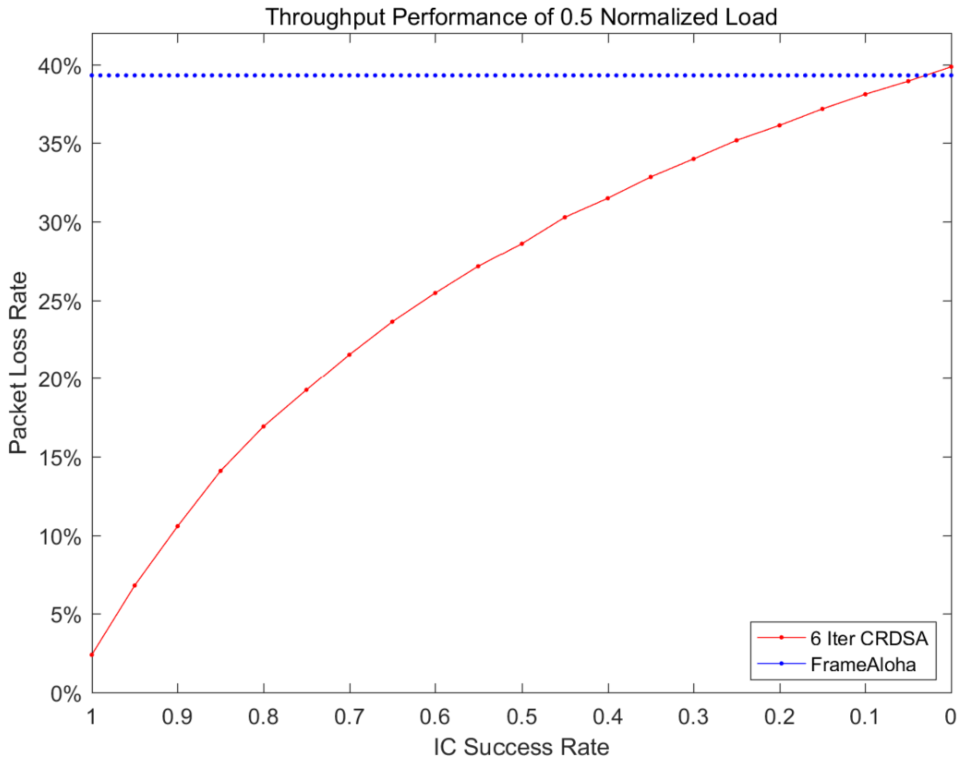
Throughput Performance of 0.5 Normalized Load
Packet Loss Rate
40%
35%
30%
25%
20%
15%
10%
5%
0%
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
IC Success Rate
6 Iter CRDSA
FrameAloha

Figure 7.5

Charpter 8

Conclusion

Various smart city applications require IoT to support ideal outdoor performance. In this case, MTC has to be taken into consideration in future LTE network scenario (e.g. 5G). However, collision problem caused by massive connectivity of smart city devices is the major obligation. To deal with this, several load relief schemes have been proposed, including ACB, eNB selection, slotted access and grouping devices. In this project, CRDSA is applied to OFDMA LTE network.

Simulation shows CRDSA is a feasible and reliable approach to reduce packet loss rate in uplink random access in OFDMA system for given RA load. Collision problem of massive connectivity for IoT could be remarkably alleviated by CRDSA but requires existing load relief schemes to control the RA load. According to simulation results, RA load is suggested to be controlled no more than 0.4~0.6 at most of time and maximum iteration is suggested to be set as 6.

Future work includes practical test of time delay and power consumption caused by whole system, which is vital because of iterative demodulation in CRDSA. In addition, IC success rate is also important because it directly affects the amount of increased throughput for given RA load. Therefore, future research could focus on what type of channel environment could significantly affect the IC success rate in OFDMA-based CRDSA system.

Bibliography

[1] J. Belissent, "Getting Clever About Smart Cities: New Opportunities Require New Business Models", Forrester Research Inc., 2010.

[2] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey", *Computer Network*, vol. 54, no. 15, pp. 2787 – 2805, 2010.

