Dynamic Inter-Channel Resource Allocation for Massive M2M Control Signaling Storm Mitigation

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***Abstract*—Massive M2M (Machine-to-Machine) Communications has been envisioned as a corner stone for next-generation 5G Communications. In addition, LTE has been evolving to accommodate increasing number of IoT devices with Machine Type Communications (also known as LTE-M) and Narrow-Band IOT (NB-IOT). Current cellular network systems are originally engineered for human-to-human communications. So the system allocates major portion of the radio resource to transmit the data packets. However, when devices with different traffic types access the LTE network, this might be a problem. For example, when massive M2M devices access the LTE network, the overhead of control signals might be too high for the system to support. Previous cellular M2M research focused mostly on control signaling in the first step of network entry process (i.e. RACH procedure). Nevertheless, a more complete study on the control signaling overhead for massive M2M devices need to be investigated. There are multiple control signaling steps and several types of channel resources are consumed when an idle state device enters active state. System bottleneck might happen in any of these steps. An inter-channel dynamic resource allocation method is proposed to improve the efficiency of control signaling and to reduce the control signaling storm caused by massive M2M devices. The proposed model estimates the traffic and calculates the demand on each channel. Reallocating of these channel resources leads to efficient resource utilization and thus the system could serve a greater number of M2M devices. In this paper, the investigation is conducted under LTE control plane procedure. Nevertheless, the same design principle could be applied to future 5G M2M.**

***Index Terms*—M2M, LTE, Control Signaling Storm, 5G, RACH, Cellular IoT, Machine Type Communication**

I. Introduction

In general, the cellular network system would run for decades after it was built. During this period, it should serve UEs with different traffic types. For instance, it is estimated that the number of Machine-Type device (or M2M device) would be boosted in the near future [1]. So the LTE system would face the massive M2M device issues.

However, the LTE system is originally designed for human to human (H2H) communications. The design of the radio resource of each channel is customized for H2H communications. The system expects that devices access the network and request a great number of radio resources for data packets such as voice and video packets. To meet the need of H2H communications, most of the radio resources are allocated to the data channels, and only minor portions of the resources are left for the control messages. However, from [2], we know that most of the M2M devices merely request the resources to transmit light-weight uplink packets. The demand of M2M traffic on data resources is not as much as the H2H traffic, so the data resource is sufficient enough to support the service of the M2M traffic. But there are several steps of signal exchanges for the devices to access the LTE network system. When massive M2M device access the network, the demand of control signals increases dramatically and it forms the signaling storm. The overhead of control packets could be too high for the system to maintain the service. This would be the shortage of LTE system to face the massive M2M device traffic.

Some research work has been done to handle it [3] - [12]. But most of the work focuses only on the RACH procedure, which is the first step of network entry process. These research tries to limit the number of UEs when the network is too crowded. However, maximizing the RACH throughput is not necessarily maximizing the system throughput. The radio resource of whole channels should be considered to improve the system throughput thoroughly. If we look at the capacity of each channel in LTE system under the M2M traffic, then we would find that the capacities of channels vary greatly. The minimal capacity, which comes from the control channel, would be the constraint of the system throughput. Once the resource in this channel runs out, the system would not serve more UEs no matter how much unused resource in other channels is. In other words, the resource usage is not efficient, and it is caused by the design of the LTE channels.

Without any mechanism to handle this problem, the connections between UEs and eNB would fail when the control resource runs out. Therefore, the system throughput might be extremely low. On the other hand, the RACH overload control mechanisms under the proper settings could guarantee a low failure rate once the UEs finish the RACH procedure. But the number of UEs finishing the RACH procedure is limited by the system configuration. So these mechanisms could not enlarge the system throughput. They just adjust the arrival rate to fit the system. Furthermore, once the mechanisms postpone the UEs' arrival many times, the UEs would also give up the transmission. Therefore, the improvement of RACH overload control mechanisms does not prominent.

So an inter-channel dynamic resource allocation is proposed

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in this paper to tackle the unbalanced capacity in each channel. The proposed model blends the resource in data channels and control channels into resource pools, and reallocates the resource in the resource pools to the signals. In this way, the system throughput could be upgraded by meeting the need of the devices.

