SEVENTH FRAMEWORK PROGRAMME

LOLA

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PP	Restricted to other programme participants (including the Commission	
RE	Restricted to a group defined by the consortium (including the Commission)	
CO	Confidential, only for members of the consortium (including the Commission)	X

Revision History

The following table is a record of the main modifications done to the document since its creation.

Revision	Date	Author (Organisation)	Description
V1.0	M39	AT4 wireless, Eurecom	First version for EC review released

Table of Contents

1. EXECUTIVE SUMMARY

This deliverable is the final validation report on the integration of LOLA WP4 innovations in test bed 2.

Test bed 2 was first presented in the LOLA deliverable D5.1 Testbed definitions [1] and is intended to be a real-time validation platform consisting of the interconnection of a Long Term Evolution (LTE™)[1] Evolved-Universal Terrestrial Radio Access Network (E-UTRAN) Node B (eNB) emulator and an LTE User Equipment (UE) emulator.

The eNB emulator is provided by AT4 wireless and is hereinafter referred to as AT4 wireless LOLA Platform (AT4LP), while the UE emulator is provided by Eurecom and is based on the OpenAirInterface.org (OAI) platform [1] using the ExpressMIMO hardware with high-performance LTE-compliant radio-frequency (RF) components from Lime Semiconductor.

The LOLA WP4 objective is to derive new algorithms and adaptations to existing 3rd Generation Partnership Project (3GPP™) LTE Physical (PHY) and Medium Access Control (MAC) functionalities with the objective of the reduction of UE channel acquisition times and end-to-end user plane latency.

Test bed 2 integration progresses were later updated in deliverable D5.4 First report on the integration of WP4 algorithms on testbed 2 [2], where development and integration efforts carried out during Y2 were detailed.

The objective of D5.5 is twofold:

- Describe details on the interconnection of the AT4LP and OAI platforms
- Serve as a report on the integration of a set of LOLA WP4 adaptations

D5.5 is structured as follows:

- Section 1 contains the executive summary of the document
- Section 2 details developments that have done towards the integration of the test bed during year 3, including developments on the AT4LP, the OAI UE and the performance measurement tools
- Section 3 is a compilation of findings from different test campaigns carried out during year 3 towards the integration and proper interoperability between the AT4LP and the OAI UE
- Section 4 presents test results from the integration of a number of WP4 adaptations into the test bed and the analysis of the performance gains obtained with these adaptations
- Section 5 lists the acronyms used in the document
- Section 6 lists the references used throughout the document

[1] The terms LTE™ and 3GPP™ are registered Trade Marks of ETSI.

2. DEVELOPMENTS TOWARDS TESTBED DELIVERY

The AT4LP is based on a pre-existing advanced real time protocol simulator multi-purpose hardware/software initially focused in the 3GPP LTE technology. This design was initially intended to operate using the Frequency Division Duplex (FDD) mode of 3GPP LTE.

However, the only duplex mode initially supported by the Eurecom's platform at the time of starting WP5 was Time Division Duplex (TDD).

Significant efforts were put during Year 2 to enable TDD operation in the AT4LP. Details are provided in D5.4 [2]. First steps towards the integration of WP4 adaptations into testbed 2 were also detailed in [2].

This section describes developments that have been carried out during Y3 to overcome a few issues found during Year 2 and identified in [2] (see section 2.1). Developments done on the OAI platform are presented in section 2.2. This section also details progress towards the enabling of means to assess IP performance in testbed 2 (see section 2.3).

2.1. Developments on the AT4LP

Phase 3 tests executed on the AT4LP using commercial UEs during Year 2 (see D5.4) showed two issues:

- A non-stable behaviour in UL IP data performance
- Radio Link Control (RLC) buffering issues when handling Downlink (DL) Internet Protocol (IP) data

These issues have been solved during Year 3. There was a wrong behaviour when data was allocated on the Uplink Pilot Time Slot (UpPTS) part of special subframes that was fixed. RLC buffering issues have been fixed as well.

The following table shows DL goodput results obtained in Year 2 and Year 3 for a few cases. Further details about the test configurations can be found in D5.4 [2].

Phase 3 Test ID	UL-DL Config.	I_{MCS}	Theoretical Link Capacity (Mbps)	Y2 Goodput (Mbps)	Y3 Goodput (Mbps)
002	1	4	1.415	0.942	1.415
004	1	12	3.871	2.583	3.871
006	1	18	6.412	3.066	6.412
008	2	4	2.123	3.750	2.123
010	2	12	5.808	3.765	5.808
012	2	18	9.618	4.296	9.618

Table 1: AT4LP TDD DL goodput results before and after Y3 fixes

2.2. Developments on the OpenAirInterface

During year 2, several tests were performed on the OAI including OAI performance tests, OAI UE with AT4LP eNB, and OAI eNB with commercial UE protocol stacks. The outcome of the tests has shown the following issues:

- Non-compliancy of Random Access Procedure (RAP), MAC header generation and parsing, control elements and logical channel group identify managements, Packet Data Convergence Protocol (PDCP) header.

- PDCP, RLC, MAC configuration through asn1 messages.
- Issues related to performance at MAC and RLC. There was a wrong behaviour for Mac rate matching for the 2 smallest Transport Block (TB) sizes (mcs0 nb_rb=1,2). Neither UL nor DL works for these cases. The scheduler schedules these on DL during the connection procedure, which does not affect the Radio Resource Control (RRC) connection procedure.

These issues have been solved during Year 3.

2.3. Developments on the performance measurement tools

Phase 3 of the Interoperability (IOT) Verification Strategy presented in D5.4 [2] is intended to demonstrate that the AT4LP and its counterpart UE can successfully exchange IP data in both the downlink and uplink directions before WP4 adaptations can be implemented and evaluated.

Tests defined for Phase 3 are oriented to check the ability of the AT4LP and the UE to exchange user plane data in different cell configurations but are also intended to measure aspects like the Packet Error Rate (PER), IP throughput, IP One-Way Delay (OWD) or IP Delay Variation (IPDV). AT4 wireless has developed tools to measure the IP performance metrics above (among others) that can be used for this phase. A preliminary version of these tools was used for the Phase 3 tests evaluated and presented in D5.4.

These tools include a test controller, a traffic generator and two agents (one at the AT4LP side, MP0, and another at the UE side, MP1). The test setups used for both DL and Uplink (UL) tests are illustrated in Figure 1.

Significant efforts have been put on the evolution of these tools towards the integration of the WP3 traffic models and WP4 adaptations.

The most relevant developments performed on the IP performance measurement tools during Year 3 include:

1. Integration of typical distribution functions for the Packet Size (PS) and Inter-Arrival Time (IAT) in the traffic generation
2. Integration of additional Key Performance Indicators (KPIs) to be computed at the test controller (PS and IAT Probability Density Functions, PDFs, aggregated throughput, etc.)
3. Integration of User Datagram Protocol (UDP) traffic generation with and without IP fragmentation
4. Integration of Monitor mode to measure external traffic other than that created with the traffic generator
5. Memory optimization in the packet meter controller
6. Improvements in several high computation algorithms
7. Mechanism to recover from dropped connections

Each of the items identified above are detailed next.

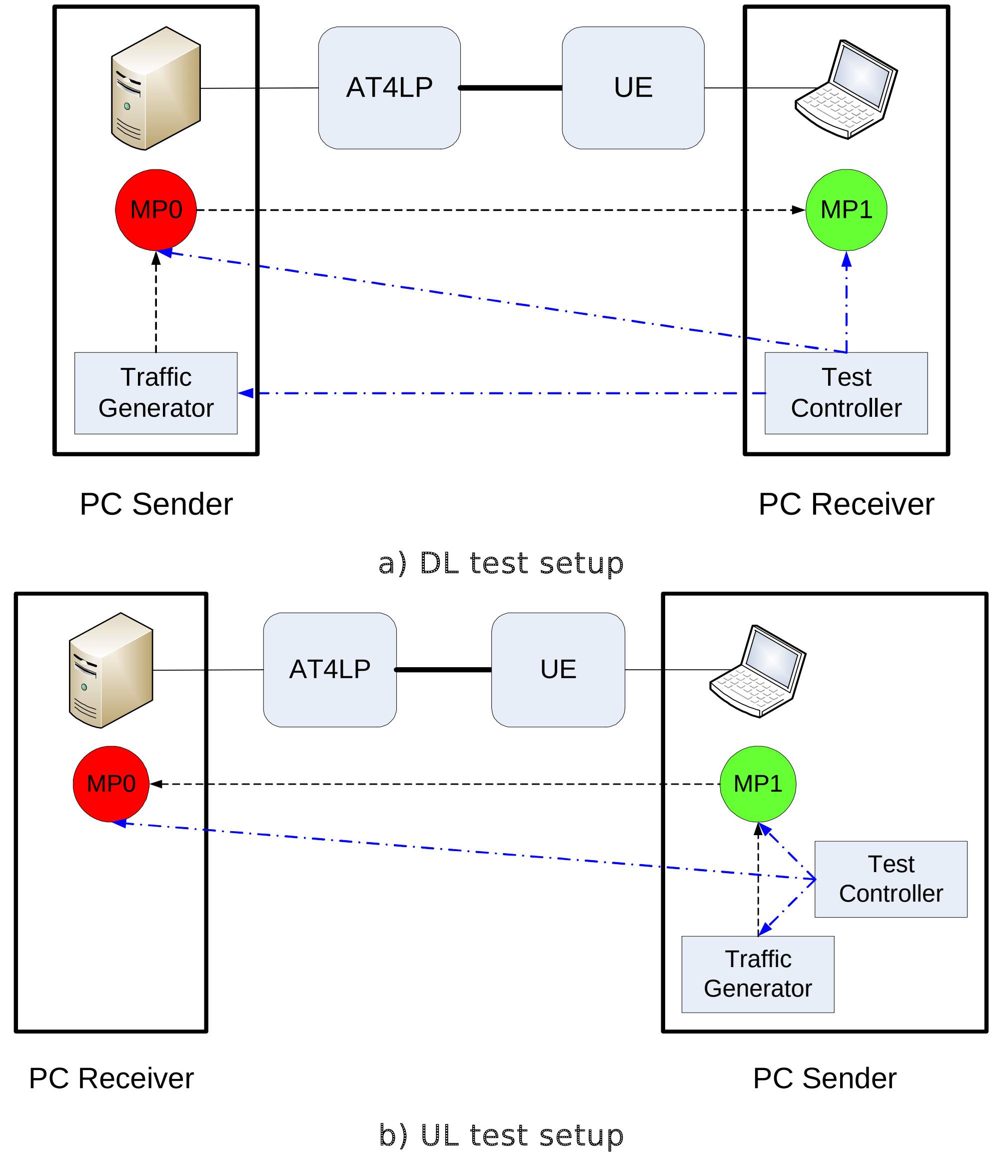

Figure 1: DL and UL test setups for IP performance evaluation

Integration of typical distribution functions in the traffic generator

During Year 1, WP3 was in charge of the analysis of traffic characteristics for different traffic sources (e.g. online gaming and Machine to Machine, M2M) and the generation a methodology to create traffic models for the studied sources. Actual traffic models were derived later using the methodology presented in D3.3 [3]. One of the outcomes of deliverable D3.3 was the approximation of PS and IAT distributions with typical probability distribution functions (normal, Gaussian, uniform, etc.) as well as their corresponding parameters (mean, variance, etc.). This exercise was done to provide WP5 with a temporary and approximate version of the traffic models before the actual traffic models were made available to other work packages.

For the traffic model approximations in D3.3 to be integrated in the AT4 wireless traffic generation tool, the following typical distribution functions were included for the IAT:

- Constant: defined by a constant number of packets per second

- Uniform: defined by a minimum and a maximum number of packets per second

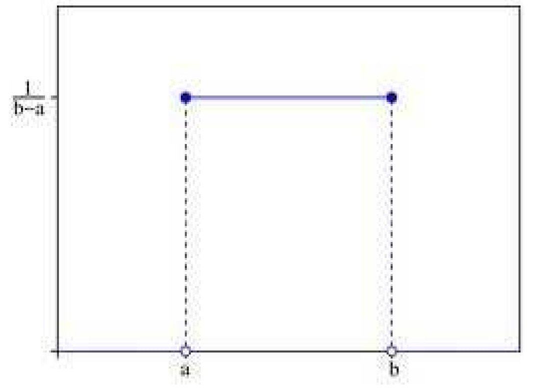

Figure 2: Uniform distribution

- Exponential: defined by an average number of packets per second

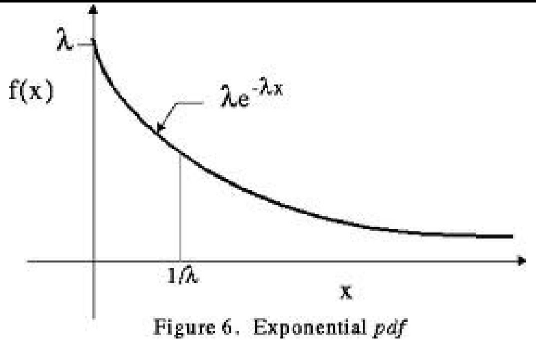

Figure 3: Exponential distribution

- Normal: defined by mean and standard deviation

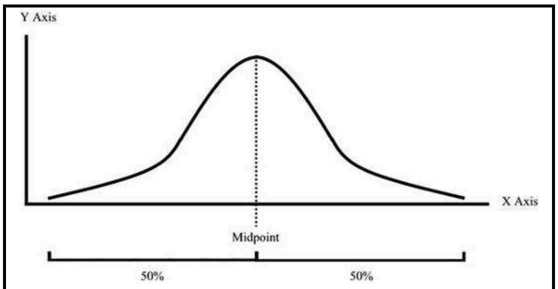

Figure 4: Normal distribution

The same distributions were also included for the PS.

Bursty traffic was also integrated to be able to simulate some of the M2M traffic sources analyzed in D3.3 [3].

Bursts are characterized by ON and OFF periods whose duration follow the same distributions as for the IAT and PS.

Given a traffic pattern by the couple Inter-Departure Time (IDT) and PS, when Burst is ON, the traffic is generated when the Burst distribution belongs to ON period. This is represented in the figure below.

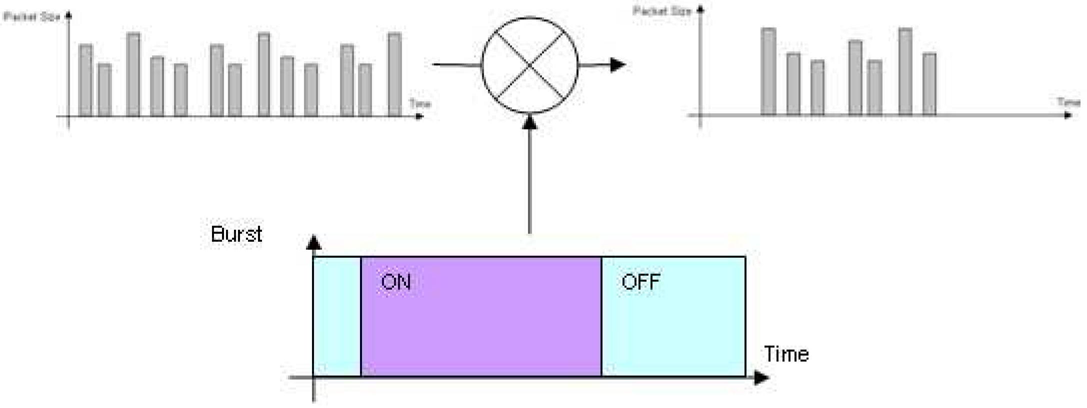

Figure 5: Traffic generation ON/OFF periods

Integration of additional KPIs

The test controller used during Year 2 measurements (see D5.4 [2]) included the following KPIs:

- Evolution of UDP OWD over time (average, percentiles, PDF)
- Evolution of average UDP generated data rate and goodput over time
- Evolution of IPDV over time (average)

An additional set of KPIs have been included in the test controller during Year 3:

- PS and IAT PDFs
- Aggregated throughput (for multiple flows) and throughput percentiles

PS and IAT PDFs are useful to guarantee that the traffic created by the traffic generators follows the traffic characteristics of the real traffic sources.

The following figure shows a simple scenario where traffic is generated from a source following a Normal distribution for the PS and an Uniform distribution for the IAT. This traffic is sent through an IP path (Ethernet without impairments) and received at the destination.

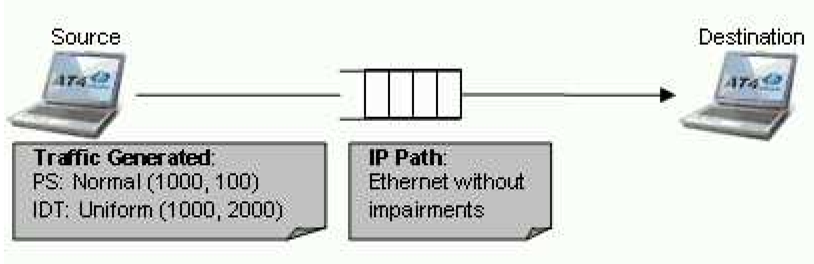

Figure 6: Traffic generation simple scenario

The test controller now computes the PS and the IAT PDFs both at the source and destination agents. Next figure shows the distribution of the packet size (including IP headers) measured at the receiver.