[3] "Smart Networked Objects and Internet of Things", white paper, Association Institutes Carnot, 2011.

[4] T. S. Lopez, D. Ranasinghe, M. Harrison and D. McFarlane, "Adding sense to the Internet of Things an architecture framework for smart object systems", *Personal and Ubiquitous Computing*, vol. 16, no. 3, pp. 291 – 308, 2012.

[5] J. Yick, B. Mukherjee and D. Ghosal, "Wireless sensor network survey", *Computer Network*, vol. 52, pp. 2292 – 2330, 2008.

[6] J. Vasseur and A. Dunkels, *Interconnecting Smart Objects with IP: The Next Internet*, Elsevier, 2010.

[7] 3GPP TS 22.368 V11.5.0, "Service Requirements for Machine-Type Communications", June 2012.

[8] C. Perera et al., "Context Aware Computing for the Internet of Things: A Survey", *IEEE Communications Surveys & Tutorials*, vol. 16, no. 1, Feb. 2014, pp. 414 – 454.

[9] J. Joung, C. K. Ho and S. Sun, "Spectral Efficiency and Energy Efficiency of OFDM Systems: Impact of Power Amplifiers and Countermeasures", *IEEE JSAC*, vol. 32, no. 2, Feb., 2014, pp. 208–220.

[10] T. Maksymyuk et al., "Quasi-Quadrature Modulation Method for Power Efficient Video Transmission over LTE Networks," IEEE Transactions Vehic. Tech., vol. 63, no. 5, pp. 2083-92, June 2014.

[11] E. Hossain, D. Niyato and M. Hasan, "Random Access for Machine-to-Machine Communication in LTE-Advanced Networks: Issues and Approaches", *IEEE Communications Magazine*, pp. 86-93, June 2013.

[12] K. Zhou, N. Nikaein, "Packet aggregation for machine type communications in LTE with random access channel", *IEEE Transaction on Wireless Communications and Networking Conference (WCNC)*, 2013, pp. 262–267, April 2013.

[13] M. Luise, R. Reggiannini and G. Vitetta, "Blind equalization/detection for OFDM signals over frequency-selective channels", *IEEE J. Select. Areas*

Communications, vol. 16, pp. 1568 – 1578, Oct. 1998.
[14] U. Mengali and M. Morelli, "Data-aided frequency estimation for burst digital transmission", *IEEE Transactions on Communications*, vol. 45, pp. 23 – 25, Jan. 1997.
[15] M. Morelli and U. Mengali, "An improved frequency offset estimator for OFDM applications", *IEEE Communications Letters*, vol. 3, pp. 75 – 77, Mar. 1999.
[16] U. Mengali and A. Andrea, *Synchronization Techniques for Digital Modems*, New York: Plenum, 1997.
[17] M. Speth, S. Fechtel, G. Fock and H. Meyr, "Optimum receiver design for wireless broadband systems using OFDM – Part I", *IEEE Transactions on Communications*, vol. 47, pp. 1668–1677, Nov. 1999.
[18] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-efficient resource allocation in multi-cell OFDMA systems with limited backhaul capacity", *IEEE Transactions Wireless Communications*, vol. 11, pp. 3618–3631, Oct. 2012.
[19] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-efficient resource allocation in OFDMA systems with hybrid energy harvesting base station", *IEEE Transactions on Wireless Communications*, vol.12, no.7, pp: 3412-3427, 2013.
[20] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-efficient resource allocation in OFDMA systems with large numbers of base station antennas", *IEEE Transactions on Wireless Communications*, vol.11, no.9, pp: 3292-3304, 2012.
[21] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-efficient resource allocation for secure OFDMA systems", *IEEE Transactions on Vehicular Technology*, vol.61, no.6, pp: 2572-2585, 2012.
[22] D. W. K. Ng, E. S. Lo and R. Schober, "Dynamic resource allocation in MIMO-OFDMA systems with full-duplex and hybrid relaying", *IEEE Transactions on Communications*, vol.60, no.5, pp: 1291-1304, 2012.
[23] D. W. K. Ng, E. S. Lo and R. Schober, "Secure resource allocation and scheduling for OFDMA decode-and-forward relay networks", *IEEE Transactions on Wireless Communications*, vol.10, no.10, pp: 3528-3540, 2011.
[24] D. W. K. Ng, E. S. Lo and R. Schober, "Resource Allocation and Scheduling in Multi-Cell OFDMA Decode-and-Forward Relaying Networks", Global Telecommunications Conference, IEEE, 2010.
[25] D. W. K. Ng, E. S. Lo and R. Schober, "Cross-layer scheduling for OFDMA amplify-and-forward relay networks", *IEEE Transactions on Vehicular Technology*, vol.59, no.3, pp: 3528-3540, 2011.
[26] V. K. Lau, W. K. Ng, and D. S. W. Hui. "Asymptotic tradeoff between cross-layer goodput gain and outage diversity in OFDMA systems with slow fading and delayed CSIT", *IEEE transactions on wireless communications*, vol.7, no.7, pp: 2732-2739, 2008.
[27] D. W. K. Ng, E. S. Lo and R. Schober, "Wireless information and power transfer: Energy efficiency optimization in OFDMA systems", *IEEE Transactions on Wireless Communications*, vol.12, no.12, pp: 6352-6370, 2013.
[28] H. Zhu and J. Wang, "Chunk-based resource allocation in OFDMA systems –part II: joint chunk, power and bit allocation", *IEEE Transactions on Communications*,