The contribution of this paper is as follows:

- The capacities of channels are different in the LTE system, especially when non-H2H devices access the network. The capacity of the system would be limited by the minimum capacity among all channels, and that is so-called *bottleneck*. An inter-channel dynamic resource allocation mechanism is proposed to tackle this issue.
- When serving M2M devices, there are large number of devices with low data rate for each device. The bottleneck becomes control channels rather than data channels. As dormant M2M devices enter active state, control messages are sent and might lead to control signaling storm when the device number is huge. In this research, a complete investigation on the control plane steps for network entry is analyzed.
- Performance evaluation is conducted following simulation setting for 3GPP Machine Type Communication system specifications.

II. Radio Resource

The radio resource in LTE system are split into uplink (UL) band and downlink (UL) band.

In the UL band, there are three main physical channels, which are Physical Uplink Control Channel (PUCCH), Physical Uplink Shared Channel (PUSCH), and Physical Random Access Channel (PRACH).

In the DL band, there are five main physical channels, which are Physical Downlink Control Channel (PDCCH), Physical Downlink Shared Channel (PDSCH), Physical Control Format Indicator Channel (PCFICH), Physical Hybrid-ARQ Indicator Channel (PHICH), and Physical Broadcast Channel (PBCH) [13].

There are several signal exchanges between a UE and an eNB before the UE transmits data packets to the eNB. The eNB transmits the Downlink Control Indicator (DCI) in the PDCCH to decide the resource allocation for all packets from UEs and himself. And most of the data packets and control signals are transmitted in the PDSCH and PUSCH. When UE receives the signals from eNB, the UE might reply the signal in the PUCCH or PUSCH, and then eNB might respond with an ACK signal in PHICH. The signaling continues until all steps in Fig. 1 are finished or UE fails.

Since we know the signal exchange steps, we could use the byte estimation for each signal in [14] and [15] to estimate the resource requirement of each UE from accessing the network to finishing the data packet transmission. If the setting in LTE system is given, then we could know the resource amount of channels. As system resource in each channel is known, we could calculate the expected maximum throughput of whole system. We find that the LTE system could support at most 2

	Step	Direction	Message	Memo	Resource(DL)	Resource(UL)
RACH	1	UL	Preamble	RACH Msg1, PRACH		1 preamble
		DL	DCI format 1A/1C	PDCCH	123/84 bits	
	2	DL	RACH Response	RAR, PDSCH	7/14/21 bytes	
	3	UL	RRC Connection Request	RACH Msg3, PUSCH		7 bytes
		DL	ACK	PHICH	1 PHICH	
		DL	DCI format 1/1A	PDCCH	129 bits	
	4	DL	RRC Connection Setup	RACH Msg4, PDSCH	38bytes	
NAS		UL	ACK	PUCCH		
		UL	Scheduling Request	PUCCH		
		DL	UL Grant (DCI 0)	PDCCH	123bits	
	5	UL	RRC Connection Setup Complete + NAS:Attach Request	PUSCH		16 bytes
		DL	ACK	PHICH	1 PHICH	
		DL	DCI format 1/1A	PDCCH	129/123 bits	
	6	DL	NAS:Authentication Request	PDSCH	36bytes	
		UL	ACK	PUCCH		
		UL	Scheduling Request	PUCCH		
		DL	UL Grant (DCI 0)	PDCCH	123bits	
	7	UL	NAS:Authentication Response	PUSCH		7–19 bytes
		DL	ACK	PHICH	1 PHICH	
		DL	DCI format 1/1A	PDCCH	129/123 bits	
	8	DL	NAS:Security Mode Command	PDSCH	21bytes	
		UL	ACK	PUCCH		
		UL	Scheduling Request	PUCCH		
		DL	UL Grant (DCI 0)	PDCCH	123bits	
	9	UL	NAS:Security Mode Complete	PUSCH		13bytes
		DL	ACK	PHICH	1 PHICH	
RRC		DL	DCI format 1/1A	PDCCH	129/123 bits	
	10	DL	RRC Security Mode Command	PDSCH	11bytes	
		UL	ACK	PUCCH		
		UL	Scheduling Request	PUCCH		
		DL	UL Grant (DCI 0)	PDCCH	123bits	
	11	UL	RRC Security Mode Complete	PUSCH		10bytes
		DL	ACK	PHICH	1 PHICH	
		DL	DCI format 1/1A	PDCCH	129/123 bits	
	12	DL	RRC Connection Reconfiguration	PDSCH	58bytes	
		UL	ACK	PUCCH		
		UL	Scheduling Request	PUCCH		
		DL	UL Grant (DCI 0)	PDCCH	123bits	
	13	UL	RRC Connection Reconfiguration Complete	PUSCH		10bytes
data		DL	ACK	PHICH	1 PHICH	
		UL	Scheduling Request	PUCCH		
		DL	UL Grant (DCI 0)	PDCCH	123bits	
	14	UL	**DATA Traffic**	PUSCH		
		DL	ACK	PHICH	1 PHICH	
		DL	DCI format 1/1A	PDCCH	129/123 bits	
	15	DL	RRC Connection Release	PDSCH	10 bytes	

