HARQ in Relay Assisted Transmission for Machine Type Communications

Ayesha Ijaz, Lei Zhang, Atta ul Quddus, and Rahim Tafazolli, *Senior Member, IEEE*

***Abstract*— This letter describes the impact of unknown channel access delay on the timeline of Hybrid Automatic Repeat Request (HARQ) process in the 3rd Generation Partnership Project Long Term Evolution (3GPP LTE) system when a Relay Node (RN) is used for coverage extension of Machine Type Communication (MTC) devices. A solution is also proposed for the determination of unknown channel access delay when the RN operates in the unlicensed spectrum band. The proposed mechanism is expected to help MTC operation in typical coverage holes areas such as smart meters located in the basement of buildings.**

***Index Terms*— Hybrid Automatic Repeat Request, Long Term Evolution, Machine type communications, Relay assistance**

I. Introduction

Hybrid automatic repeat request (HARQ) is used in Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard for reliable data transmission [1]. HARQ feedback is not only helpful to indicate error free transmission in Human-to-Human (H2H) and Machine Type Communications (MTC), but it is also advantageous for other applications e.g. paging and broadcasting in MTC [2], [3]. MTC User Equipments (UEs) such as smart meters may be installed in the basements of residential buildings or other locations where they experience significantly greater penetration losses on the radio interface than the normal LTE devices. Therefore, coverage extension is an important 3GPP study / work item particularly for MTC applications [4].

For MTC coverage extension, several techniques such as Power Spectral Density (PSD) boosting and repetition coding have been studied extensively in the 3GPP study item [5]-[7]. Although significant gains have been observed in coverage extension for downlink (DL) transmission using PSD boosting, PSD boosting for uplink (UL) transmission is challenging since in most of the MTC application scenarios, extra low power consumption is desired for MTC devices due to the constraints of limited resources of energy in the form of a battery which may be cumbersome to be replaced. Moreover, low cost MTC devices supporting narrowband operation [8] may not be able to achieve desired coverage extension using PSD boosting. Towards this end, a relay-assisted transmission scheme is likely to be useful in order to improve LTE coverage for MTC UEs located in coverage holes. Since 3GPP Type-I or Type-II relays [1] are operator deployed (i.e. they need deployment planning), they will not be feasible for MTC applications and devices. Moreover, limited spectrum availability also renders outband Type-I RNs infeasible due to exponentially growing number of MTC UEs.

To avoid aforementioned issues, we suggest the use of unlicensed spectrum on the access link between the UE and the RN. Section II describes such a scenario where other Radio Access Technologies (RATs) are used for relaying for UL coverage extension of MTC UEs. The impact of relaying on the HARQ time line is described in Section III. In Section IV, we propose and discuss signalling mechanisms to adjust the corresponding HARQ time lines in such a scenario. Finally, conclusions are given in Section V.

II. Relay-assisted uplink transmission

Fig. 1 illustrates a scenario where a connected smart meter (i.e. an MTC UE) is installed in the basement of a residential building. The MTC UE is in the eNode B (eNB) coverage region and receives DL transmission directly from the eNB. However, in order to extend the UL coverage while ensuring lower transmission power consumption, the UE establishes a connection in an unlicensed spectrum band with a device within its communication range.