vol. 60, pp. 499 – 509, Feb. 2012.

[29] K. Seong, M. Mohseni and J. Cioffi, “Optimal resource allocation for OFDMA downlink systems”, *IEEE International Symposium on Information Theory*, pp. 1394 – 1398, 2006.

[30] Y. Chen, S. Zhang, S. Xu and G. Li, “Fundamental trade-offs on green wireless networks”, *IEEE Communications Magazine*, vol. 49, pp. 30 – 37, Jun. 2011.

[31] C. Han, et al, “Green radio: radio techniques to enable energy-efficient wireless networks”, *IEEE Communications Magazine*, vol. 49, pp. 46–54, Jun. 2011.

[32] H. Bogucka and A. Conti, “Degrees of freedom for energy savings in practical adaptive wireless systems”, *IEEE Communications Magazine*, vol. 49, pp. 38 – 45, Jun. 2011.

[33] G. P. Fettweis and E. Zimmermann, “ICT energy consumption—trends and challenges”, *International Symposium on Wireless Personal Multimedia Communications*, pp. 1 – 5, 2008.

[34] C. Li, S. Song, J. Zhang and K. Letaief, “Maximizing energy efficiency in wireless networks with a minimum average throughput requirement”, *IEEE Wireless Communications and Networking Conference*, pp. 1130 – 1134, 2012.

[35] G. Miao, N. Himayat, and G. Li, “Energy-efficient link adaptation in frequency-selective channels”, *IEEE Transactions on Communications*, vol. 58, pp. 545 – 554, Feb. 2010.

[36] G. Miao, N. Himayat, G. Li and S. Talwar, “Low-complexity energy efficient scheduling for uplink OFDMA”, *IEEE Transactions on Communications*, vol. 60, pp. 112 – 120, Jan. 2012.

[37] CATT, “R2-100182: access control of MTC devices”, in 2010 3GPP TSG RAN WG2 Meeting 68bis.

[38] ZTE, “R2-104662: MTC simulation results with specific solutions”, in 2010 3GPP TSG RAN WG2 Meeting 71.

[39] 3GPP TR 37.868 V11.0.0, “Study on RAN Improvements for Machine Type Communications”, September 2011.

[40] S. Lien, T. Liau, C. Kao and K. Chen, "Cooperative Access Class Barring for Machine-to-Machine Communications", *IEEE Transactions on Wireless Communications*, vol. 11, no. 1, January 2012

[41] K. Chatzikokolakis1 et al., "On the Way to Massive Access in 5G: Challenges and Solutions for Massive Machine Communications", *Cognitive Radio Oriented Wireless Networks, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering,* vol. 156, pp. 708-717, October 2015.