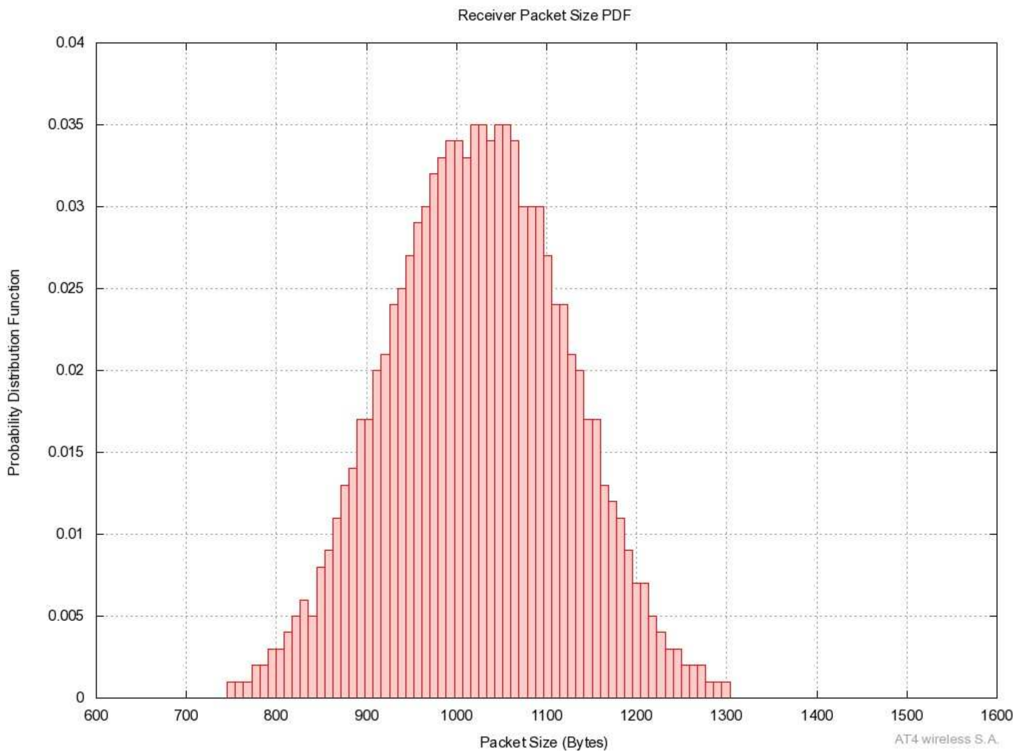

Figure 7: Packet size distribution KPI

The path influence on the PS and IAT distributions is easily characterized with the addition of these new KPIs.

Integration of UDP traffic generation with and without IP fragmentation

A new feature has been added to the UDP traffic generation settings. The traffic generator now allows IP Fragmentation so that the Packet Size value is allowed to be any value. Therefore, if the selected Packet size value is higher than the link Maximum Transfer Unit (MTU), there will be IP fragmentation.

Integration of Monitor mode

With the integration of the actual WP3 traffic models in Year 3, a new mode has been integrated into the test controller. In the Monitor mode (or Passive mode) traffic is generated by external applications (i.e. the traffic generator is OFF) and the test controller monitors the agents and computes KPIs over this external traffic. This was done to allow the integration of WP3 traffic generation tools.

Memory optimization in packet meter controller

In order to provide metrics, both the agents and the controller require storing information for each packet transmitted/received by the device. When performing tests with a high number of packets (high throughput or long duration tests), the program can get out of memory. In order to increase the number of records captured, the tool has been improved and now it stores the information related to each packet in a more optimum way.

Improvements in several high computation algorithms

For the statistics to be calculated the tool uses a set of algorithms that compare packets captured by the sender and those captured by the receiver. This comparison is made one by one, requiring a lot of time as the number of packets increases. These algorithms have been improved in order to avoid some of the comparisons in particular cases (not affecting to the results provided), requiring shorter time to calculate the statistics.

Mechanism to recover dropped connections

The agents send the information related to the traffic they have measured to the controller after the test has finished. If the connection is lost during the test, the information obtained until that moment is lost, and a new test must be executed. This can be a typical situation in low Signal to Noise Ratio (SNR) scenarios. To solve this problem, the tool now incorporates a mechanism to recover the connection between controller and agents after connection is dropped.

3. INTEGRATION CAMPAIGNS

3.1. Previous integration state

This section compiles a set of evidences and test results to show to what extent the AT4LP and the OAI platform interoperate. An interoperability verification strategy was defined and presented in D5.4 [2]. Three phases were identified:

- Phase 1: Test vectors exchange (L1 testing)
- Phase 2: L2 integration
    - Phase 2.1: Non-signalling mode
    - Phase 2.2: Signalling mode
- User-plane data exchange

Integration efforts carried out during year 2 included:

- Phase 1 tests between the AT4LP and the OAI
- Phase 1 tests between the AT4LP and a number of commercial UEs
- Additional physical layer tests between the OAI
- Phase 2 tests between the AT4LP and a number of commercial UEs
- Phase 3 tests between the AT4LP and a commercial UE

3.2. Integration efforts during year 3

AT4 wireless and Eurecom have met several times during year 3 with the purpose of integrating test bed 2. Tests carried out during these meetings were oriented to demonstrate interoperability between the AT4LP and the OAI UE. Results and evidences from these tests are illustrated and analyzed in the following paragraphs.

3.2.1. Cell configuration

AT4 wireless used an existing test tool intended to set the eNB emulator in the AT4LP to operate according to a specific cell configuration. This tool is an RF design validation and parametric testing tool used by engineers involved in the integration and verification of LTE UEs. The test tool was already presented in D5.4 [2] section 4.2.1.

The main physical layer cell parameters used during these IOT AT4LP – OAI UE integration campaigns are listed below:

- Duplex mode: TDD
- Frequency band: 33
- E-UTRA Absolute Radio Frequency Channel Number (EARFCN): 36126 (1912.6 MHz)
- Channel bandwidth: 5 MHz
- Multiple-Input Multiple-Output (MIMO) mode: Single-Input Single-Output (SISO) (1x1)
- TDD UL-DL configurations: 1 and 3

- Special subframe configuration: 0
- Number of Physical Downlink Control Channel (PDCCH) symbols per subframe: 2

Details about other cell parameters will be discussed in next sub-sections or have been omitted due to lack of relevance for this study.

3.2.2. SIB decoding

Once all cell parameters have been configured, the AT4LP is set to transmit broadcast information using the appropriate Physical Broadcast Channel (PBCH) resources according to the cell configuration used. The PBCH contains the System Information, needed for the UE to properly operate with the eNB. This information is organized in blocks, called System Information Blocks (SIBs), each including different data and transmitted with different periodicity.

The OAI UE is able to decode all SIB information broadcasted by the ATLP. Traces attached below demonstrate the correct reception of the different SIBs.

```
[RRC][D][UE 0] Frame 9 Found SIB2 from eNB 0
[RRC][D]radioResourceConfigCommon.rach_ConfigCommon.preambleInfo.numberOfRA_Preambles : 12
[RRC][D][UE]radioResourceConfigCommon.rach_ConfigCommon.powerRampingParameters.powerRampingStep : 1
[RRC][D][UE]radioResourceConfigCommon.rach_ConfigCommon.powerRampingParameters.preambleInitialReceivedTarge
tPower : 8
[RRC][D]radioResourceConfigCommon.rach_ConfigCommon.ra_SupervisionInfo.preambleTransMax  : 3
[RRC][D]radioResourceConfigCommon.rach_ConfigCommon.ra_SupervisionInfo.ra_ResponseWindowSize : 7
[RRC][D]radioResourceConfigCommon.rach_ConfigCommon.ra_SupervisionInfo.mac_ContentionResolutionTimer : 5
[RRC][D]radioResourceConfigCommon.rach_ConfigCommon.maxHARQ_Msg3Tx : 4
[RRC][D]radioResourceConfigCommon.prach_Config.rootSequenceIndex : 22
[RRC][D]radioResourceConfigCommon.prach_Config.prach_ConfigInfo.prach_ConfigIndex : 3
[RRC][D]radioResourceConfigCommon.prach_Config.prach_ConfigInfo.highSpeedFlag : 0
[RRC][D]radioResourceConfigCommon.prach_Config.prach_ConfigInfo.zeroCorrelationZoneConfig : 0
[RRC][D]radioResourceConfigCommon.prach_Config.prach_ConfigInfo.prach_FreqOffset 0
[RRC][D]radioResourceConfigCommon.pdsch_ConfigCommon.referenceSignalPower  : 24
[RRC][D]radioResourceConfigCommon.pdsch_ConfigCommon.p_b : 0
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.pusch_ConfigBasic.n_SB  : 1
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.pusch_ConfigBasic.hoppingMode  : 0
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.pusch_ConfigBasic.pusch_HoppingOffset : 4
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.pusch_ConfigBasic.enable64QAM : 0
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.ul_ReferenceSignalsPUSCH.groupHoppingEnabled : 0
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.ul_ReferenceSignalsPUSCH.groupAssignmentPUSCH : 0
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.ul_ReferenceSignalsPUSCH.sequenceHoppingEnabled : 0
[RRC][D]radioResourceConfigCommon.pusch_ConfigCommon.ul_ReferenceSignalsPUSCH.cyclicShift : 1
[RRC][D]radioResourceConfigCommon.pucch_ConfigCommon.deltaPUCCH_Shift : 1
[RRC][D]radioResourceConfigCommon.pucch_ConfigCommon.nRB_CQI : 2
[RRC][D]radioResourceConfigCommon.pucch_ConfigCommon.nCS_AN : 0
[RRC][D]radioResourceConfigCommon.pucch_ConfigCommon.n1PUCCH_AN : 0
[RRC][D]radioResourceConfigCommon.soundingRS_UL_ConfigCommon.present : 1
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.p0_NominalPUSCH : -95
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.alpha : 5
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.p0_NominalPUCCH : -117
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.deltaFList_PUCCH.deltaF_PUCCH_Format1 : 1
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.deltaFList_PUCCH.deltaF_PUCCH_Format1b :1
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.deltaFList_PUCCH.deltaF_PUCCH_Format2  :1
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.deltaFList_PUCCH.deltaF_PUCCH_Format2a :1
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.deltaFList_PUCCH.deltaF_PUCCH_Format2b :1
[RRC][D]radioResourceConfigCommon.uplinkPowerControlCommon.deltaPreambleMsg3 : 4
[RRC][D]radioResourceConfigCommon.ul_CyclicPrefixLength : 0
[RRC][D]ue_TimersAndConstants.t300 : 5
```

```
[RRC][D]ue_TimersAndConstants.t301 : 5
[RRC][D]ue_TimersAndConstants.t310 : 5
[RRC][D]ue_TimersAndConstants.n310 : 0
[RRC][D]ue_TimersAndConstants.t311 : 3
[RRC][D]ue_TimersAndConstants.n311 : 0
[RRC][D]freqInfo.additionalSpectrumEmission : 1
[RRC][D]freqInfo.ul_CarrierFreq : 403871656
[RRC][D]freqInfo.ul_Bandwidth : 403875688
[RRC][D]mbsfn_SubframeConfigList : 0
[RRC][D]timeAlignmentTimerCommon : 6
```

3.2.3. Random access procedure

The Random Access Procedure (RAP), detailed in 3GPP TS 36.213, consists of 4 messages exchanged between the UE and the eNB. For the initial access these messages are defined as follows:

- Message 1 - Random Access Preamble (RAP): sent by the UE on a special set of physical resources containing the RA preamble identifier
- Message 2 – Random Access Response (RAR): sent by the eNB on the PDCCH using a specific set of physical resources indicated in the SIB. It contains the RA preamble identifier sent received in message 1, timing alignment information, assignment of Cell-Radio Network Temporary Identifier (C-RNTI) and an initial UL grant
- Message 3 – scheduled transmission: initial UL transmission sent by the UE on the initial UL grant specified in the RAR using the Physical Uplink Shared Channel (PUSCH) containing the layer 3 *RRCConnectionRequest* message
- Message 4 – contention resolution: sent by the eNB to end the RAP

If the UE receives a message 4 indicating that contention resolutions has been resolved then the UE has successfully completed the random access procedure.

AT4 wireless and Eurecom have run several IOT tests to ensure that RAP is successfully completed between the AT4LP and the OAI UE. Issues found during this phase are detailed below.

Issue 1: Invalid PUSCH power for message 3

The UE successfully decodes the RAR (message 2) but generates message 3 using an invalid PUSCH. The table below compiles data extracted from AT4LP PUSCH traces where it can be observed that the OAI UE performs 4 transmission attempts for message 3 with no feedback being received from the AT4LP as no valid PUSCH power is detected.

SFN	sfn	TBS	N PRBs	MCS	RV	TX Attempt	DCI Subframe	PUSCH Power (dBm)
275	2	144	2	5	0	1	8	Invalid
276	2	144	2	5	2	2	8	Invalid
277	2	144	2	5	3	3	8	Invalid
278	2	144	2	5	1	4	8	Invalid

Table 2: AT4LP PUSCH traces (invalid PUSCH power)

The following Message Sequence Chart extracted from the AT4LP illustrates that the meesage 3 is never received by the AT4LP higher layers.

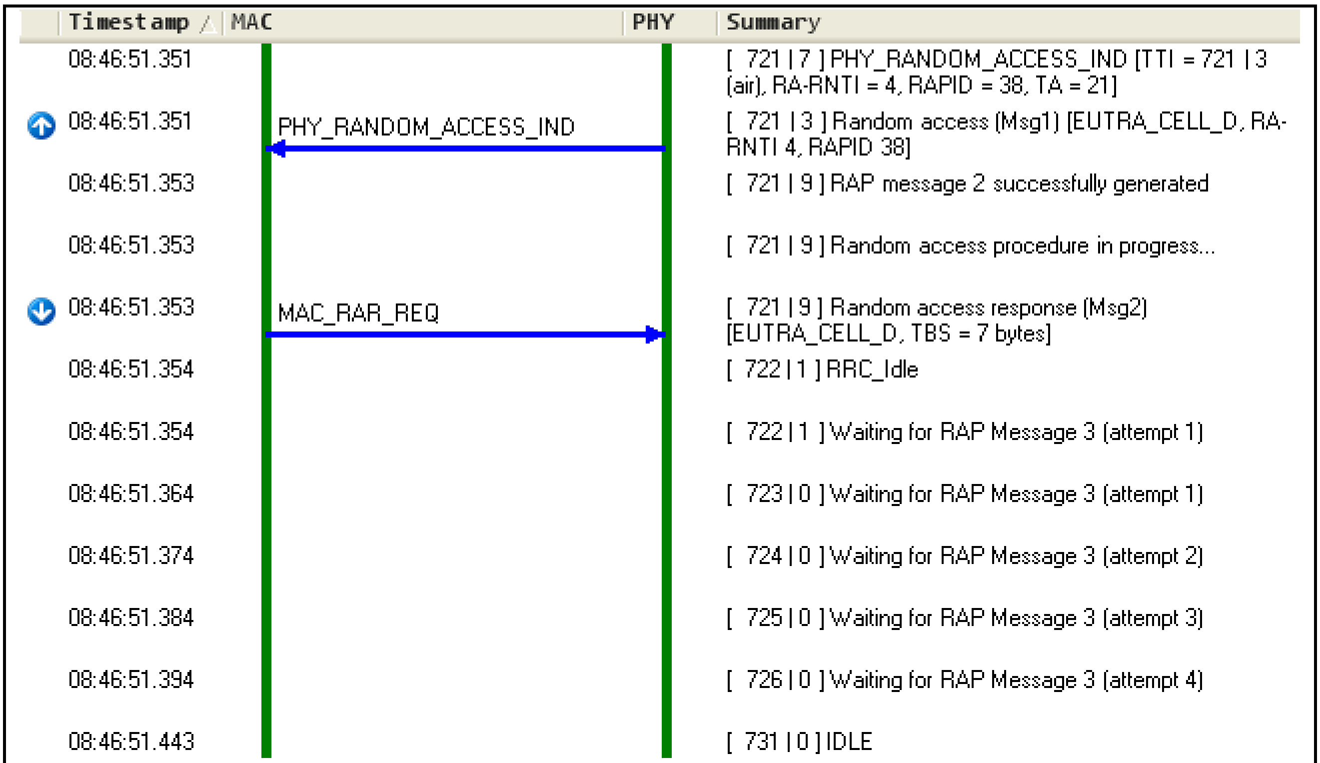

Figure 8: RAP message 3 not being received at the AT4LP

Eurecom found issues measuring path loss due to a wrong interpretation of the Cell-specific Reference Signals power, which is Energy Per Resource Element (EPRE) instead of absolute power (see section 5.2 in 3GPP TS 36.213 [5]). This issue was fixed.

However, the AT4LP still reported invalid PUSCH power for message 3 tries so an external Power Spectrum Analyzer (PSA) was used to determine whether message 3 transmissions were being transmitted or not. Figure 9 below shows a time domain capture of the OAI UE transmissions during the RAP. The figure demonstrates that the UE attempts the transmission of the RAP message 3 up to 4 times (once per subframe, i.e. once per 10 ms).