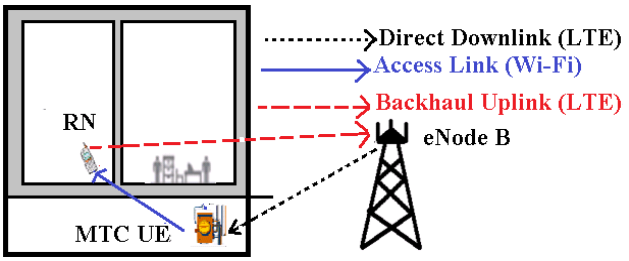

Fig. 1 An illustration of the relay-assisted UL transmission

The device, which acts as an RN, assists UL transmission to the eNB. Use of unlicensed spectrum on the access link saves the expenses a network operator will have to bear if indeed a second carrier frequency is used for the outband RNs. Furthermore, the relay for assistance in UL transmission, as shown in Fig. 1, could very well be another UE who is in close proximity of MTC UE and could act as an RN for the latter. Thus, the MTC UE to RN link could also be described as a device-to-device link in that case. Note that we will focus on Wi-Fi as one of the possible connections in the unlicensed spectrum. However, the proposal is applicable to any technology e.g. this could also be an LTE connection in the unlicensed bands i.e. LTE-U.

This paper was submitted to IEEE Wireless Communications Letters on September 3, 2015. This work was supported by University of Surrey 5GIC (http://www.surrey.ac.uk/5gic) programme and by Sony Europe Limited.

The authors are with the Institute for Communication System, home of 5GIC, University of Surrey, UK, GU2 7XH (e-mail: a.ijaz@surrey.ac.uk).

III. IMPACT ON 3GPP HARQ TIMELINE

In order to send data and/or control signal to the RN on Wi-Fi access link as shown in Fig. 1, the MTC UE is required to gain access to the channel that may be shared among a number of other devices. The 802.11n (Wi-Fi) Medium Access Control (MAC) supports shared access to the wireless medium through Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [9]. Use of CSMA/CA implies that the channel may not always be available instantly when the MTC UE wishes to transmit data. To determine the channel access delay on the access link (MTC UE to RN), simulations were performed for typical MTC traffic characteristics as captured in 3GPP report [4]. Therefore, considering Poisson distribution, packet inter-arrival time of 1 second and data packet length of 1000 bits (i.e. maximum transport block size for MTC UE [10]) (the corresponding length of 802.11n frame is 40 orthogonal frequency division multiplexing symbols[1]), the average access delay was found to be approximately 0.3ms, as shown in Fig. 2, for the number of MTC UEs accessing a RN varying from 1 to 20. Fig. 2 shows that the access delay for a particular MTC UE transmitting data packet of fixed length does not increase significantly for moderate to higher user density. This can also be verified from the Cumulative Distribution Function (CDF) plot of access delay for different packet lengths given in Fig. 3 for 20 users. This is due to small packet length, large inter-arrival rate and relatively very small access delay. We observed from simulation results that instantaneous delay is within ±70us of the average access delay for 99.5% observations. These observations also hold true for smaller (10 OFDM symbols i.e. ~250 bits) and larger (100 OFDM symbols i.e. more than 2000 bits) packets transmission and simulation results are given in Fig. 2 and Fig. 3 for completeness.