[42] Y. Zhou et al., "Advances in IEEE 802.11ah Standardization for Machine-Type Communications in Sub-1GHz WLAN", *IEEE International Conference on Communications 2013: IEEE ICC'13 (Second IEEE Workshop on Telecommunication Standards: From Research to Standards)*, pp. 1269-1273, 2013.

[43] R. D. Vegt, *Potential compromise for 802.11ah use case document*, doc.: IEEE 802.11-11/0457r0, March 2011.

[44] L. G. Roberts, “ALOHA packet systems with and without slots and capture”, *ARPANET System Note 8 (NIC11290)*, June 1972.

[45] N. Abramson, "The throughput of packet broadcasting channels", *IEEE Transactions on Communications*, vol. 25, pp. 117–128, Jan. 1977.

[46] J. C. Arnbak and W. Van Blitterswijk, "Capacity of slotted ALOHA in Rayleigh-fading channels", *IEEE J. Sel. Areas Communications*, vol. 5, no. 2, pp. 261–269, February 1987.

[47] L. Kleinrock and S. S. Lam, "Packet switching in a multi-access broadcast channel: Performance evaluation", *IEEE Transactions on Communications*, vol. COM-23, no. 4, pp. 410–423, April 1975.

[48] R. Cheng, C. Wei, S. Tsao and F Ren, "RACH collision probability for machine-type communications", *IEEE 75th Vehicle Technology Conference*, pp. 1–5, May 2012.

[49] G. L. Choudhury and S. S. Rappaport, "Diversity ALOHA - A random access scheme for satellite communications", *IEEE Transactions on Communications*, vol. 31, pp. 450–457, March 1983.

[50] F. Schoute, "Dynamic Frame Length ALOHA", *IEEE Transactions on Communications*, vol. COM-31, no. 4, pp. 565–568, April 1983.

[51] E. Casini, R. Gaudenzi and O. Herrero, "Contention Resolution Diversity Slotted ALOHA (CRDSA): An Enhanced Random Access Scheme for Satellite Access Packet Networks", *IEEE Transactions on wireless communications*, vol. 6, no. 4, pp.1408-1419, April 2007.

[52] G. Liva, "Graph-Based Analysis and Optimization of Contention Resolution Diversity Slotted ALOHA", *IEEE Transactions on Communications*, vol. 59, no. 2, pp.477-487, February 2011.

Appendix

simCRDSA.m (Matlab Fuction)

```
function [throughput,iter]=simCRDSA(m,n,u,r,iterMax)
%[throughput,iter]=simCRDSA(m,n,u,r,iterMax)
%m                              t-slot of OFDMA frame
%n                              f-slot of OFDMA frame
%u                              load
%r                              rate of good packet recover leading successful
IC
%iterMax                         maximum iteraion set (0 means iteraion stops
when no new clean packet or throughput achieves 100%)

%Transimitter
s=cell(m,n);
for k=1:u
    p1=floor(rand*m*n);
    if p1==m*n
        p1=p1-1;
    end
    p2=floor(rand.*(m*n-1));
    if p2==(m*n-1)
        p2=p2-1;
    end
    if p2==p1
        p2=m*n-1;
    end
    m1=floor(p1/n)+1;
    n1=rem(p1,n)+1;
    m2=floor(p2/n)+1;
    n2=rem(p2,n)+1;                 %random pick 2 TFslots
    s{m1,n1}=[s{m1,n1};[k,m2,n2]];  %add packet [preamble,pointer] to frame
    s{m2,n2}=[s{m2,n2};[k,m1,n1]];
```

```
end

%Receiver
throughput=0;
newCleanPacket=1;
iter=0;
while newCleanPacket && ((iterMax==0) ||(iter<iterMax)) && (throughput<u)
    iter=iter+1;
    newCleanPacket=0;
    for i=1:m
        for j=1:n
            if ((size(s{i,j},1)==1) && (s{i,j}(1,1)>0))   %detect 'clean'
packtet
                throughput=throughput+1;
                newCleanPacket=1;
                userTag=s{i,j}(1,1);
                TS=s{i,j}(1,2);
                FS=s{i,j}(1,3);
                twin=s{TS,FS}(:,1)==userTag;
                if rand<=r                        %proceed packet recover & IC
                    s{TS,FS}(twin,:)=[];
                else
                    s{TS,FS}(twin,:)=[0];
                end
                s{i,j}=[];                        %remove self
            end
        end
    end
end
```