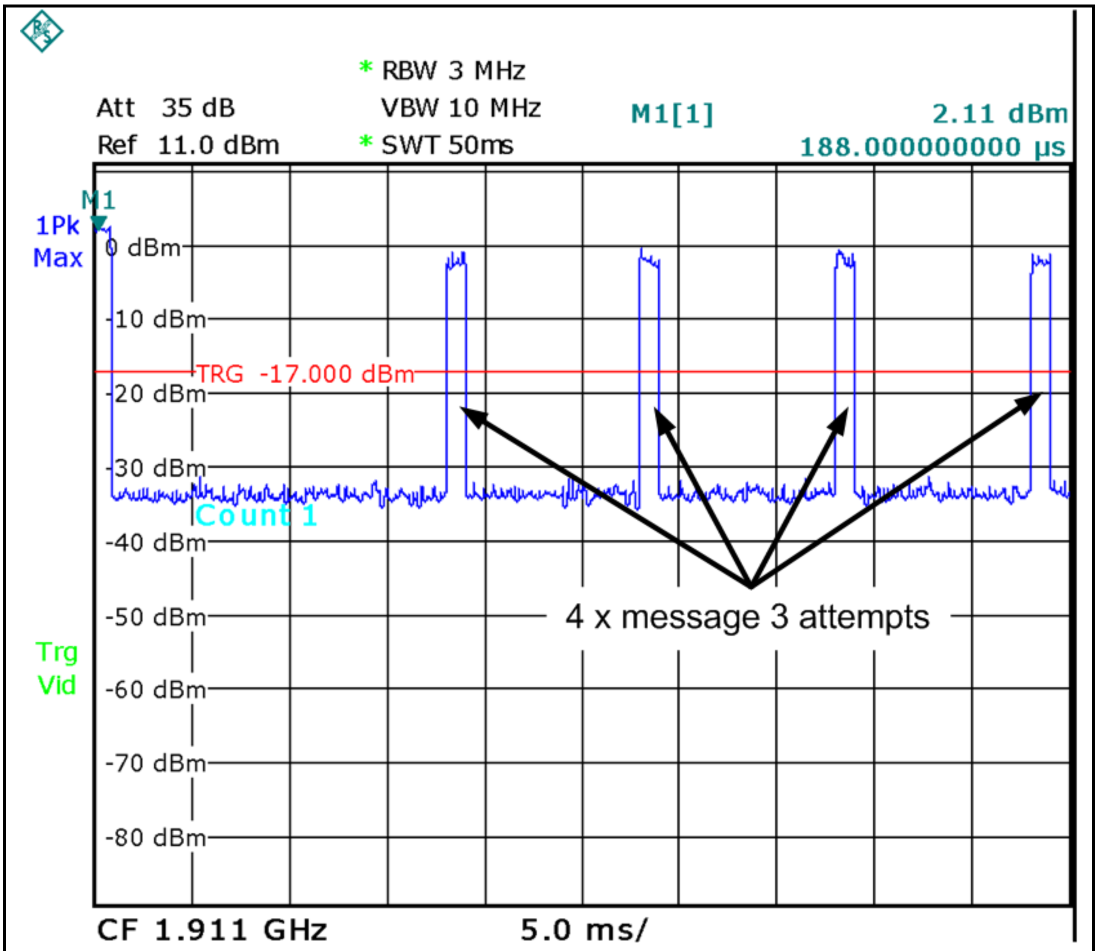

Figure 9: Message 3 attempts from the OAI UE

Several modifications on the cell configuration were applied to determine the reason why PUSCH message 3 transmissions were not properly detected:

- Simulated path loss was changed from 100 dB to 80 dB (the OAI UE cannot transmit at a power higher than 4 dBm)
- Message 3 resource allocation was changed from 1 PRB in RB 0 with Modulation and Coding Scheme (MCS) 10 (TBS of 144 bits) to 2 Physical Resource Blocks (PRBs) starting in RB 6 with MCS 5 (TBS of 144 bits)

None of the changes above solved the problem which led to consider that the issue might not be related to power exclusively, but to transmission timing as well. With this in mind AT4 wireless and Eurecom found a bug in the way cyclic shift was used to calculate parameter $n^{(1)}_{(DMRS)}$ (see section 5.5.2.1.1 in 3GPP TS 36.211 [6]). This parameter has a direct impact on the demodulation of the reference signals for PUSCH transmission. This issue was fixed.

This change allowed RAP to move one step further as messages 3 are received at the AT4LP from then and on. The table below shows proper reception of OAI UE message 3 in the 3rd transmission attempt.

SFN	sfn	TBS	N PRBs	MCS	RV	TX Attempt	DCI Subframe	PUSCH Power (dBm)
99	2	144	1	10	0	1	8	Invalid
100	2	144	1	10	2	2	8	Invalid
101	**2**	**144**	**1**	**10**	**3**	**3**	**8**	**-6.32**

Table 3: AT4LP PUSCH traces (ACK in the 3rd attempt)

Issue 2: DL transmissions using non-common search spaces

After solving issue 1 previously detailed, RAP reached its last step: transmission and successful reception of message 4. The following MSC illustrates a RAP in which the AT4LP successfully detects message 3 and generates message 4 accordingly.

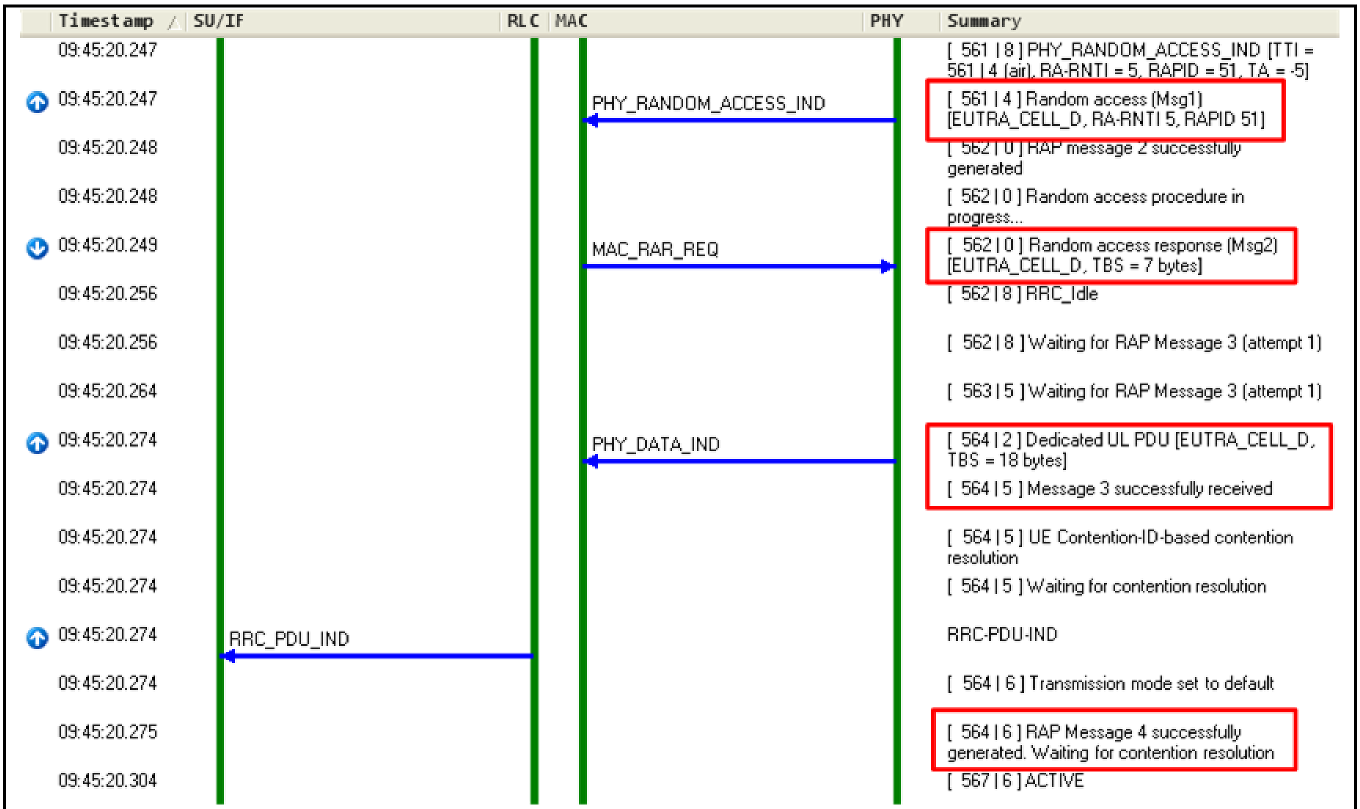

Figure 10: RAP message 4 successfully generated

However, the OAI does not receive message 4, which is the first DL transmission where non-common search spaces are used. Eurecom found a bug when selecting the proper aggregation level to search for the DCI that indicates the resources used to convey the message 4. This issue was not fixed by the time this deliverable was submitted.

3.2.4. Integration efforts with other equipment

The level of compliance with 3GPP specifications in the OAI UE was not sufficient to initiate phase 2 tests. Not all checks and tests described in each of the phases of the IOT verification strategy have been executed between the AT4LP and the Eurecom's UE platform. However, both AT4 wireless and Eurecom have performed equivalent or similar checks with other units to show that the developments done towards the interoperation of both units are in-line with what is expected.

Eurecom performed compliance tests with a commercial UE MAC protocol stack on the data plane (PHY layer bypassed) to ensure eNB correct operation. The results are used to compare the OAI UE operation against the commercial protocol stack. The tests revealed that BSR operation and logical channel group identify are not in-line with the standard, among the other minor issues. These issues have been resolved. Traces provided in the following sub-sections illustrate the data plane for the layer 2 protocol in these tests.

3.2.4.1. Tracing downlink/uplink IP packet (no fragmentation)

This packet is generated by the OAISIM traffic generator, called OAI Traffic Generator OTG, and originates from the eNB PDCP layer for transmission over E-UTRAN interface to the UE commercial protocol stack. The RLC acknowledge mode (AM) is used for this testing to validate the full operation of the RLC.
In the experimentation, the first outgoing packet has a payload of 591 bytes and thus 631 bytes for the packet + headers (TCP over IP).

```
[OTG][D]Header size is 40 [IP V=1][PROTO=2]
[OTG][D]Size Distribution idx= 1
[OTG][D][src 0] [dst 1] [application 0] [state 3]Packet :: Size=591  Distribution= 1
[OTG][D][0][1] [0x ffff] [m2m Aggre 0] [Flow 0]TX INFO pkt at time 194 Size= [payload 
591]       [Total       631]       with       seq       num       0,       state=3       :
|390885096385611598481030444476317596 2178|rg0uy6@m2^HW>Vg5BFyCt\k;V2Gw;6;hPKpFin8K|}_u8QS
A`R{_K]cw61jepyLDKPS@\bK=K`sxF3J5@TDL1C`n?x^`<I|YaW7{D@`W2?Ztm5fGIKFsrFzGF<k2_`^u?Z95j>lF
1WWlS<JlyA2`i4k=AZSE|H8im`5p;PAJT`E}W22hwjE9HgPUIMnJD|JpVQSwOqW`5U}R=mbXmi{Iup`9:mZT5H{_2
I0N1DXFbsLWUFD=@EKw|gL`uH7P]X7_=T7ym4<f=1MfE\=HYrq;AZ7E<G=790Hsh0LgBm}[[KZaA[b|xOA2k6]Oyz
F{{L=DC{fwajsXtdQ0Ut?GV?UEJ<UHSt::EA??wXJLqC9PB7{t``\B]1b{dK\:Od9|t@;\FUlZd2^8x_W4Nn|;Ddd
_;gsUIna^fc2;CX]k;dm^gy:n<yCIrOui^6diNy1Eay04FOUISYAa2FCfAoFU@y6A;;TxR=[O1Gw8{K_XeME?by6J
`QJ9sK<FSx[oXI4RdVDu3Sdw<JH3N^SRq^NhNfPr6lWtgOy=Z1@imAO;8Ljuqii8axmxY2<G@ac?cqW2Dic7EJ\bB
bn?eFbH;du|
[OTG][D][eNB 0] sending packet from module 0 on rab id 3 (src 0, dst 1) pkt size 658
[PDCP][I][eNB]Data request notification for PDCP entity with module ID 0 and radio bearer 
ID 3 pdu size 660 (header2, trailer0)
[PDCP][D]Asking for a new mem_block of size 660
[PDCP][D]Setting PDU as a DATA PDU
[PDCP][D]Sequence number 0 is assigned to current PDU
[PDCP][D]Following content with size 660 will be sent over RLC (PDCP PDU header is the 
first two bytes)
rlc_data_req: module_idP 0 (32), rb_idP 3 (64), muip 0, confirmP 0, sud_sizeP 660, sduP 
0xf715160
[RLC][D][FRAME 00019][RLC][MOD 00][RB 03] Display of rlc_data_req:
[RLC][D]      |  0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f |
[RLC][D]------+------------------------------------------------|
[RLC][D]RLC_TYPE : 1 RLC_AM
[RLC][D]#[1;31m
[RLC][D][MSC_MSG][FRAME  00019][PDCP][MOD  00][RB  03][---  RLC_AM_DATA_REQ/660  Bytes  ---
>][RLC_AM][MOD 00][RB 03]
[RLC][D]#[0;39m
[RLC][I][FRAME 00019][RLC_AM][MOD 00][RB 03] RLC_AM_DATA_REQ size 660 Bytes,  NB SDU 1 
current_sdu_index=0 next_sdu_index=1 conf 0 mui 0
[PDCP][D]Data sending request over RLC succeeded!
```

Once the packet is forwarded to PDCP layer, a single byte header is added to indicate the nature of PDU (here a Data PDU). The packet is forwarded to RLC AM layer in the same subframe. Please note that the DRB3 is the default bearer.
During a TX occurrence, MAC layer checks for buffer status of RLC and generates DLSCH header for the RLC SDU.

```
[MAC][D]dlsch_mcs = 22
[MAC][eNB 0] Generated DLSCH header (mcs 22, TBS 693, nb_rb 12)
[MAC][D][eNB] Generate DLSCH header num sdu 1 len sdu 662
[MAC][D][eNB] generate long sdu, size 296 (MSB 2, LSB 96)
[MAC][I][eNB 0][USER-PLANE DEFAULT DRB] Generate header : sdu_length_total 662, num_sdus
1, sdu_lengths[0] 662, sdu_lcids[0] 3 => payload offset 4,timing advance value : 0,
next_ue 0,padding 0,post_padding 28,(mcs 22, TBS 693, nb_rb 12),header_dcch 0,
header_dtch 3
[MAC][eNB 137012074] First 16 bytes of DLSCH :
a0.0.80.0.ff.ff.0.0.92.2.0.0.0.0.c2.0.0.
```

After successful reception of the MAC PDU on UE side, headers from MAC layer are decoded and MAC header and SDU corresponding to user-plane are sent to the commercial UE stack using the Stub. Using Wireshark network packet analyzer and the associated plug-in to dissect stub protocol, the header and SDU sent to commercial UE stack can be checked. Wireshark is able to decode RLC/PDCP headers.

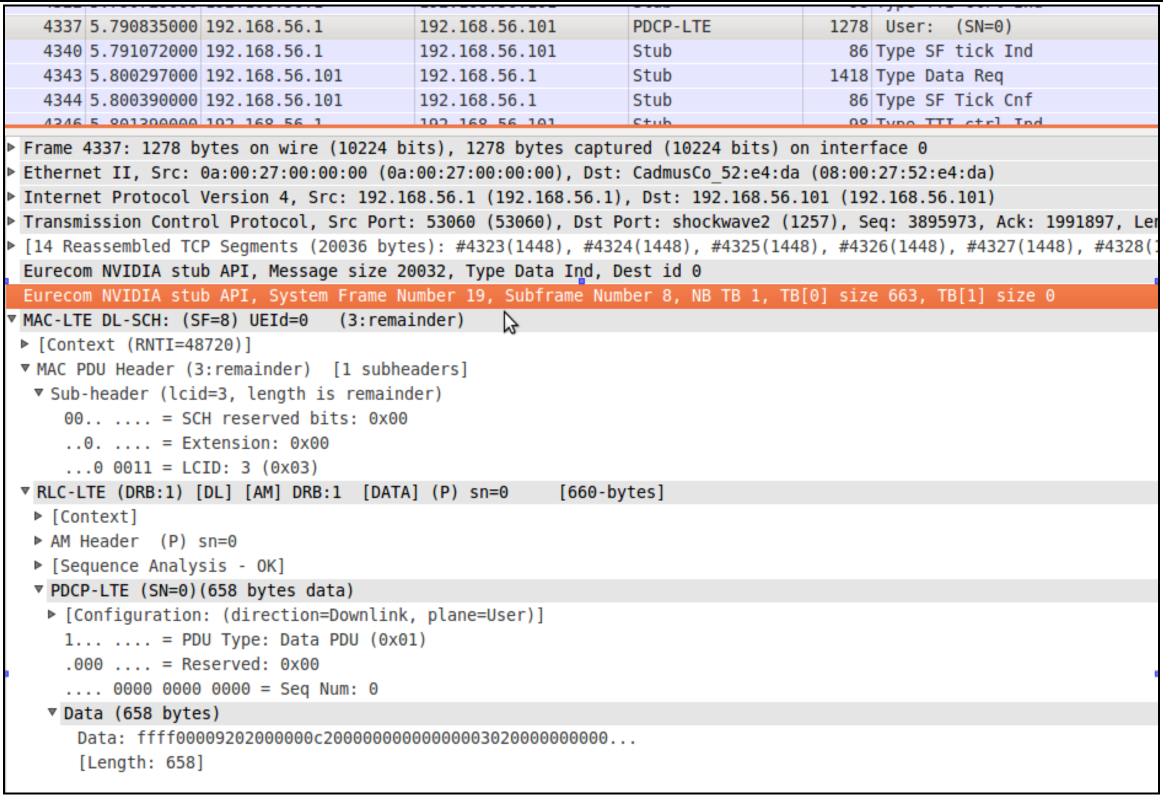

Figure 11: OAI Wireshark trace #1

After reception of the data indication message by the stack, the packet can be further traced; MAC/RLC/PDCP headers are decoded and IP packet looped back on top of the PDCP layer (see figure below).