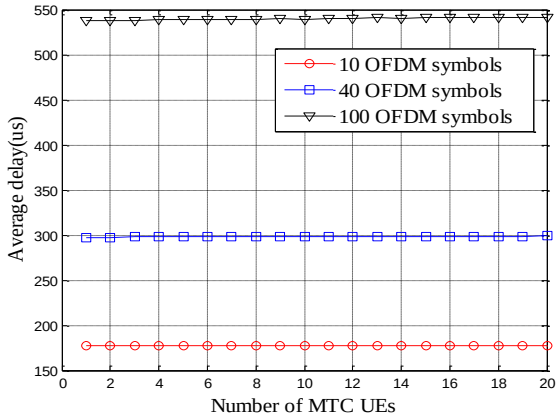

Fig. 2 802.11n Average access delay as a function of number of users

Due to access delay, the introduction of RN is likely to disturb the well-defined 3GPP procedures of UL Resource Grants (RGs) and HARQ timeline [1]. In the downlink HARQ process, due to the fact that the Acknowledgement (ACK)/Negative ACK (NACK) response does not arrive at an a priori known subframe, it is difficult for the eNB scheduler to decide which HARQ process it is related to. This becomes particularly difficult because the eNB is performing three-state detection on Physical UL Control Channel (PUCCH): ACK, NACK and discontinuous transmission (i.e. DTX). If there is only DTX in the UL subframe, the eNB concludes that the UE has missed the initial transmission of systematic bits and would retransmit those bits instead of transmitting additional parity bits. The synchronous UL HARQ process will also be disrupted due to relay assisted transmission. All uplink transmissions from a UE can only take place after a Scheduling Grant (SG) is received in the Physical DL Control Channel (PDCCH). Upon detection of a valid uplink SG, the UE will transmit data in Physical UL Shared Channel (PUSCH) according to the information included in the SG (transport format etc.). The timing of the UL transmission is similar to the legacy HARQ process, i.e. an uplink grant in subframe *n* triggers an uplink transmission in subframe *n* + 4 [1]. The access delay in the UE-to-RN radio link and processing delay at the RN introduce the problem that the actual PUSCH transmitted by the RN no longer is able to occupy the resources originally reserved in the UL SG. In effect, the RN would have to send a scheduling request of its own to access the UL channel whereas the original SG to the UE ended up being a wasted UL resource allocation. In order to retain the synchronous process, the UL ACK/NACKs and retransmissions can be envisioned to take place between the RN (which buffers UL transport blocks from the UE) and eNB only. In this case the UE would have to know when the UL transmission has completed successfully so it can send the next resource request to the eNB, i.e. both the UE and RN must understand the downlink control channel messages that are relevant to the particular UE-RN-eNB connection.

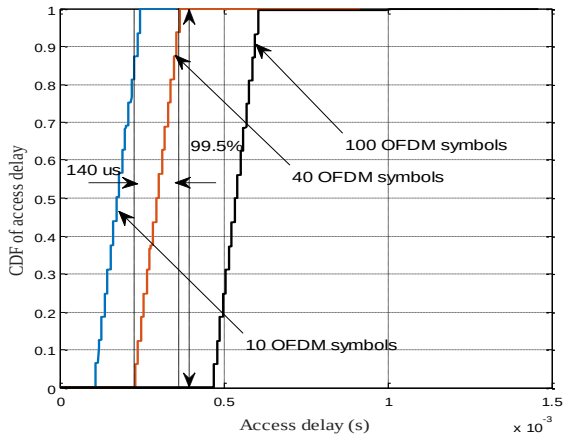

Fig. 3 CDF of access delay for different packet lengths

IV. SIGNALLING MECHANISMS

In this section, we propose a transmission scheme where the resource grant and HARQ processes adapt to the additional delay introduced by multi-RAT relay assisted transmission in the uplink. In order to do so, it is necessary to determine the aforementioned additional delay. We propose the mechanisms for both MTC UE initiated and eNB initiated procedures to determine the delay as described below.

[1] Packet length = 40 OFDM symbols, including 5 for preamble, 35 for data. With QPSK modulation and 1/3 code rate, 35 OFDM symbols (48 subcarriers each) can transmit 1120 bits that is sufficient for the MTC based traffic model [4].

A. MTC-UE Initiated Procedure

Assuming that the UE is already associated with the RN, we propose a signalling exchange method to estimate the access delay and transmit this estimate to the eNB through the RN while performing Random Access Procedure (RAP) as shown in Fig. 4. When the UE has UL data to transmit, it estimates the average access delay and then sends a request to the RN to initiate a contention based RAP as described below.

Step 0: The UE sends a packet carrying Cell Radio Network Temporary Identifier (C-RNTI) if the UE already has one (RRC_CONNECTED UE) or the unique UE identity to the RN and waits for an ACK. The length of this packet is equal to average length of data packet transmitted by UE. Let t_0 be the time instant the UE initiates CSMA-CA to send the packet and t_{ACK} be the instant an ACK is received for the corresponding packet. The UE determines the time elapsed between t_0 and t_{ACK} to determine the access delay. This procedure is repeated N (pre-defined) times to obtain a statistically reliable estimate of the delay as $\Delta t = \frac{1}{N}\sum_{n=1}^{N} \Delta t_n$ where $\Delta t_n = t_{n,ACK} - t_{n,0}$ and the subscript n denotes n-th trial. The average access delay, estimated at the end of step 0, is then quantized into number of TTIs by the UE.