Fig. 1: The basic call flow

TABLE I: Simulation setting in TR 37.868[3]

Parameter	Setting
Cell bandwidth	5 MHz
PRACH Configuration Index	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
Ra-ResonseWindowSize	5 subframes
mac-ContentionResolutionTimer	48 subframes
Backoff Indicator	20 ms
HARQ retransmission probability for Msg3 and Msg4 (non-adaptive HARQ)	10%
Maximum number of HARQ TX for Msg3 and Msg4 (non-adaptive HARQ)	5

UEs per frame (about 12,000 UEs in 1 min) under the setting of Table I.

III. System Model

To meet the need of different traffic types in LTE system, this paper proposed a mechanism as in Fig. 2. And the steps are as follows:

1) Estimate traffic
2) Calculate and allocate control and data resource
3) Broadcast the result to UEs

In the first step, the UEs attempting to access the network are categorized to few types according to their traffic load. And the system will serve the UEs type by type. It estimates the number of UEs in one of the types. For example, the system estimates the amount of UEs with data packet less than 1KB. Given the traffic level, then the system would calculate how many UEs it could support and how much resource it

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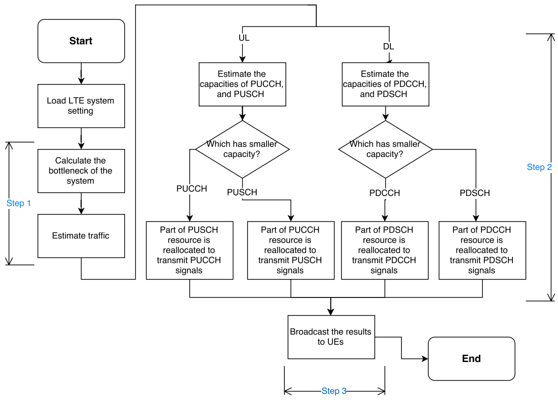

Fig. 2: The flow chart of the proposed system model

should allocate to each UE in the next step. After knowing how many UEs it could support, the system could use the overload control method like ACB or EAB to control the number of UEs finishing the RACH procedure. This is not mandatory, but it is helpful when the arrival rate is still too high.

In the second step, the resource of PDCCH and PDSCH are combined, and so does PUCCH and PUSCH. The combined resource in DL is used to transmit signals, which use PDCCH or PDSCH resource in the traditional LTE system; and the combined resource in UL is also allocated to transmit the signals, which use PUCCH or PUSCH resource in the traditional LTE system. In the new model, we limit the modulation coding scheme to be QPSK in both combined resource, because the resource in the DL resource pool might be allocated to transmit the PDCCH signals. The resource allocation unit in this model is resource block (RB). If the allocation unit is too large, then the resource might be over-allocated and then be wasted. On the other hand, if the unit is too small, then the DCI for addressing resource would be so complex. So, the system has known that the resource amount in each channel ("PDCCH+PDSCH", "PUCCH+PUSCH", PHICH, PRACH, and so on). The system could calculate how many UEs it could serve and how much resource should be allocated to a UE. Afterwards the system broadcasts the reallocation result of the radio resource to UEs. Then the UEs transmit RACH preamble to access the network, and eNB serves the UEs, who succeed in the RACH procedure. Repeat this procedure until all UEs in this type are served or failed, and then start to serve UEs in another type.