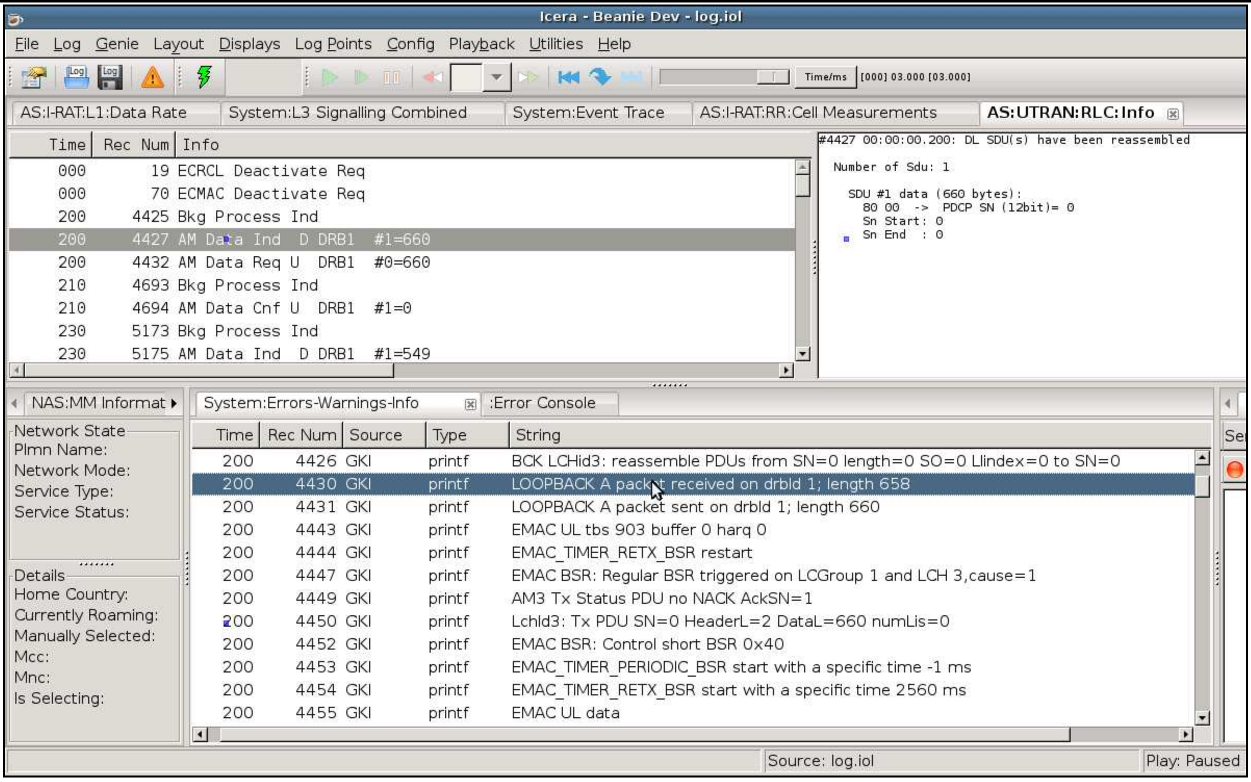

Figure 12: Loopback packet received

The PDCP PDU length is 658 bytes (see figure below) which is the expected length of the packet generated by the OAI traffic generator (OTG).

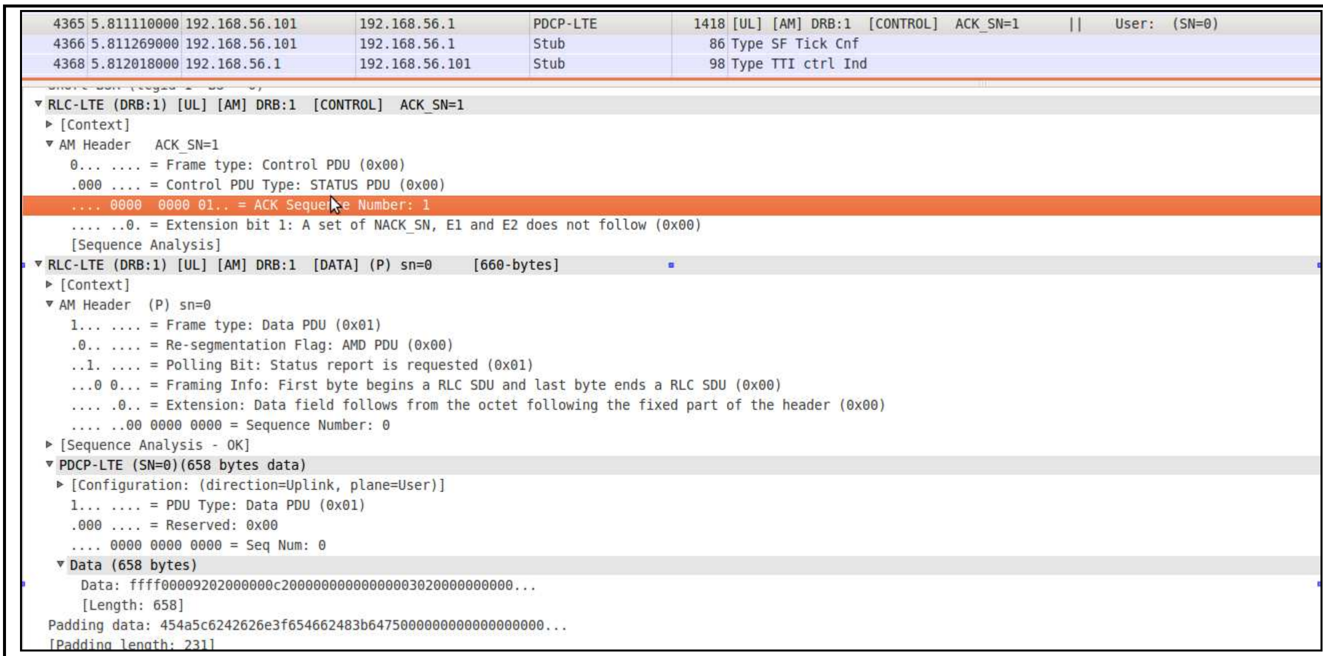

Figure 13: PDCP PDU length

After a grant of 903 bytes, the packet is forwarded from NVIDIA to OAI stack. The MAC PDU, the PDCP ACK for the first IP packet in downlink and the same IP packet forwarded to OAI for uplink transmission to eNB can be seen in the trace below. At the same time, RLC layer has requested a status report to eNB (polling bit set to 1).

```
[MAC][D][eNB 0] Received ULSCH sdu from PHY (rnti ec5, UE_id 0), parsing header
[MAC][D][eNB] sdu 0 lcid 3 length 2 (offset now 3)
[MAC][D][eNB] sdu 1 lcid 3 length 662 (offset now 6)
[MAC][I][eNB] MAC CE_LCID 29 : Received short BSR LCGID = 1 bsr = 0
[MAC][D]SDU Number 0 MAC Subheader SDU_LCID 3, length 2
[MAC][I][eNB 0] Frame 20 : ULSCH -> UL-DTCH, received 2 bytes from UE 0 for lcid 3
[RLC][D][RLC_AM][MOD 0][RB 3][FRAME 00020] MAC_DATA_IND 1 TBs
[RLC][D][MSC_MSG][FRAME 00020][MAC_eNB][MOD 00][][--- MAC_DATA_IND/ 1 TB(s) \nSTATUS ACK
SN 1 --->][RLC_AM][MOD 00][RB 03]
[RLC][D]
[FRAME 00020][RLC_AM][MOD 00][RB 03] Retransmission buffer  TX BUFFER BEFORE PROCESS OF
STATUS PDU VT(A)=0000 VT(S)=0001:[RLC][D]
TX SN: [RLC][D]0000 662/660 Bytes (RTX:-1 [RLC][D]SO:0000->0000)  [RLC][D]
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03] RX CONTROL PDU VT(A) 0000 VT(S) 0001 POLL_SN
0000 ACK_SN 0001
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][T_POLL_RETRANSMIT] STOPPED AND RESET
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][FREE SDU] SDU INDEX 000 current_sdu_index=1
next_sdu_index=1 nb_sdu_no_segmented=0
[RLC][D]
[FRAME 00020][RLC_AM][MOD 00][RB 03] Retransmission buffer VT(A)=0001 VT(S)=0001:[RLC][D]
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][RX ROUTING] VR(R)=000 VR(MR)=512
[MAC][D]SDU Number 1 MAC Subheader SDU_LCID 3, length 662
[MAC][I][eNB 0] Frame 20 : ULSCH -> UL-DTCH, received 662 bytes from UE 0 for lcid 3
[RLC][D][RLC_AM][MOD 0][RB 3][FRAME 00020] MAC_DATA_IND 1 TBs
[RLC][D][MSC_MSG][FRAME  00020][MAC_eNB][MOD  00][][---  MAC_DATA_IND/  1  TB(s)  \nSN  0
_P{}_/662 Bytes  --->][RLC_AM][MOD 00][RB 03]
[RLC][D]
=========================================================================================
=========================
[RLC][D]         26   00:00:00.-1224131903   <----D-----      UL   DRB3      LC999      A1
[RLC][D]P[RLC][D]F[RLC][D]      SN0
[RLC][D]=================================================================================
=================================
[RLC][D]Number of PDU: 1, total size: 662 bytes

[RLC][D]#26 00:00:00.-1224131903: PDU  1 of   1,  UL  LC999, AM

[RLC][D]    Data AM (662 bytes):
[RLC][D]      [RLC][D]A0 [RLC][D]00 [RLC][D]

[RLC][D]      A0 00: SN = 0000         , Poll=1, FI=[], E=DATA(0)
[RLC][D]      Data filtered (660 bytes)
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][DISPLAY DATA PDU] RX DATA PDU SN 0000 FI 0
POLL 1 [RLC][D]hidden size 00660 [RLC][D]
[RLC][D][FRAME  00020][RLC_AM][MOD  00][RB  03][PROCESS  RX  PDU]   POLL  BIT  SET,  STATUS
REQUESTED:
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][PROCESS RX PDU] VR(R) 0000 VR(H) 0000 VR(MR)
0512 VR(MS) 0000 VR(X) 0000
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][INSERT PDU] LINE 320 RX PDU SN 0000 (only
inserted)
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][PROCESS RX PDU]  RX LIST AFTER INSERTION:
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][UPDATE VR(MS)] UPDATED VR(MS) 0000 -> 0001
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][UPDATE VR(R)] UPDATED VR(R) 0000 -> 0001
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][REASSEMBLY PDU] TRY REASSEMBLY PDU SN=000
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][DISPLAY DATA PDU] RX DATA PDU SN 0000 FI 0
POLL 1 [RLC][D]hidden size 00660 [RLC][D]
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][REASSEMBLY PAYLOAD] reassembly()  660 bytes
[RLC][D]


[FRAME 00020][RLC_AM][MOD 00][RB 03][SEND_SDU] 660 bytes sdu 0xf7251e0
[RLC][D][FRAME 00020][RLC][MOD 00][RB 03] Display of rlc_data_ind:
[RLC][D]      |  0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f |
[RLC][D]------+------------------------------------------------|
[RLC] TTI 20, INST 0 : Receiving SDU (0xf7251e0) of size 660 bytes to Rb_id 3
[RLC][D][MSC_MSG][FRAME  00020][RLC_AM][MOD  00][RB  03][---  RLC_DATA_IND/660  Bytes  ---
>][PDCP][MOD 00][RB 03]
[PDCP][D][eNB] Data indication notification for PDCP entity with module ID 0 and radio
```

```
bearer ID 3 rlc sdu size 660
[PDCP][D]Incoming RX Seq # is 0000
[PDCP][D]Marking 1. bit of 0. octet of status bitmap
[PDCP][I]Received sequence number successfuly marked
[PDCP][I]Next expected SN (0) arrived, advancing RX window
[PDCP][I]Advancing RX window...
[PDCP][D]Incoming PDU has a sequence number (0) in accordance with RX window, yay!
[OTG][D]Check received buffer : enb_flag 1 mod id 0, rab id 3 (src 1, dst 0)
[OTG][I]MAX_RX_INFO 1 1
[OTG][I][SRC 1][DST 0] [FLOW_idx 0][APP TYPE 0] RX INFO pkt at time 203: flag 0x ffff,
seq number 0, tx time 194, size (hdr 658, pdcp 658)
[OTG][D][1][0] AGGREGATION LEVEL (RX) 0
[OTG][D]check_packet :: (src=1,dst=0, flag=0xffff) packet seq_num TX=0, seq_num RX=0
[OTG][D](RX) [src 1] [dst 0] [ID 0] TRAFFIC WITHOUT M2M [Capillary const]
[OTG][I]INFO LATENCY :: [SRC 1][DST 0] radio access 9.00 (tx time 194, ctime 203),
OWD:55.13 (ms):
[OTG][I]PACKET SIZE RX [SRC 1][DST 0]: Flag (0xffff), time(203), Seq num (0), Total size
(658)
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][PROCESS RX PDU] VR(R) 0001 VR(H) 0001
VR(MS) 0001 VR(MR) 0513
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][RX ROUTING] VR(R)=001 VR(MR)=513
```

As the RLC layer from the commercial stack has requested a status report, the OAI RLC eNB layer sends it correctly as can be seen in the following Wireshark trace file.

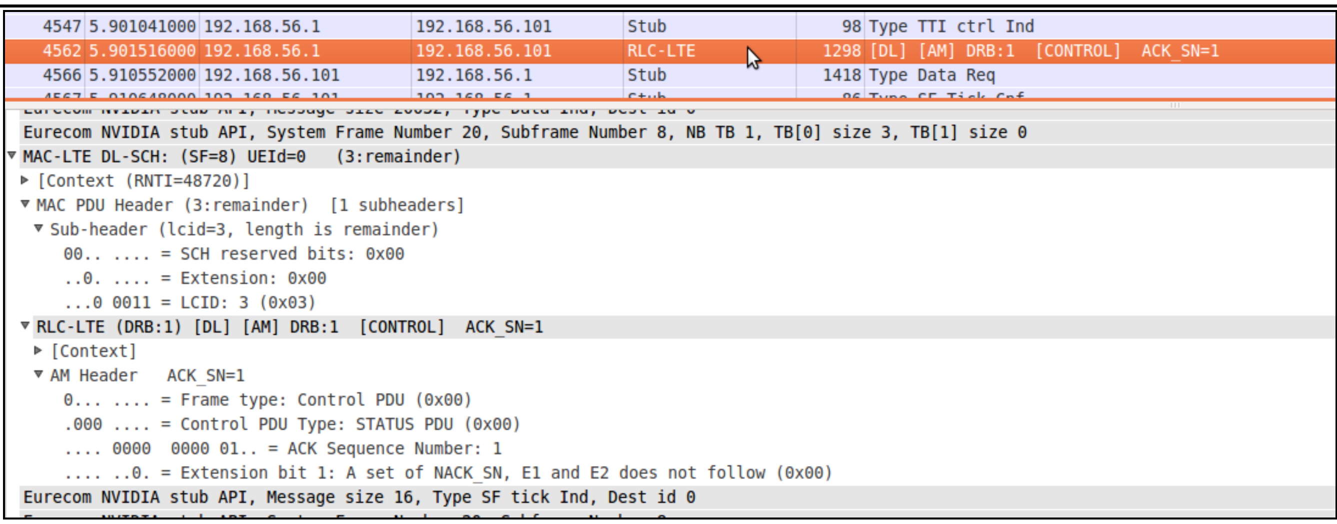

Figure 14: OAI Wireshark trace #2

The eNB RLC trace is shown below.

```
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][PROCESS RX PDU]  POLL BIT SET, STATUS
REQUESTED:
[RLC][D][FRAME 00020][RLC_AM][MOD 00][RB 03][PROCESS RX PDU] VR(R) 0000 VR(H) 0000 VR(MR)
0512 VR(MS) 0000 VR(X) 0000
```

3.2.4.2. Short BSR

In this trace the buffer status report index for Logical Channel Group Id 1 (associated to RB3) is 26, indicating a size of MAC buffer between 440 bytes and 515 bytes.