Step 1: The UE sends a request to RN to initiate RA. The bits that indicate quantized Δt are also transmitted in this message along with the preamble sequence index and Random Access Radio Network Temporary Identifier (RA-RNTI) that is identified by the UE taking into account the estimated access delay. If the UE does not receive an ACK within ACK time out, it will retransmit the above message unless an ACK is received.

Step 2: Upon successful reception of the request sent by UE, the RN will transmit the random access preamble with embedded one bit of information to indicate the information related to the amount of transmission resource needed to transmit the message at Step 4 in the time-frequency slot identified by the information sent by the UE in Step 1.

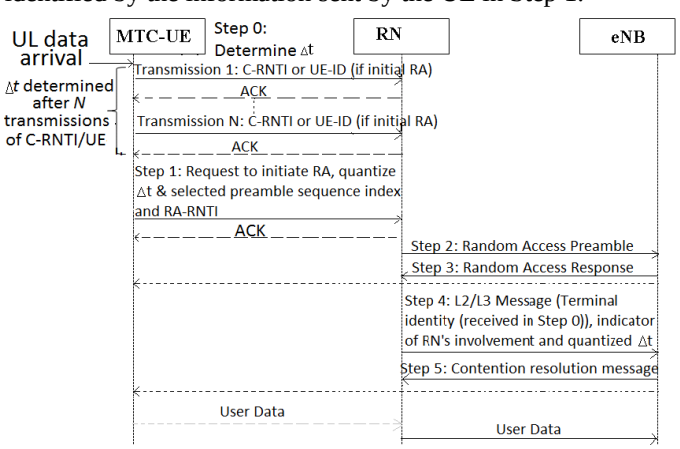

Fig. 4 Random Access procedure through RN

Step 3: The Random Access Response (RAR) message, addressed with RA-RNTI, sent by the eNB in Step 3 is decoded by both the UE and the RN. It is a normal LTE RAR message, that is, it conveys the index of the detected preamble, the timing correction calculated by the RAP preamble receiver, an UL resource grant for the transmission of message in Step 4 and a temporary identity i.e. Temporary C-RNTI (TC-RNTI) (which may or may not be made permanent, in case of initial RA, for the UE after contention resolution). The UE decodes this message to obtain TC-RNTI useful for decoding the message in Step 5.

Step 4: If RAR message is successfully decoded, the RN sends the Layer 2 / Layer 3 (L2/L3) message in Step 4 to the eNB using the PUSCH resources assigned in the RAR message in Step 3. It contains the actual random access procedure message, such as Radio Resource Control (RRC) connection request or scheduling request, and includes TC-RNTI allocated in Step 3. Another important part of this UL message is the inclusion of either the C-RNTI or the unique UE-ID (transmitted by the UE in Step 1) as a MAC control element in the UL shared channel. In this solution it is also proposed to include quantized Δt and the information (a flag) about the presence of an RN in this message. The eNB will adjust the HARQ time line in accordance with the access delay received in L2/L3 message received in Step 4.

Step 5: This is the last step in the proposed RAP wherein the normal LTE contention resolution message is transmitted on the DL shared channel. Both the UE and the RN receive and decode this message and the RN compares the identity received in this message with the identity transmitted in the L2/L3 message in Step 4 by the RN to eNB while the UE compares the received identity with the identity sent to the RN by the UE in Step 0. If a match is observed between these identities, the RAP is successful. If the UE has not yet been assigned a C-RNTI, the TC-RNTI from Step 3 is promoted to C-RNTI and the RN also updates the identity of the UE to decode further scheduling grants sent to the UE in PDCCH.