The main ideas of the proposed allocation method is that *if the capacities of channels are the same, then the system throughput would be maximized.*

Imagine that each channel is like a tube, and the capacity of the channel is just like the diameter of the tube. These tubes with different size in diameter are concatenated. When the water flows through this system, the part with minimum diameter would be the bottleneck as illustrated in Fig. 3. Essentially, improving the system bottleneck is a maxmin problem. The best way to increase the system throughput,

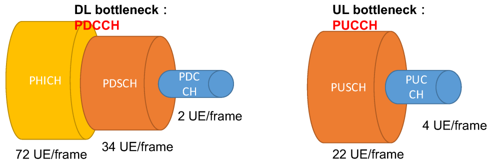

Fig. 3: The illustration of the capacity of each channel

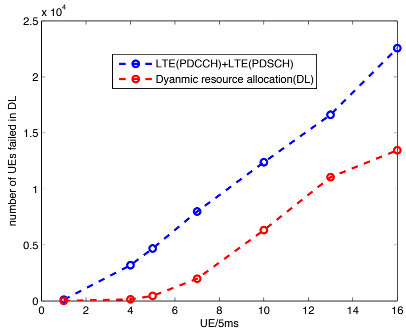

Fig. 4: The number of UEs failed in DL band

when the total resource is fixed, is to adjust the capacities of all channels to be the same amount. Therefore, the radio resource could be better utilized. If we focus on the data channel and control channel, it means that the capacity of the control channel is increased by borrowing the resource from the data channel. The bottleneck becomes loose, and therefore the total throughput of the system would also be improved.

IV. Simulation

We use the same setting as Table I. To fit the configuration, we also set CFI is equal to 3, antenna port is equal to 4, cyclic prefix is normal, and PHICH Ng factor is equal to 2. In the simulation, we compare the LTE system and the proposed one with 7 cases. The only difference in each case is the arrival rate of UEs. And in our simulation, every UE has only 1 uplink packet to send, the simulation time is 10 seconds, and we repeat each case 3 times to find the average of the uniform distribution. The arrival rates of the cases are as follows:

- *Case 1:* 1 UE/5 ms
- *Case 2:* 4 UE/5 ms
- *Case 3:* 5 UE/5 ms
- *Case 4:* 6 UE/5 ms
- *Case 5:* 10 UE/5 ms
- *Case 6:* 13 UE/5 ms
- *Case 7:* 16 UE/5 ms

From Fig. 4, we could observe that LTE system faces the problem of UE's failure much more than the proposed model when the total resource is given. In Fig. 5, the unit of y-axis is the number of signals that the unused resource could supports, and the resource requirement of signals is shown in the legend. From this figure, we could find that there are still abundant of the resource in PDSCH in LTE system when the

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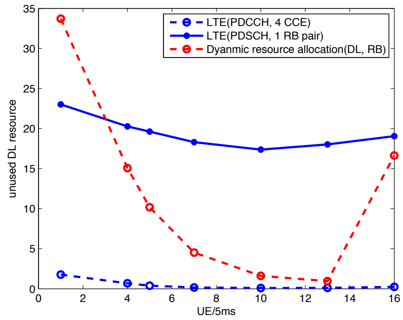

Fig. 5: The number of unused DL resource

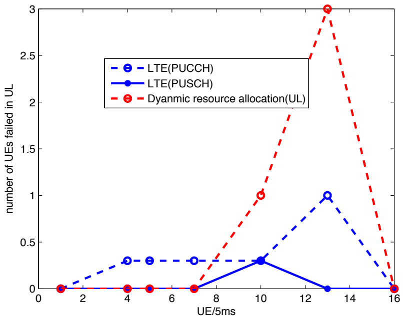

Fig. 6: The number of UEs failed in UL band

PDCCH resource runs out, and the curve of dynamic resource allocation always lies above the PDCCH curve. That means the insufficient resource for signals in PDCCH is alleviated, and that is how the proposed model outperforms in the Fig. 4.

The Fig. 6 and Fig. 7 show the similar results as Fig. 4 and Fig. 5. But the value of PUCCH curve in Fig. 7 is always non-zero, and the number of UEs failed in UL band is very small. That means the bottleneck of the whole system in this scenario should be the PDCCH but not PUCCH.