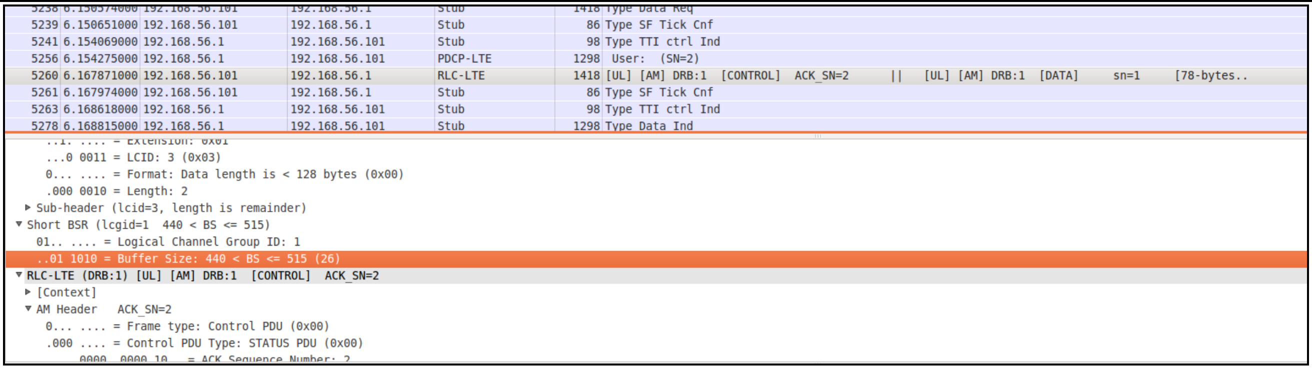

Figure 15: BSR trace

The eNB reception of the short BSR can be seen in the frame below.

```
[MAC][D][stub][00] UE is to be scheduled
[MAC][D][stub][00] ul_SR | LCGID0 | LCGID1 | LCGID2 | LCGID3 |
[MAC][D][stub][00]  0000 |  0000  |  0026  |  0000  |  0000  |
[MAC][D][eNB 0][PUSCH ec5] Frame 24 subframe 8 Scheduling UE 0 (SR 0)
[MAC][D][eNB 0] Scheduler Frame 24, subframe 8, nCCE 0: Checking ULSCH next UE_id 0 mode
id 0 (rnti ec5,mode PUSCH), format 0
[PHY][D][eNB 0][PUSCH 4] Frame 24 subframe 8 Checking HARQ, round 0
[MAC][D][eNB 0] ULSCH scheduler: Ndi 1, mcs 18
[MAC][D][eNB 0][PUSCH 0/ec5] Frame 24 subframe 8 Scheduled UE, BSR for LCGID0 0, LCGID1
26, LCGID2 0 LCGID3 0, BO 515
```

The reception of the PUSCH scheduling grant can be seen in the following frame.

```
[PHY][D][UE 0][PUSCH 4] Frame 24, subframe 8 : Programming PUSCH with n_DMRS2 0 (cshift
0)
Format 0 DCI : ulsch (ue): NBRB        15
Format 0 DCI :ulsch (ue): first_rb    1
Format 0 DCI :ulsch (ue): harq_pid    4
Format 0 DCI :ulsch (ue): Ndi         1
Format 0 DCI :ulsch (ue): TBS         5352
Format 0 DCI :ulsch (ue): mcs         18
Format 0 DCI :ulsch (ue): O           18
Format 0 DCI :ulsch (ue): O_ACK       1
Format 0 DCI :ulsch (ue): Nsymb_pusch   12
Format 0 DCI :ulsch (ue): cshift        0
[MAC][D][stub]SFN 24, sub 9, Granting of 669 bytes with NDI 1
```

And the corresponding grant sent to the commercial UE stack is shown below.

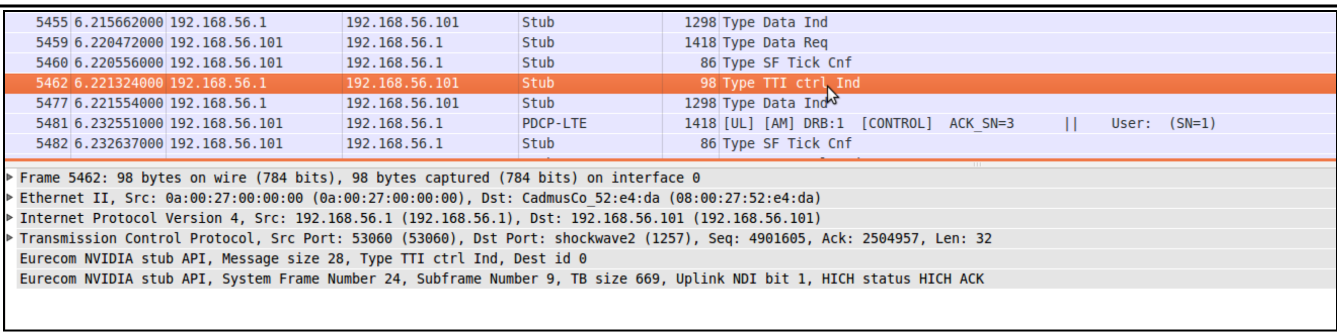

Figure 16: Grant sent to the commercial UE

3.2.4.3. Downlink Packet Transmission

The Wireshark trace related to the downlink packet transmission is shown below.

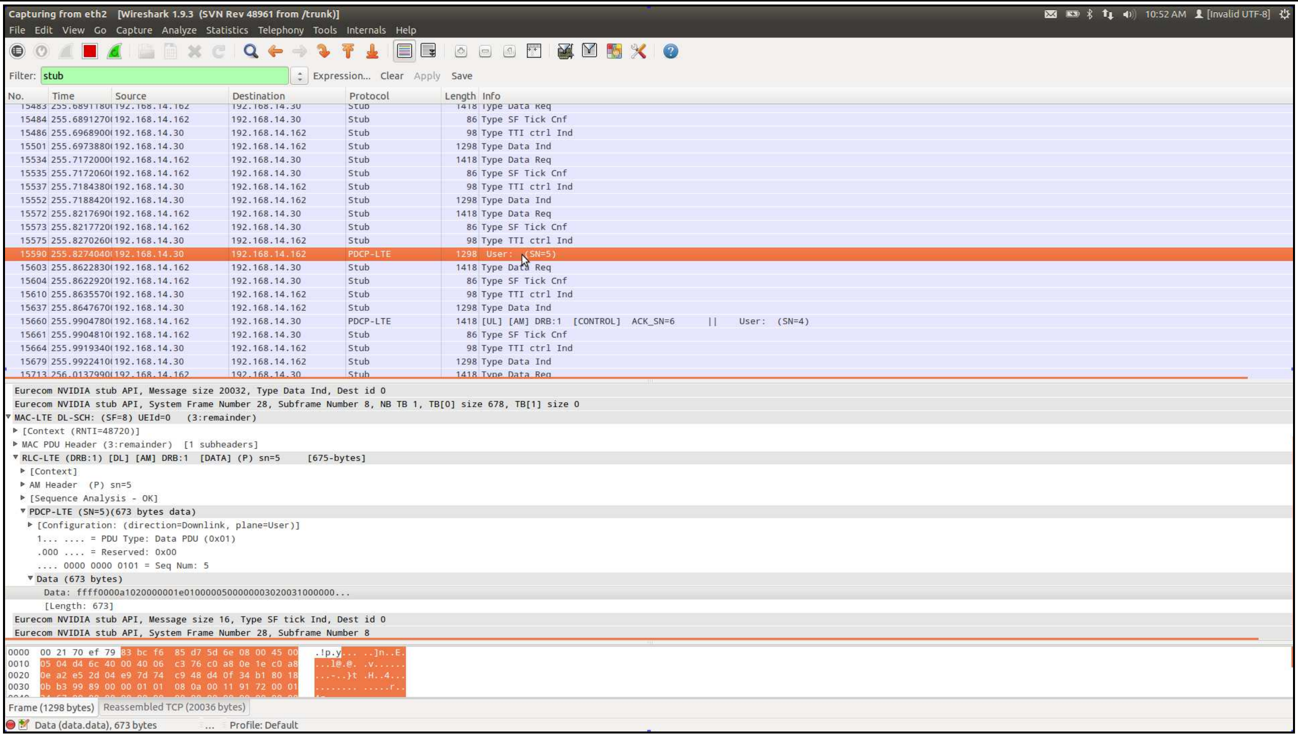

Figure 17: Downlink packet transmission

3.2.4.4. Uplink Grant

The uplink grant trace obtained with Wireshark is shown in the figure below.

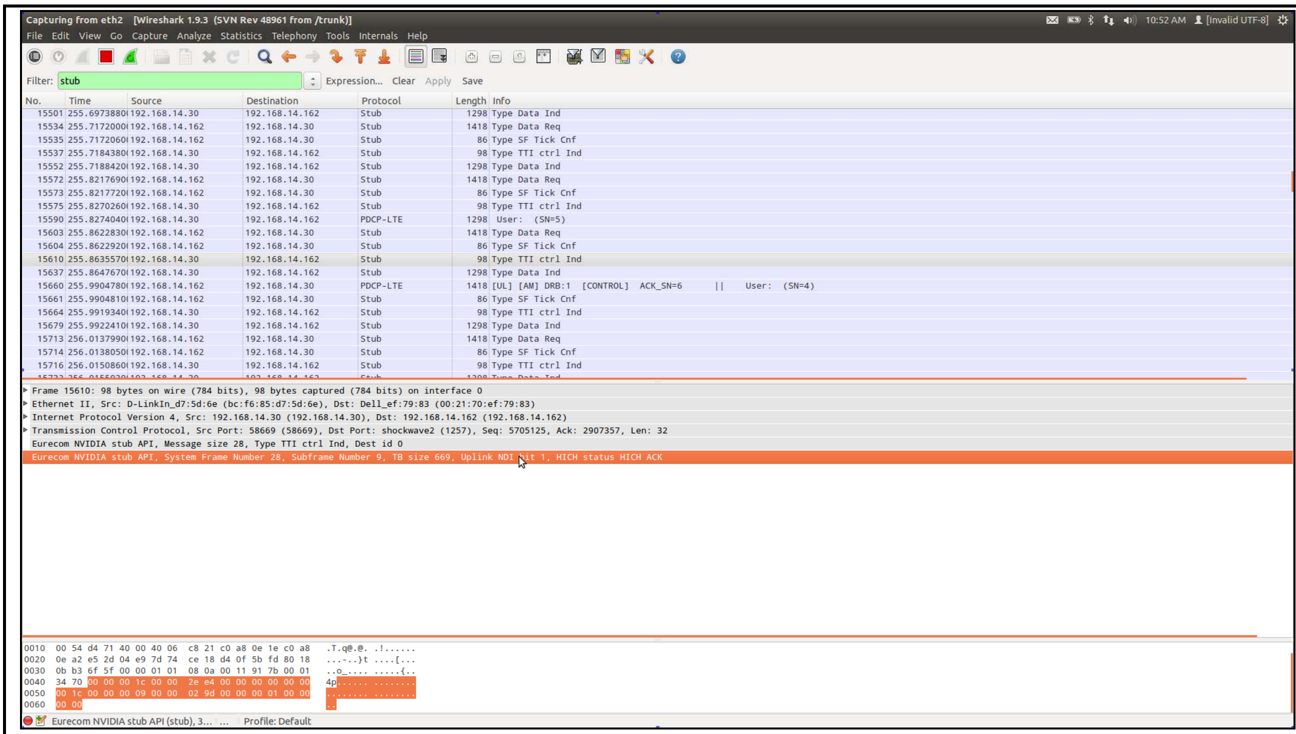

Figure 18: UL Grant transmission

3.2.4.5. Uplink Data Transmission

The Wireshark trace related to the uplink packet transmission is shown below.

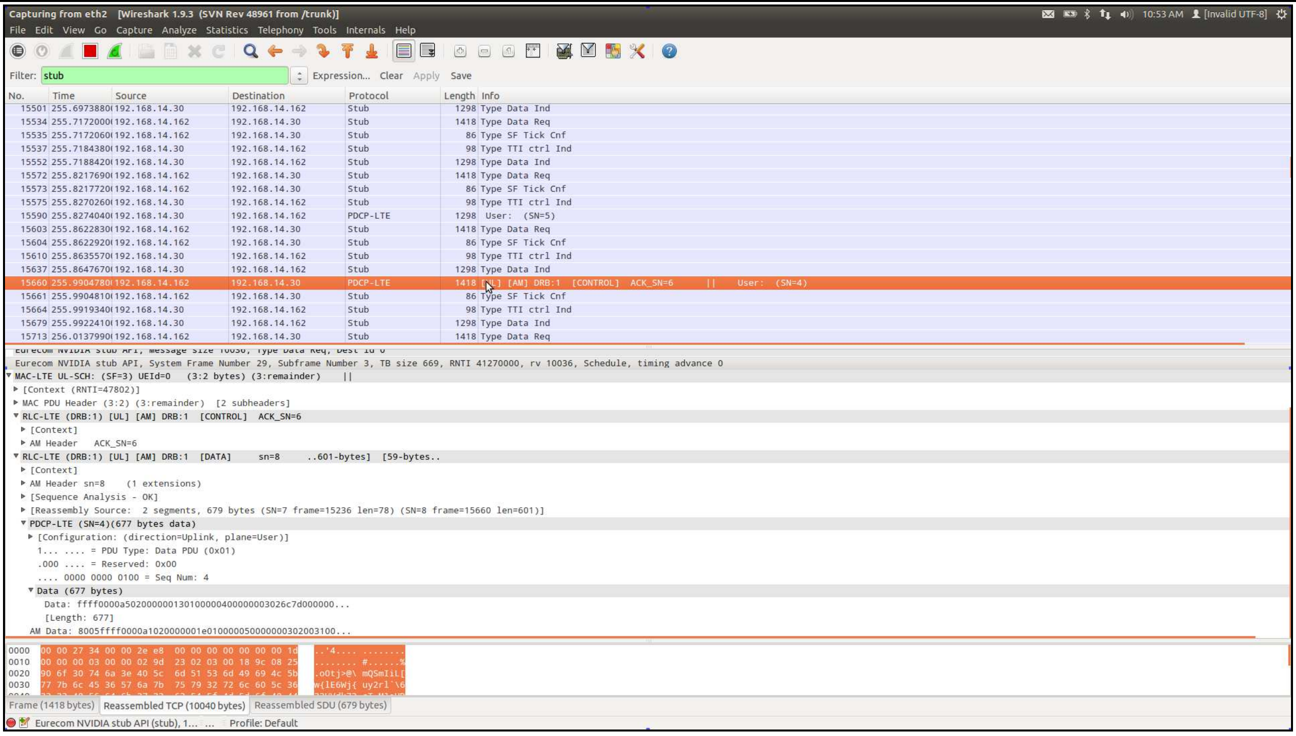

Figure 19: UL Data transmission

3.2.4.6. Downlink RLC ACK

The RLC downlink acknowledgement is shown in the Wireshark traces below.