After contention resolution in Step 5, the UE sends data to the RN, over Wi-Fi link, which decodes and forwards it to the eNB over the LTE/LTE-A air interface.

It must be noted that in the proposed solution, the UE will determine channel access delay on the access link. Since different UEs will have different values of access delay, each UE will have different HARQ time line and the eNB will issue grants to different UEs accordingly in order to avoid collision between UL transmissions from multiple UEs. For a grant sent to i-th UE in subframe (SF) k, the data in PUSCH will be received in SF $k + 4 + \delta_i$ where δ_i is the offset in terms of TTIs for the i-th user i.e. quantized Δt_i. In the absence of a RN, δ_i will be zero. Since access delay is rounded up to quantize it in terms of TTIs (multiples of 1ms), small variation in instantaneous delay (i.e. within ±70 us of the average delay for 99.5% of observations) is not expected to disrupt the adjusted HARQ time line. Errors due to occasional larger variations can be corrected by HARQ retransmissions.

B. eNB Initiated Procedure

It is assumed that UL and DL HARQ time lines are adjusted after the RAP via RN as described in the previous sub-section and the MTC UE is in RRC connected mode. If, over time, access delay deviates largely from δ_i, e.g. due to changes in the environment, user density etc., eNB will detect scheduled resources are unutilized in UL HARQ process and DTX or NACK in DL HARQ process. If this continues, eNB will

determine the delay by sending a command to the UE in subframe n and determining when the reply is received at eNB receiver (Rx). This can e.g. be done by issuing an UL resource grant to the MTC UE for providing its identity i.e. C-RNTI and meter reading. The eNB notes when (subframe $n + k$) it actually receives a message from the RN containing this information and determines the additional delay from the expected subframe $n + 4$. This process may be repeated a number of times to get statistically reliable estimate of the delay caused by relaying. Consequently, whenever the eNB assigns uplink resources to the UE, it gives resource grant to RN for the eventual relay transmission in the new, delayed subframe.

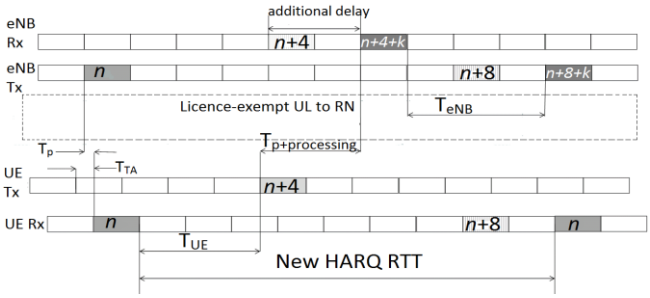

Fig. 5 Additional delay established by the eNode B

Once the new Round Trip Time (RTT) has been established, uplink resource grants and downlink and uplink HARQ processes adopt the new timing relation at eNB, UE and RN. The UE continues to be mandated to transmit PUSCH, ACK/NACK and retransmissions at $n + 4$ subframes as it does based on current specifications. The eNB appends the delay k to all the timings where it is expecting UL transmissions at subframes n as shown in Fig. 5. Here, T_{UE} and T_{eNB} denote processing delay at UE and eNB, respectively. T_p is the channel propagation delay and $T_{p+prcessing}$ is the sum of processing delay at the RN and the overall propagation delay from the UE to the eNB via the RN. For the UL resource grant, it may be most straightforward to assign it directly to the RN for UL subframe $n + 4 + k$, since it is the RN that will actually transmit in the UL resource. In the downlink HARQ process, the eNB can detect which particular UE sends feedback in a given subframe based on the UE specific orthogonal phase rotation of a cell-specific length-12 frequency domain sequence.