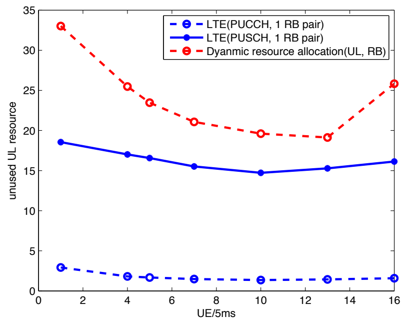

Fig. 7: The number of unused UL resource

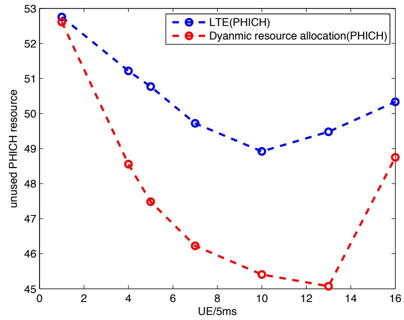

Fig. 8: The number of unused PHICH resource

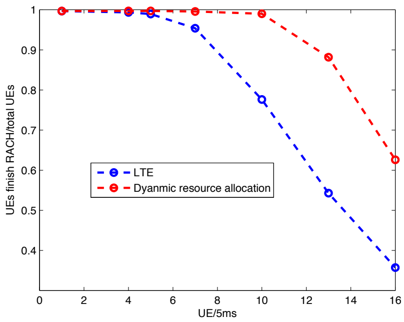

Fig. 9: The ratio of UEs finishing the RACH proceudre in 1 min

Fig. 8 shows that the PHICH resource is always ample under this setting. That is why we only need to consider about the data channel and control channel but not PHICH. There are still 2 things noteworthy. First, the curve of proposed model is always under the curve of LTE system. That is because more UEs fail in the signal exchanges in LTE system, so there are less downlink ACK would be transmitted. This could be proved by Fig. 10. And the second one is that the minimal value is not at the two sides (case 1 or case 7) of the curves in Fig. 8. The reason is that when the arrival rate is not heavy, the total amount of UEs is less, so lots of resource remains unused. On the other hands, when the network is crowded, most of UEs would fail in the RACH procedure, so there is lots of resource left.

Fig. 9 shows that more UEs finish the RACH procedure in the proposed mechanism. That is because the signal exchanges in RACH procedure would consume the resource in PDCCH, but the LTE system faces a shortage of that kind of resource. And if we calculate the number of UEs finishing the RACH procedure, we would find that the number would be about 20,000 UEs in case 5 and case 7 of the proposed model, and 23,000 UEs in case 6 of the proposed model. This makes the total throughput of case 5 and case 7 closed, and the throughput of case 6 becomes lower due to the crowded network.

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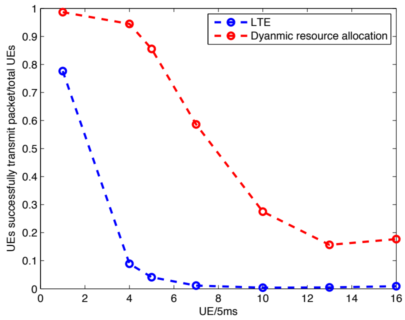

Fig. 10: The ratio of UEs successfully transmit a packet in 1 min

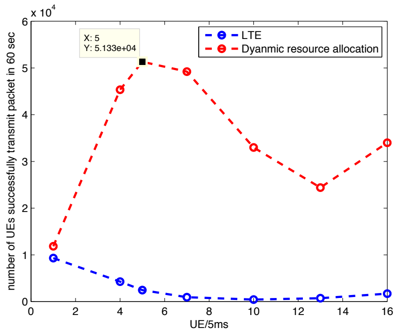

Fig. 11: The number of packets be received by eNB in 1 min

Fig. 10 shows the ratio of UEs, which successfully transmit the packet to the eNB. The curve of dynamic resource allocation is always above the curve of the LTE system. In addition, both curves decrease at first, then then increase a little bit. This phenomenon accords with what we have mentioned, and the minimal value is not at two sides of the curves.

Finally, we could know that the maximum throughput for proposed model is about 50,000 UE/min and 10,000 UE/min for LTE system from Fig. 11. The simulation results are quite closed to the estimation, which are 9 UE/frame for the proposed system, and 2 UE/frame for the LTE system, respectively.