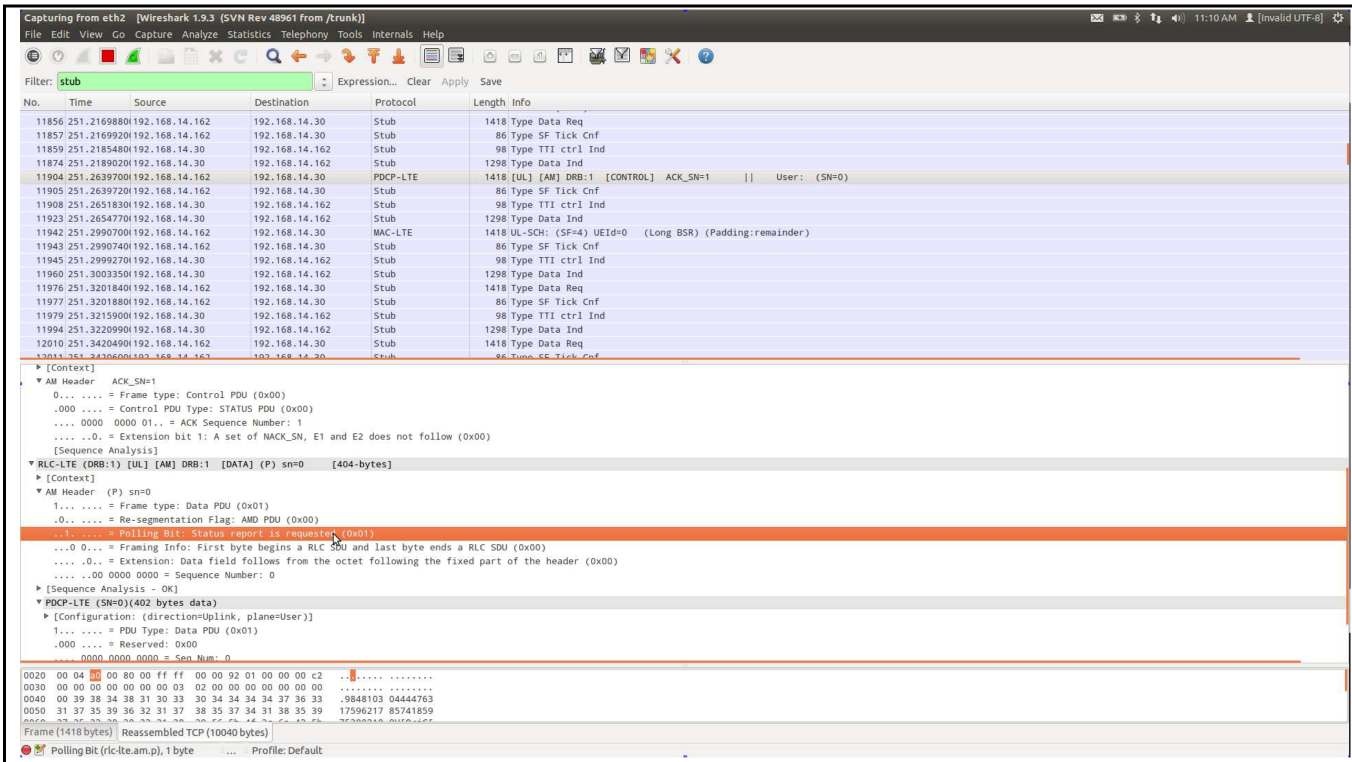

Figure 20: DL RCL ACK #1

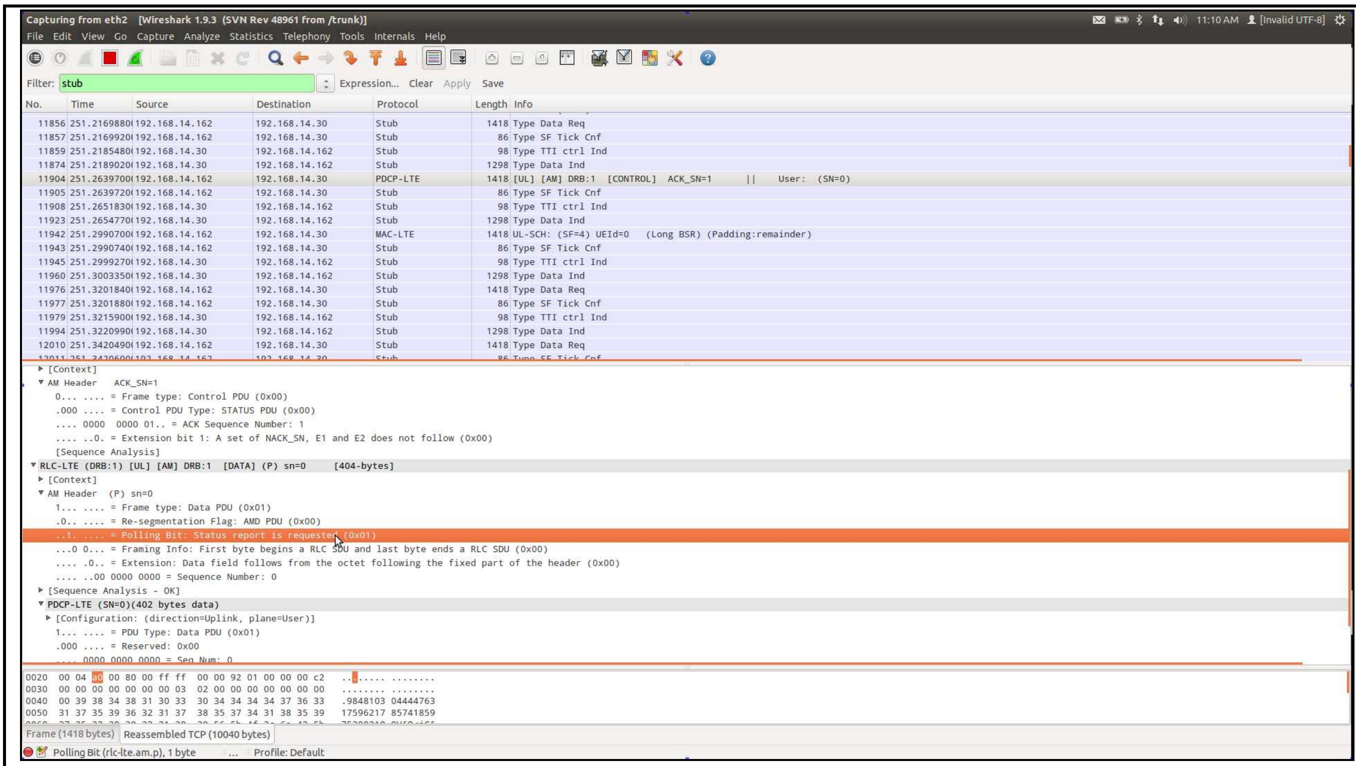

Figure 21: DL RCL ACK #2

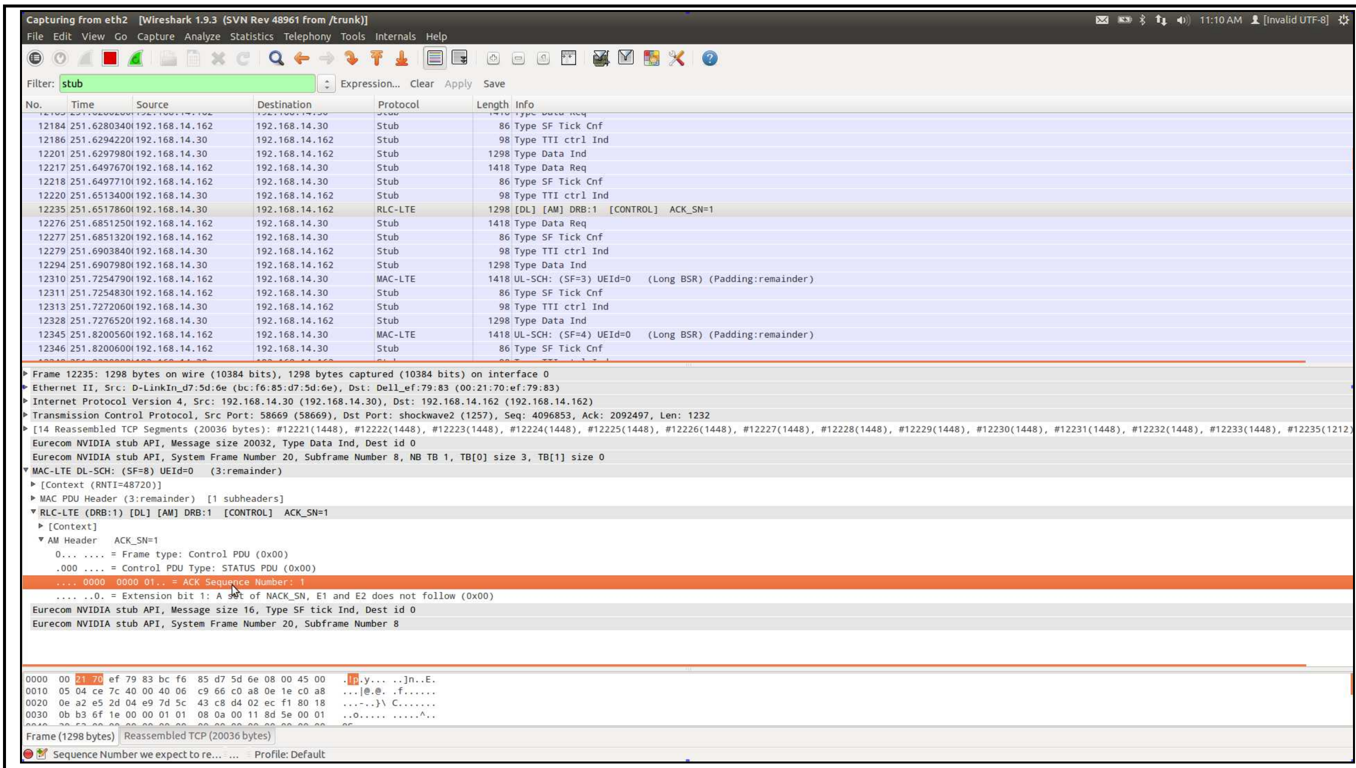

Figure 22: DL RCL ACK #3

3.2.4.7. Uplink RLC ACK

The RLC uplink acknowledgement is shown in the Wireshark traces below.

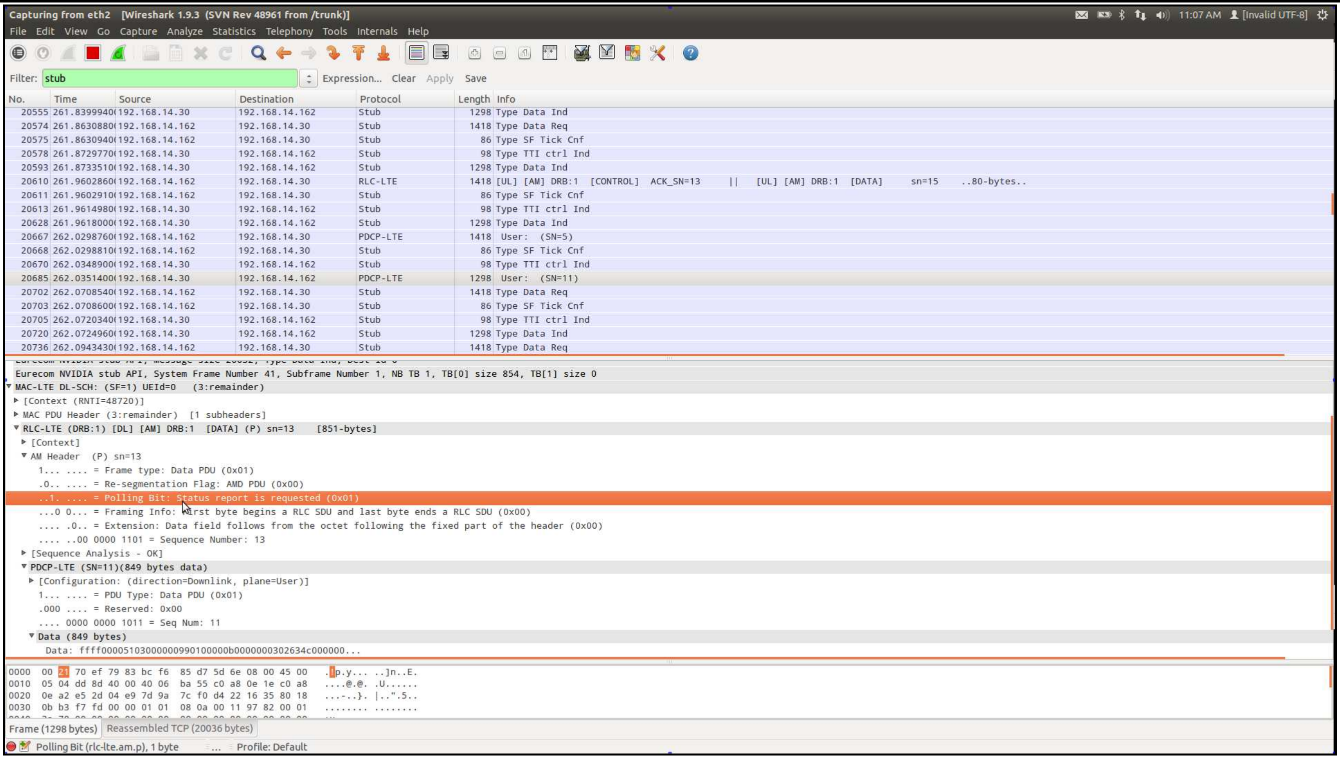

Figure 23: UL RCL ACK #1

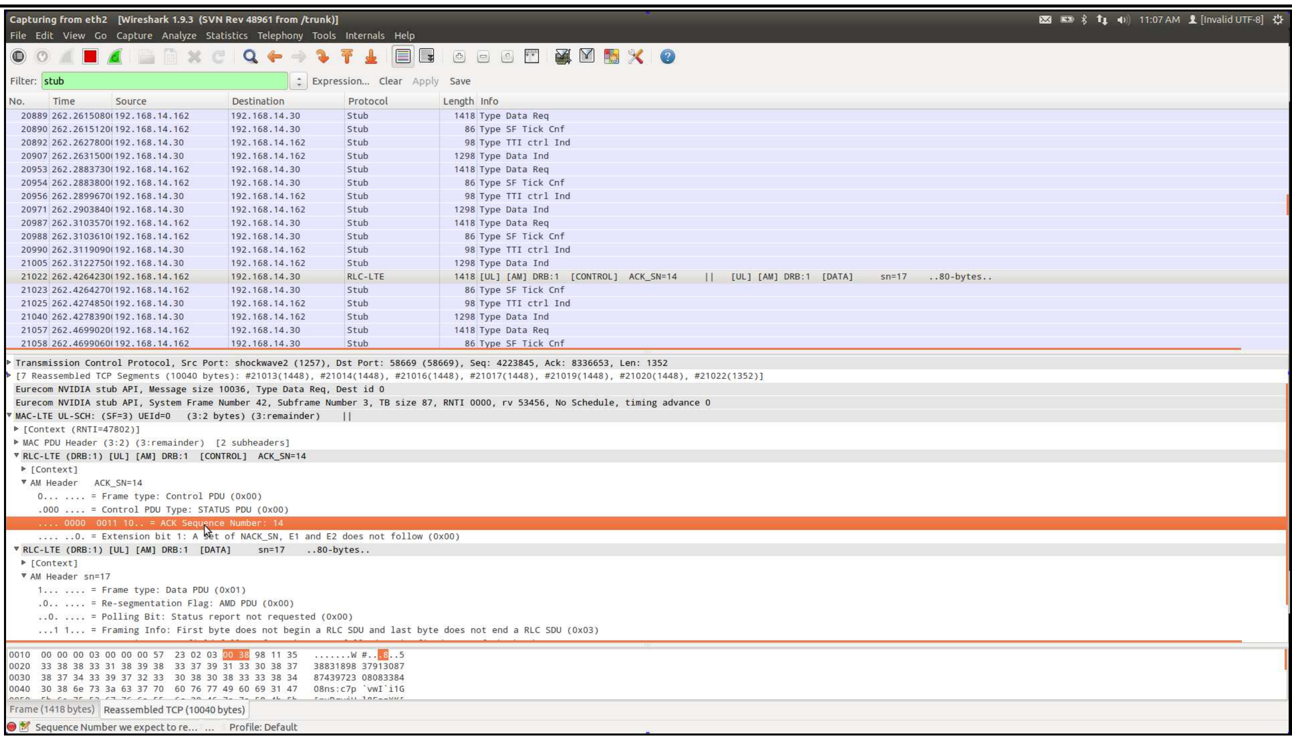

Figure 24: UL RCL ACK #2

3.2.4.8. Timing Issues

Approximately a 100 – 150 ms latency between both PCs running stacks due to the large amount of bytes exchanged for DL data indication and UL data request stub messages is induced.

4. INTEGRATION OF WP4 ADAPTATIONS

This section is intended to describe the developments driven towards the integration of WP4 adaptations in test bed 2.

4.1. Introduction

The AT4LP was fully developed according to 3GPP specifications as if it were a real eNB emulator in terms of protocol stacks. This compliance spirit allowed a quick integration with already existing and commercial equipment (such as signal analyzers and commercial UEs). However, the way the AT4LP was developed does not allow significant deviations with respect to what the standard defines.

The OAI UE implementation was developed with a different perspective, focusing on the most important functionalities of the standard, which was sufficient to demonstrate interoperability against the OAI counterpart and some pre-compliance test equipment. However, some other functionality needed for operation with the AT4LP was not implemented and therefore IOT was not demonstrated at all levels.

This differentiation in the way both test bed 2 sides were implemented required the use of additional equipment for the integration and analysis of WP4 adaptations. This way, for the evaluation of WP4 adaptations, two different versions of test bed 2 have been commissioned:

- AT4LP vs commercial UE
- OAI UE vs OAI eNB

The use of these two versions of test bed 2, even if not initially planned, conform a test framework that is equally valid for the evaluation of WP4 adaptations in a real-time test environment as that of the test bed 2 described in D5.1 [1].

4.2. More robust MCS for retransmissions

During Year 2, AT4 wireless put efforts in enabling a Software Development Kit (SDK) to allow external programmers not involved in the development of the AT4LP to develop MAC schedulers for it. The objective was to provide LOLA partners with the means for the development of WP4 scheduling techniques that can later be tested in test bed 2. This SDK is described in D5.4 [2].

As explained in D5.4, AT4 wireless developed a basic and fixed scheduler following abovementioned SDK to demonstrate that the SDK worked as expected. This basic scheduler has the following characteristics:

- It works on FDD only
- It allocates all PRBs for DL/UL transmission and uses a fixed TB size and IMCS
- It does not take into account Channel Quality Indicator (CQI)
- It does not take into account buffer status
- It does not take into account Quality of Service (QoS) requirements

It was understood that the performance obtained by this scheduler could be the baseline that can be achieved. It can serve as reference to compare the performance of other WP4 scheduling techniques.

Performance results for this basic scheduler, hereinafter referred to as scheduler FDD_0, can be found in D5.4 [2].

During Year 3, focus has been put on the integration of WP4 adaptations for test bed 2.

AT4 wireless has developed a number of scheduling techniques following the SDK presented in D5.4 [2] towards the integration of the technique “more robust MCS for retransmissions” presented in D4.3 [4]. This technique provides extra redundancy to retransmissions by reducing the CQI value reported by the UE. Therefore, this technique is focused on reducing the number of retransmissions. In all cases, the adaptations are applied for the DL transmissions only; UL transmissions follow static scheduling rules.

A number of intermediate versions of the scheduler have been developed before the final version of the technique “more robust MCS for retransmissions” was derived. All developed schedulers are listed in the following table.