simFrameALOHA.m (Matlab Function)

```
function throughput=simFrameALOHA(m,n,u)
%throughput=simFrameALOHA(m,n,u)
%m                              t-slot of OFDMA frame
%n                              f-slot of OFDMA frame
%u                              load

%Transimitter
s=cell(m,n);
for k=1:u
    p=floor(rand*m*n);
    if p==m*n
```

```
        p=p-1;
    end
    m1=floor(p/n)+1;
    n1=rem(p,n)+1;
    s{m1,n1}=[s{m1,n1};[k]];                    %random pick 1 TFslot
end

%Receiver
throughput=0;
for i=1:m
        for j=1:n
            if size(s{i,j},1)==1                %non colision packtet
                throughput=throughput+1;
            end
        end
end
```

DataAcquire.m (Matlab Script for Load test)

```
TimeSlots=64;
FreqSlots=32;
TestIter=500;
Slots=TimeSlots*FreqSlots;
ItTag=0;
for PktLoad=1:(floor(0.05*Slots)):Slots
    ItTag=ItTag+1;
    for ii=1:TestIter
        [t1(ii,1),itr(ii,1)]=simCRDSA(TimeSlots,FreqSlots,PktLoad,1,0);
        [t2(ii,1)]=simFrameALOHA(TimeSlots,FreqSlots,PktLoad);
        [t3(ii,1),itrd(ii,1)]=simCRDSA(TimeSlots,FreqSlots,PktLoad,1,1);
    end
    TrptCRDSA(ItTag,1)=mean(t1);
    IterCRDSA(ItTag,1)=mean(itr);
    TrptFAloha(ItTag,1)=mean(t2);
    TrptDSA(ItTag,1)=mean(t3);
    IterDSA(ItTag,1)=mean(itrd);
    LoadMarix(ItTag,1)=PktLoad;
end
```

DataAcquire2.m (Matlab Script for IC Success Rate test)

```
TimeSlots=64;
FreqSlots=32;
```

```
TestIter=500;
Slots=TimeSlots*FreqSlots;
PktLoad=1024;
ItTag=0;
for Rattte=0:0.05:1
    ItTag=ItTag+1;
    for ii=1:TestIter
        [t1(ii,1),itr(ii,1)]=simCRDSA(TimeSlots,FreqSlots,PktLoad,Rattte,6);
    end
    TrptCRDSAreal(ItTag,1)=mean(t1);
    IterCRDSAreal(ItTag,1)=mean(itr);
    RateMarix(ItTag,1)=Rattte;
end
for ii=1:TestIter
    [t2(ii,1)]=simFrameALOHA(TimeSlots,FreqSlots,PktLoad);
end
TrptFAlohaLoad=mean(t2);
```

Plot Command

```
plot(LoadMarix./Slots,TrptCRDSA./LoadMarix,'r.-',LoadMarix./Slots,TrptFAloh
a./LoadMarix,'b.-',LoadMarix./Slots,TrptDSA./LoadMarix,'g.-');

plot(LoadMarix./Slots,TrptCRDSA./Slots,'r.-',LoadMarix./Slots,TrptFAloha./S
lots,'b.-',LoadMarix./Slots,TrptDSA./Slots,'g.-');

plot(LoadMarix./Slots,(TrptCRDSA-TrptFAloha)./LoadMarix./IterCRDSA,'r.-');

plot(LoadMarix./Slots,IterCRDSA,'r.-');

plot(RateMarix,TrptCRDSAreal./1024,'r.-',0:0.01:1,TrptFAlohaLoad./1024,'b.-
');
```