V. Conclusion

Current cellular network system would face the problems when massive M2M devices attempt to access the network. The problem has its origin in the design of LTE radio resource. However, most of previous research tries to tackle the massive M2M issues by limiting the UEs' arrival. It could also impose the constraint on the system throughput. So the paper proposed a new model to solve the problem in a systematic view. The proposed model blends the resource of the data channel and the control channel in both DL and UL, and lifts the capacity of the control channel to the same level as the capacity of the data channel. By using radio resource efficiently, the proposed model improves the throughput of the whole system.

The future work of this model is to control the traffic load to keep the throughput maximal. There is always a limit of the throughput when the total radio resource is given. This model has its maximum throughput only under some traffic load like 50,000 UE/min in Fig. 11. Once the traffic load is too heavy, the system throughput would goes down. If we want to keep the throughput optimal at any time, we should adopt the RACH overload control mechanisms in the model. While these mechanisms are used in the proposed model, then the system could reach its maximum throughput.

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References

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015-2020", Feb. 2016. [Online]. Available: http://goo.gl/mm43ZQ [Accessed: 19- Feb. 2016].
[2] M. Z. Shafiq, L. Ji, A. X. Liu, J. Pang, J. Wang, "A First Look at Cellular Machine-to-Machine Traffic - Large Scale Measurement and Characterization", ACM SIGMETRICS '12, pages 65-76
[3] 3GPP TR 37.868 V 11.0.0, "Study on RAN Improvements for Machine-type Communications", Sept. 2011
[4] M. Tavana, V. Shah-Mansouri, V. W. S. Wong, "Congestion Control for Bursty M2M Traffic in LTE Networks", IEEE ICC, June 2015
[5] S. Duan, V. Shah-Mansouri, V. W. S. Wong, "Dynamic access class barring for M2M communications in LTE networks", IEEE GLOBECOM, Dec. 2013
[6] M. Hasan, E. Hossain, D. Niyato, "Random Access for Machine-to-Machine Communication in LTE-Advanced Networks: Issues and Approaches", IEEE Communications Magazine, page 86-93, June 2013
[7] U. Phuyal, A. T. Koc, M. H. Fong, R. Vannithamby, "Controlling access overload and signaling congestion in M2M networks", IEEE ASILOMAR, Nov. 2012
[8] A. Laya, L. Alonso, J. Alonso-Zarate, "Is the Random Access Channel of LTE and LTE-A Suitable for M2M Communications? A Survey of Alternatives", IEEE Communications Surveys & Tutorials, page 4-16, Dec. 2013
[9] A. Amokrane, A. Ksentini, Y. Hadjadj-Aoul, T. Taleb, "Congestion Control for Machine Type Communications", IEEE ICC, June 2012
[10] M. Y. Cheng, G. Y. Lin, H. Y. Wei, "Overload control for Machine-Type-Communications in LTE-Advanced system", IEEE Communication Magazine, June 2012
[11] Y. C. Pang, G. Y. Lin, H. Y. Wei, "Evaluation of LTE access class barring mechanism for IoT", IEEE ICCE-TW, June 2015
[12] Y. C. Pang, G. Y. Lin, H. Y. Wei, "Context-aware Dynamic Resource Allocation for Cellular M2M Communications", IEEE Internet of Things Journal, page 1, Nov. 2015
[13] 3GPP TS 36.321 V10.2.0, "Evolved Universal Terrestrial Radio Access (E-UTRA) Medium Access Control (MAC) protocol specification", Jun. 2011
[14] 3GPP TR 37.869 V12.0.0, "Study on Enhancements to Machine-Type Communications (MTC) and other Mobile Data Application; Radio Access Network (RAN) aspectss", Sept. 2013
[15] 3GPP TS 24.301 V13.3.0, "Non-Access-Stratum(NAS) Protocol for Evolved Packet System (EPS); Stage 3", Sept. 2015
[16] P. Osti, P. Lassila, S. Aalto, A. Larmo, "Analysis of PDCCH Performance for M2M Traffic in LTE", IEEE Transactions on Vehicular Technology VOL.63, page 4357 - 4371, April 2014

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