Scheduler ID	Duplex Mode	Characteristics
FDD_0	FDD	Fixed FDD scheduler as described in D5.4
FDD_1	FDD	Based on FDD_0 but allocating only the resources necessary to empty the RLC buffer
FDD_2	FDD	It adapts the MCS to the channel conditions by using CQI reports
FDD_3	FDD	Based on FDD_2 but including more robust MCS for retransmissions
FDD_4	FDD	Enhancements to FDD_2
FDD_5	FDD	Enhancements to FDD_3
TDD_0	TDD	Fixed TDD scheduler (analogous to FDD_0)
TDD_1	TDD	It adapts the MCS to the channel conditions by using CQI reports (TDD version of FDD_4)
TDD_2	TDD	More robust MCS for retransmissions (TDD version of FDD_5)

Table 4: More robust MCS for retransmissions scheduler versions

Further details on the particulars of each scheduler version are provided in the following sub-clause.

4.2.1. Scheduler evolution towards final version

Different scheduler versions have been implemented before the final version was released. Details are provided below.

FDD_0: FDD fixed scheduler

This is the basic and fixed scheduler presented and analyzed in D5.4. This scheduler was developed during Year 2.

FDD_1: FDD scheduler accounting for buffer occupancy

This scheduler adds one degree of intelligence to FDD_0 by taking RLC buffer occupancy into account. The scheduler now allocates the minimum number of PRBs that are necessary to empty the RLC buffer, if possible.

FDD_2: FDD CQI-adaptive scheduler

The previous two schedulers use a fixed MCS for transmissions. This scheduler takes CQI reports from the UE into account to adapt the MCS to the channel variations.

The following restrictions apply:

- Periodic CQI reporting mode 3-0 (CQI requests sent every 2 subframes, see section 7.2.1 in 3GPP TS 36.213)
- New transmissions are allocated using the block of PRBs that would potentially allow the transmission of the largest amount of bits (taking into account CQI reports). All PRBs in this block are allocated, regardless the RLC buffer occupancy.
- MCS is selected so that the resulting coding rate adjusts to the coding rate associated to the CQI report to the extent practicable.
- Retransmissions are only allocated if the selected set of resources is big enough to allow the transmission of the previous TB.

FDD_3: FDD More robust MCS for retransmissions

This scheduler is an evolution of FDD_2 to provide extra redundancy for retransmissions.

- New transmissions are allocated the same way it is done in the FDD_2 scheduler.
- Additional robustness is applied for retransmissions. The CQI of the selected resources is reduced by a given factor if and only if the previous TB still fits in the allocation with the reduced CQI.
- CQI reduction is applied taking into account that the minimum CQI value for transmission is 1.

FDD_4_1: FDD Enhanced CQI-adaptive scheduler 1/1

This scheduler provides enhancements to FDD_2, including:

- The actual coding rate is calculated more precisely.
- The scheduler now allocates the minimum number of PRBs that are necessary to empty the RLC buffer, if possible.

FDD_4_2: FDD Enhanced CQI-adaptive scheduler 1/2

Based on FDD_4_1 but including the following change:

- To emulate the existence of other users in the cell, new transmissions now have access to a maximum of half the total number of PRBs. On one hand, this eases retransmissions to take place when the MCS selected for the retransmission is lower than that of the initial transmission. On the other hand, the maximum throughput achievable is reduced.

Traces directly extracted from the AT4LP L2 are included here for the reader to get a clearer view of how retransmissions are dealt with by the FDD_4_2 scheduler.

The piece of trace below shows how the FDD_4_2 scheduler handles new transmissions when the RLC buffer is not empty (7152 bits in this example).

1. The algorithm first determines the average CQI over the largest and non in outage block of consecutive PRBs. Note that the largest allocation found for the 3 subframes illustrated here is 25 PRBs, which coincides with half the total number of PRBs for a 10 MHz bandwidth configuration. The computed average CQI over these 25 PRBs has been 6 for the 3 subframes.
2. After the largest available allocation and average CQI are determined, the algorithm determines the minimum number of PRBs that are necessary to empty the buffer or uses the largest allocation if this is not possible. For that purpose, the algorithm selects the MCS index (I_{MCS}) that adapts best to the coding rate associated to the average CQI (see 3GPP TS 36.213 Table 7.2.3-1). The scheduler uses the largest available allocation for the first two transmissions in the example, [723|9] and [724|0], for a total Transport Block (TB) of 3496 bits each time. It allocates only 2 PRBs for the third transmission, [724|1], for a total TB of 256 bits because that is sufficient to empty the remaining 192 bits in the RLC buffer.

```
[  723 | 9 ] In schedule(), wideband CQI: 6, average CQI: 6, largest allocation: 25 PRBs
[  723 | 9 ] NEW_TX: 25 PRBs allocated for DL-SCH with Imcs = 8 for a total TBS of 3496 bits. Buffer occupancy = 7152
[  724 | 0 ] In schedule(), wideband CQI: 6, average CQI: 6, largest allocation: 25 PRBs
[  724 | 0 ] NEW_TX: 25 PRBs allocated for DL-SCH with Imcs = 8 for a total TBS of 3496 bits. Buffer occupancy = 3672
[  724 | 1 ] In schedule(), wideband CQI: 6, average CQI: 6, largest allocation: 25 PRBs
[  724 | 1 ] NEW_TX: 2 PRBs allocated for DL-SCH with Imcs = 8 for a total TBS of 256 bits. Buffer occupancy = 192
```

Figure 25: New transmissions handling in FDD_4_2

The piece of trace below shows how the FDD_4_2 scheduler handles retransmissions.

1. In this example, the scheduler has allocated 18 PRBs with IMCS = 11 for a total TBS of 3112 bits in subframe [604|0].
2. The AT4LP receives a Negative Acknowledgement (NACK) for the TB transmitted in subframe [604|8] and schedules a retransmission in subframe [604|8] (as expected). The largest available allocation is now 50 PRBs which coincide with the total number of PRBs.
3. The scheduler selects IMCS = 6 for this retransmission because the average CQI computed for subframe [604|8] is 5, lower than that of the initial transmission, 7. The example also illustrates how retransmissions can be allocated on a number of PRBs higher than the largest available allocation for initial transmissions (30 PRBs in this case).

```
[ 604 | 0 ] In schedule(), wideband CQI: 6, average CQI: 7, largest allocation: 25 PRBs
[ 604 | 0 ] NEW_TX: 18 PRBs allocated for DL-SCH with Imcs = 11 for a total TBS of 3112 bits. Buffer occupancy = 3040
[ 604 | 1 ] In schedule(), wideband CQI: 6, average CQI: 6, largest allocation: 50 PRBs
[ 604 | 2 ] In schedule(), wideband CQI: 6, average CQI: 6, largest allocation: 50 PRBs
[ 604 | 3 ] In schedule(), wideband CQI: 6, average CQI: 6, largest allocation: 50 PRBs
[ 604 | 4 ] In schedule(), wideband CQI: 6, average CQI: 5, largest allocation: 50 PRBs
[ 604 | 5 ] BCH [requires 328 bytes]
[ 604 | 5 ] In schedule(), wideband CQI: 6, average CQI: 5, largest allocation: 46 PRBs
[ 604 | 6 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[ 604 | 7 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[ 604 | 8 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[ 604 | 8 ] RE_TX: 30 PRBs allocated for DL-SCH with Imcs = 6 for a total TBS of 3112 bits
```

Figure 26: Retransmissions handling in FDD_4_2

FDD_5_1: FDD Enhanced more robust MCS for retransmissions 1/1

This scheduler provides enhancements to FDD_3, including:

- The actual coding rate is calculated more precisely.
- The scheduler now allocates the minimum number of PRBs that are necessary to empty the RLC buffer, if possible.

FDD_5_2: FDD Enhanced more robust MCS for retransmissions 1/2

Based on FDD_5_1 but including the following change:

- To emulate the existence of other users in the cell, new transmissions now have access to a maximum of half the total number of PRBs. On one hand, this eases retransmissions to take place when the MCS selected for the retransmission is lower than that of the initial transmission. On the other hand, the maximum throughput achievable is reduced.

The trace presented below is directly extracted from the AT4LP L2 and provides the reader with a clearer view of how retransmissions are dealt with by the FDD_5_2 scheduler with a CQI reduction value of 1.

1. In subframe [14|6] the scheduler allocates 25 PRBs for a new transmission using IMCS = 6 for a total TBS of 2600 bits. The computed average CQI is 5.
2. The AT4LP receives a NACK for the previous transmission and allocates the corresponding retransmission in subframe [15|4].
3. The computed average CQI in subframe [15|4] is again 5, but the algorithm reduces this CQI value by 1 to provide extra redundancy for the retransmission, leading to a more robust MCS of IMCS = 4. This of course requires additional resources and the number of PRBs allocated to construct the TB of 2600 bits is now 36 instead of 25.

```
[  14 | 6 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 25 PRBs
[  14 | 6 ] NEW_TX: 25 PRBs allocated for DL-SCH with Imcs = 6 for a total TBS of 2600 bits. Buffer occupancy = 2544
[  14 | 7 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  14 | 8 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  14 | 9 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  15 | 0 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  15 | 1 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  15 | 2 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  15 | 3 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  15 | 3 ] RE_TX: 31 PRBs allocated for DL-SCH with Imcs = 4 for a total TBS of 2216 bits
[  15 | 4 ] In schedule(), wideband CQI: 5, average CQI: 5, largest allocation: 50 PRBs
[  15 | 4 ] RE_TX: 36 PRBs allocated for DL-SCH with Imcs = 4 for a total TBS of 2600 bits
```

Figure 27: Retransmissions handling in FDD_5_2

TDD_0: TDD basic scheduler

This is the TDD version of FDD_0. The following restrictions apply:

- No DL-SCH transmissions are scheduled during special subframes
- No new UL-SCH transmissions are scheduled during special subframes (only retransmissions are scheduled)

TDD_1: TDD Enhanced CQI-adaptive scheduler

This is the TDD version of FDD_4 with the TDD_0 restrictions.

TDD_2: TDD Enhanced more robust MCS for retransmissions

This is the TDD version of FDD_5 with the TDD_0 restrictions.

4.2.2. Evaluation results

Several test campaigns have been carried out in order to evaluate the performance of the technique “more robust MCS for retransmissions”. Each test campaign corresponds to an evaluation of a different version of the technique (see previous clause). In all cases performance has been compared against that obtained by the CQI-adaptive scheduler.

Two similar test setups have been used to carry out the test campaigns. The only difference between these two test setups falls on whether traffic is generated by using the AT4 wireless traffic generation tool mentioned in section 2.3 or a traffic generation tool developed within WP3 that supports various WP3 traffic models. These two test setups are illustrated in the following two figures.

Three different traffic patterns have been used during the test campaign:

- UDP constant traffic: UDP constant traffic has been used to determine the maximum throughput that can be achieved. It has been generated using the AT4 wireless traffic generation tool.
- Online gaming: D4.3 showed that the “more robust MCS for retransmissions” technique was best suited for more data-hungry traffic sources but a reduced set of tests have been run anyway to

determine if the technique has any impact on this source when used in a more realistic scenario like test bed 2. It has been generated using the AT4 wireless traffic generation tool with packet size and inter-arrival time characteristics for OpenArena in D3.5.

- IP video surveillance: This is the traffic source that was used during simulations in WP4. Packet size and inter-arrival time characteristics for this source did not follow typical probability distributions (as the OpenArena game does) and therefore the AT4 wireless traffic generation tool could not be used. A traffic generation tool developed within WP3 was used to generate this traffic instead.

In both test setups, the AT4LP and UE are connected through an RF cable. The UE connected to the AT4LP is an LTE Rel-8 dongle-type commercial UE (name kept confidential, same as UE #4 in D5.4 [2]). The UE is connected to a PC that provides IP and higher layer applications. The AT4LP is connected to a PC acting as traffic server. Traffic is generated at the PC Sender and is transferred via LTE DL to the PC Receiver. Traffic sent by the PC Sender and received at the PC Receiver is monitored and later measured by the AT4 wireless IP Measurement Tool presented in section 2.3. Two measurement points are installed, one at each PC. The Test Controller monitoring the traffic and carrying out (and also controlling the Traffic Generator in Test Setup #2) the measurements is installed in the PC Receiver for convenience.

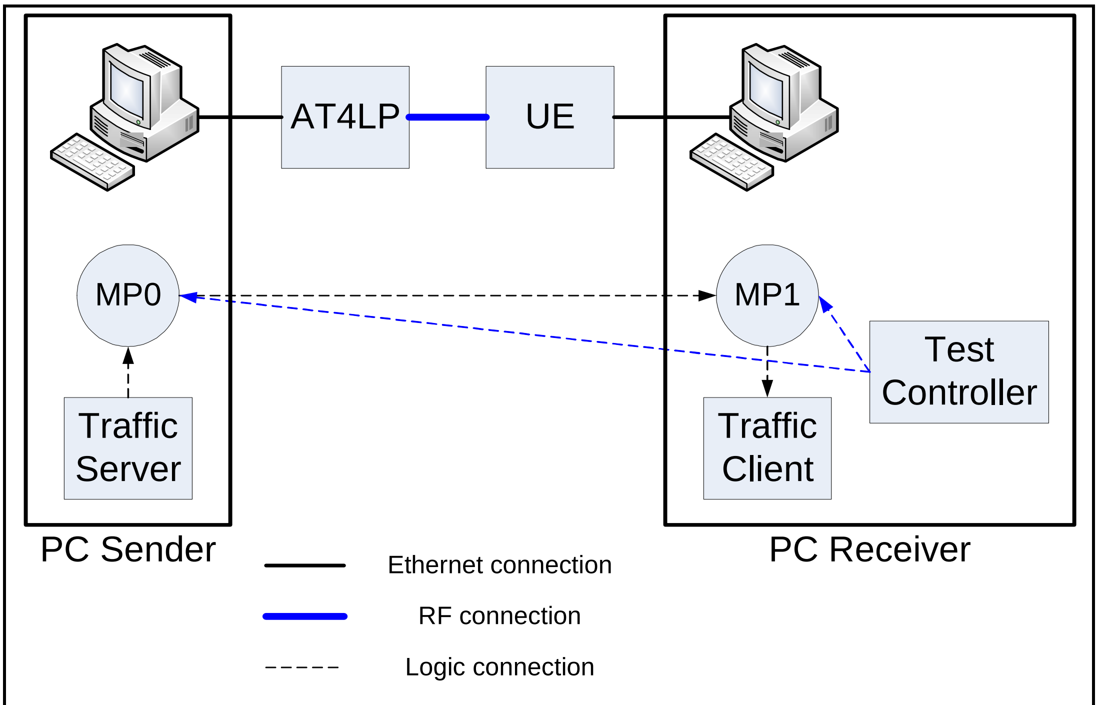

Figure 28: Test Setup #1 with WP3 traffic generation tool

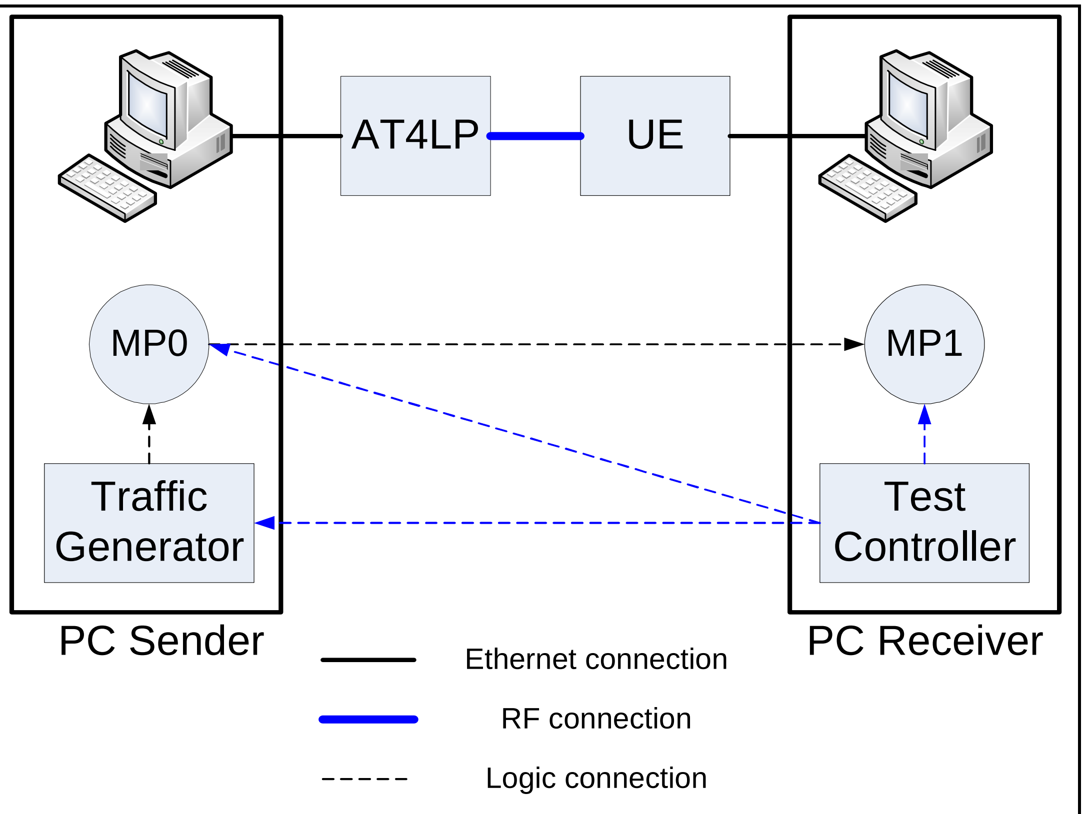

Figure 29: Test Setup #2 with AT4 wireless traffic generation tool

4.2.2.1. Test conditions

The most important test conditions applicable to the test campaigns presented in this section are provided in the following table. Two different traffic sources have been evaluated; the First Person Shooter (FPS) online game OpenArena and the IP video surveillance camera both presented and analyzed in D3.3 [3]. Packet Size (PS) and Inter-Arrival Time (IAT) distributions for these two traffic sources are presented below.