There are several advantages of the aforementioned relay-assisted UL transmission scheme and random access procedures besides coverage extension of an MTC UE in a coverage hole. Using relay would save battery power of the MTC device since less transmission power is required to communicate to the RN due to reduced path loss as compared to direct transmission to the eNB. Moreover, using Wi-Fi on the access link for uplink transmission and then relaying to the eNB, instead of direct tunneling through the Internet, would avoid large and uncertain Internet delays, which is crucial for preserving a given HARQ timeline. Furthermore, direct transmission from the eNB to the MTC UE will allow Wi-Fi interface be enabled only when required e.g. to provide feedback for a signal received from the eNB, thus conserving power. The MTC UE would only switch its Wi-Fi front-end circuitry on when advised to do so by the downlink commands from the eNB.

A key advantage of using license-exempt spectrum on the access link is that it provides outband relaying without cannibalizing other LTE spectrum resources. If this connection were using LTE inband relaying in the licensed bands, there would be interference issues to the other LTE users and eNBs. Outband relaying would use the operator's other LTE resources for access link with consequent capacity constraints. Proposed HARQ method also ensures privacy and trust for the MTC data. If two hop communication is allowed in an alternative manner (data from MTC UE to RN in both UL and DL directions while RN communicates in the both UL and DL directions with the eNB on behalf of MTC UE), any intermediate device can be brought in to hijack an MTC UE data. In another scenario, any node can act to be a relay sending malicious data to eNB on behalf of the MTC UE. In the proposed method, only a trusted relay node can assist in the UL where main control is still with the eNB to authenticate and establish a connection.

Since the eNB acts as the main node establishing and maintaining the overall link between the UE and itself, there is no need for the intermediate relay to be always switched on in the mode of an access point for the MTC UE. The link initiation is done over the downlink from the eNB to the MTC UE as well as the downlink between the eNB and the relay. Hence the relay is only alerted/switched ON in the mode to receive uplink data from the MTC UE when uplink data needs to be uploaded from the MTC UE to the eNB.

V. Conclusion

Relay assistance for uplink coverage extension in 3GPP LTE is discussed in this article to facilitate MTC in coverage hole locations. Use of unlicensed spectrum and another RAT is considered on the access link in order to avoid interference to other LTE users and eNBs. The relay node processing delay and the unknown channel access delay disrupt HARQ timelines. To avoid waste of resources, HARQ time line adjustment is necessary. Therefore, we proposed solutions for determination of the channel access delay and a signalling exchange method to adjust the corresponding HARQ timeline.

References

[1] S. Sesia, I. Toufik, M. Baker, "LTE – The UMTS Long Term Evolution from Theory to Practice," 2nd ed. Chichester, UK: J. Wiley & Sons. Ltd., 2011.

[2] R2-102781 (CATT), "Paging and downlink transmission for MTC", TSG RAN WG2 meeting #70, Montreal, Canada, May, 2010.

[3] R. L. Kuo, K. Lin, "Method and apparatus to improve machine type communication in a wireless communication systems", US Patent 2012/0281647, Nov. 8, 2012.

[4] RP-121441 (Vodafone), "Updated SID on: Provision of low-cost MTC UEs based on LTE", TSG RAN meeting #57, Chicago, USA, Sep.2012.

[5] R1-124887 (Ericsson), "General consideration on coverage enhancements for MTC," Nov. 2012.

[6] R1-130264 (LG), "Text proposal on coverage enhancement for a MTC UE," Feb. 2013.

[7] R1-130259 (Sony), "PDSCH coverage extension for low cost MTCs by power-density boosting," Apr. 2013.

[8] 3GPP TR 45.820, "3GPP Technical Specification Group GSM/EDGE Radio Access Network; Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT) (Release 13)," Aug. 2015.

[9] M. Gast. "802.11 wireless networks: The definitive guide," Southeast University Press, 2006.

[10] RP-130848 (Vodafone), "New WI: Low cost & enhanced coverage MTC UE for LTE," Jan. 2013.