Cell parameters		Traffic source parameters	
Duplex mode	FDD	OpenArena PS	Normal (0,172;0,05) kB
Band	7	OpenArena IAT	Uniform (41;47) ms
Bandwidth	10 MHz	Video camera PS	See Figure 30
Cyclic Prefix	Normal	Video camera IAT	Constant 40 ms
SNR	0 dB – 30 dB		
Noise power (Noc)	-107,8 dBm/15kHz		
Transmission mode	TM1 (SISO)		
CQI reporting mode	Aperiodic 3-0		
CSI request	Every 2 subframes		
Nº symbols PDCCH	2		
Max nº HARQ retx DL	3		
Channel conditions	AWGN		

Table 5: Test parameters for the evaluation of more robust MCS for retransmissions

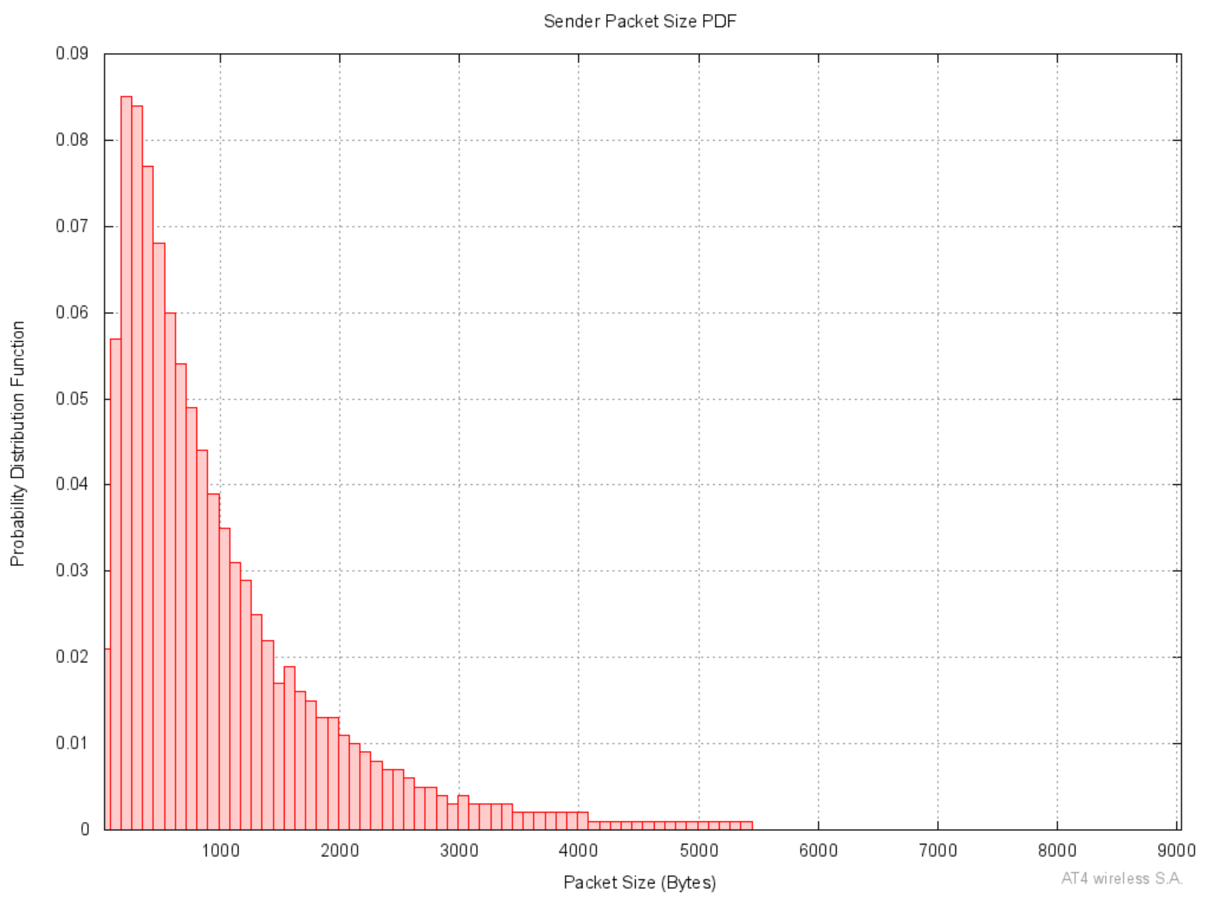

Figure 30: Packet Size distribution for video camera traffic

4.2.2.2. Test Campaign 1: FDD_4_1 vs FDD_5_1

This test campaign is intended to evaluate the performance improvement achieved with the technique “more robust MCS for retransmissions” version FDD_5_1. The baseline technique that has been used for comparisons is the Enhanced CQI-adaptive scheduler version FDD_4_1 (see section 4.2.1 for further details).

Performance has been evaluated for different SNR values, ranging from 30 dB to 0 dB in 5 dB steps. For each SNR value evaluated, multiple iterations have been carried out. Results shown below represent averages over all iterations carried out for each SNR value. The traffic source used for this test campaign is the online game OpenArena.

Results for UDP metrics such as Mean One-Way Delay (OWD), IP Delay Variation or jitter (IPDV), packet loss and throughput have been compiled in Table 6. Results in columns denoted by “CQI-a” correspond to the CQI-adaptive technique and results in columns denoted by “Robust” correspond to the “more robust MCS for retransmissions”. Figure 31 shows an OWD comparative between the two techniques.

SNR (dB)	OWD (ms)		IPDV (ms)		Packet loss (%)		Goodput (Mbps)	
	Robust	CQI-a	Robust	CQI-a	Robust	CQI-a	Robust	CQI-a
30	6,402	6,277	0,397	0,390	0,000	0,000	0,034	0,034
25	6,393	6,253	0,397	0,391	0,000	0,000	0,034	0,034
20	6,767	6,498	1,020	0,658	0,000	0,000	0,033	0,033
15	6,616	6,730	0,979	1,212	0,000	0,000	0,034	0,034
10	7,285	7,289	1,818	1,957	0,000	0,000	0,034	0,033
5	6,713	6,575	0,899	0,768	0,000	0,000	0,034	0,033
0	7,610	8,216	1,666	2,239	2,671	3,500	0,032	0,033

Table 6: Test Campaign 1 – FDD_4_1 vs FDD_5_1 OpenArena

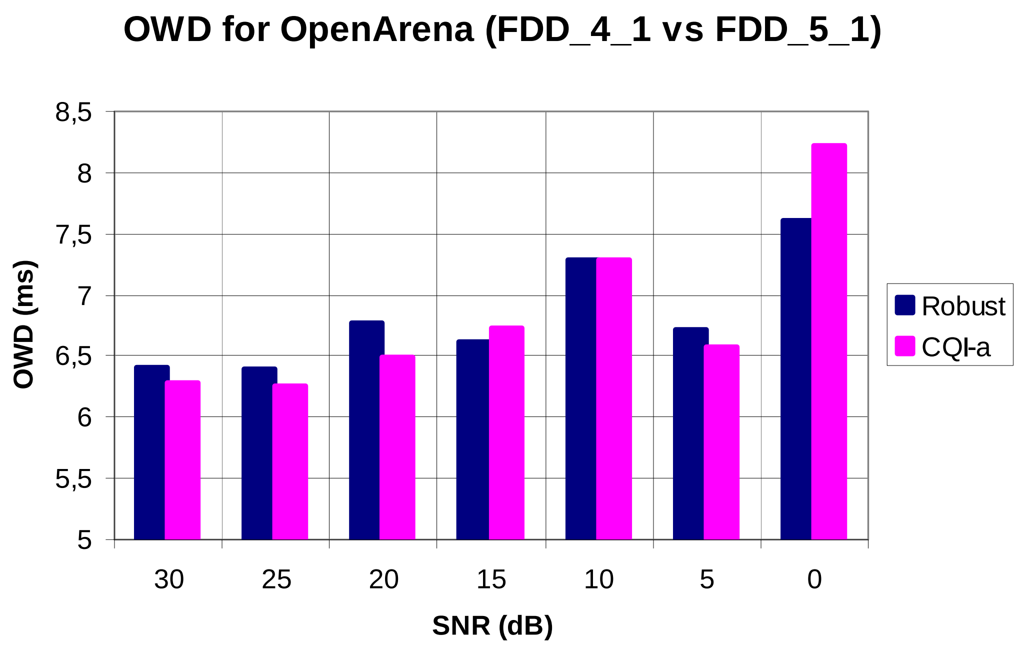

Figure 31: Test Campaign 1 – FDD_4_1 vs FDD_5_1 OWD results

Results do not show a clear benefit in the use of the “more robust MCS for retransmissions” in terms of latency (both for OWD and IPDV) for online gaming traffic such as that produced by OpenArena. Only for a SNR value of 0 dB, when outage probability increases and the link starts to drop packets, there seems to be an OWD gain slightly above 7%. In any case, as already explained in D4.3 [4], the “more robust MCS for retransmissions” is best suited for traffic sources that produce higher traffic loads.

4.2.2.3. Test Campaign 2: FDD_4_2 vs FDD_5_2

This test campaign is intended to evaluate the performance improvement achieved with the technique “more robust MCS for retransmissions” version FDD_5_2. The baseline technique that has been used for comparisons is the Enhanced CQI-adaptive scheduler version FDD_4_2 (see section 4.2.1 for further details).
In this case, two different values for the CQI reduction applied to retransmissions have been used, therefore there are three schedulers being compared: CQI-adaptive, more robust MCS for retransmissions with CQI reduction of 1 and more robust MCS for retransmissions with CQI reduction of 2.

Performance has been evaluated for different SNR values, ranging from 30 dB to 0 dB in 5 dB steps. For each SNR value evaluated, a single iteration of 1 hour duration was carried out.
The traffic source used for this test campaign is an IP video surveillance camera. Packets are generated at a fixed rate every 40 ms and packet size follows the distribution shown in Figure 30.

Results obtained for Test Campaign 2 are compiled in Table 7. Results in columns denoted by “CQI-a” correspond to the CQI-adaptive technique, results in columns denoted by “Robust 1” correspond to the “more robust MCS for retransmissions” with CQI reduction of 1 and results in columns denoted by “Robust 2” correspond to the “more robust MCS for retransmissions” with CQI reduction of 2.

SNR (dB)	OWD (ms)			IPDV (ms)			Packet Loss (%)		
	CQI-a	Robust 1	Robust 2	CQI-a	Robust 1	Robust 2	CQI-a	Robust 1	Robust 2
20	6,851	6,958	6,966	0,664	0,667	0,664	0,158	0,15	0,151
10	6,962	8,477	7,427	1,179	1,925	1,203	0,156	0,149	0,16
7	8,267	7,725	8,128	1,925	1,427	1,811	0,144	0,152	0,15
5	8,587	8,034	8,389	2,506	1,891	1,899	0,187	0,151	0,153
3	11,725	11,803	12,116	4,765	4,583	4,731	7,209	7,003	7,079

Table 7: Test Campaign 2 – FDD_4_2 vs FDD_5_2 UDP statistics

OWD results for the three variants evaluated are graphically illustrated in the following figure.

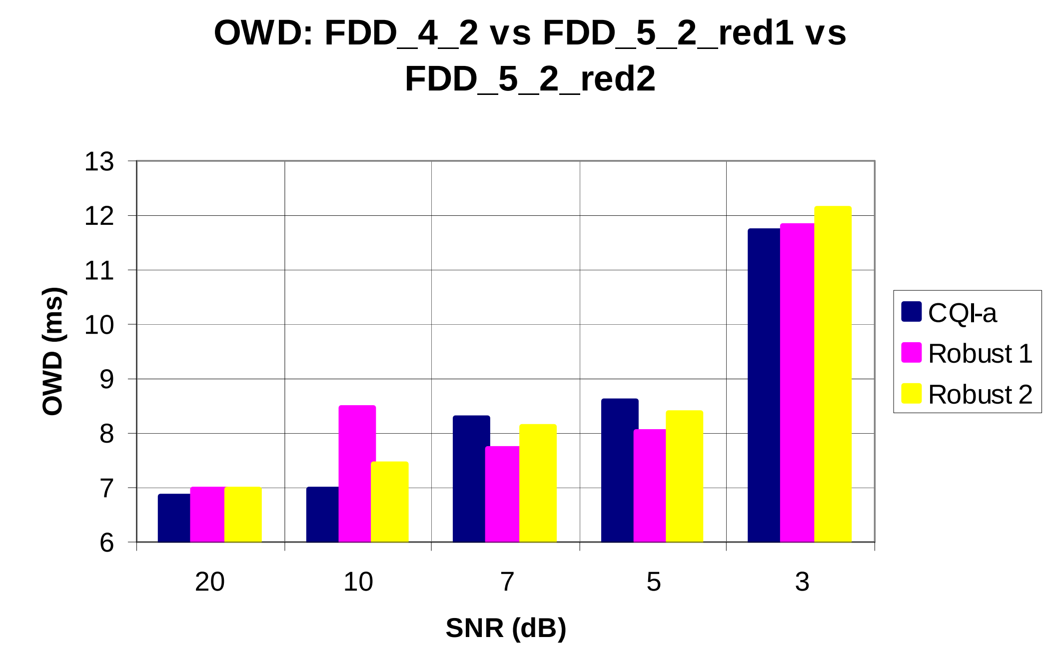

Figure 32: Test Campaign 2 – FDD_4_2 vs FDD_5_2 (red1 and red2) OWD results

Results compiled in Table 7 and illustrated in Figure 32 do not show benefits in the use of the "more robust MCS for retransmissions" in terms of latency or packet loss, at least for CQI reduction values of 1 and 2.

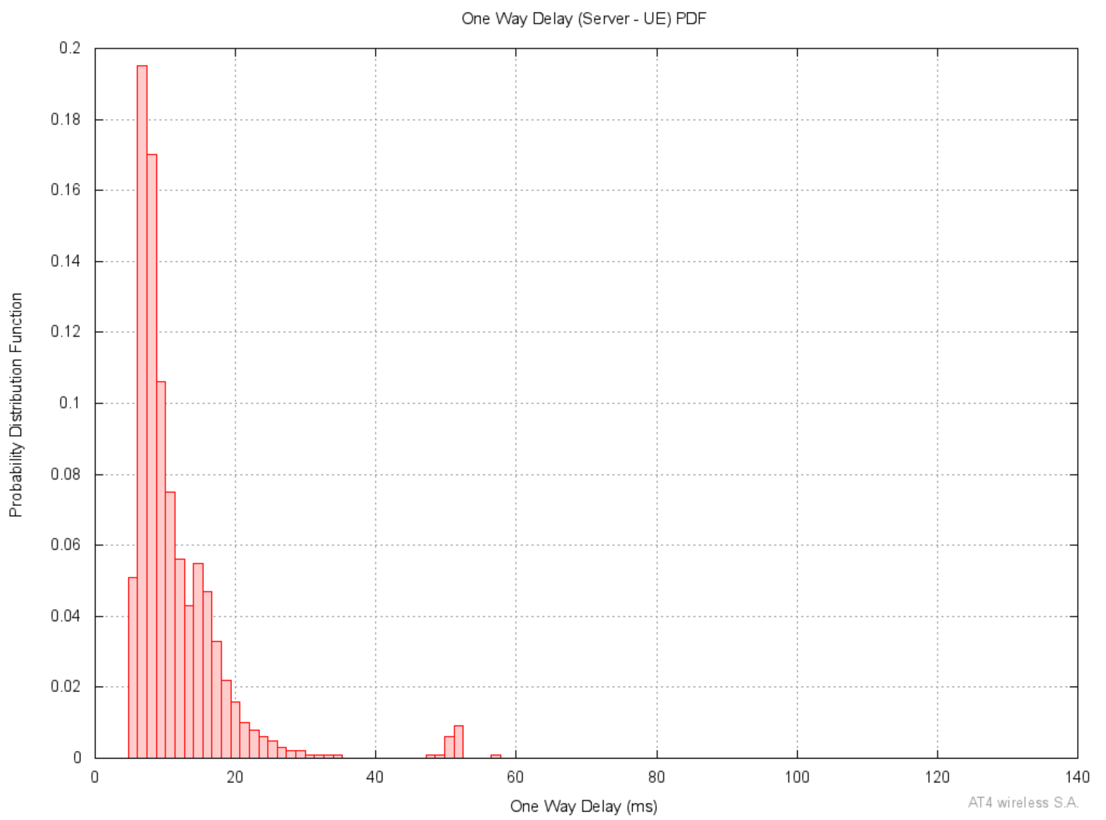

Figure 33: Test Campaign 2 – FDD_4_2 histogram

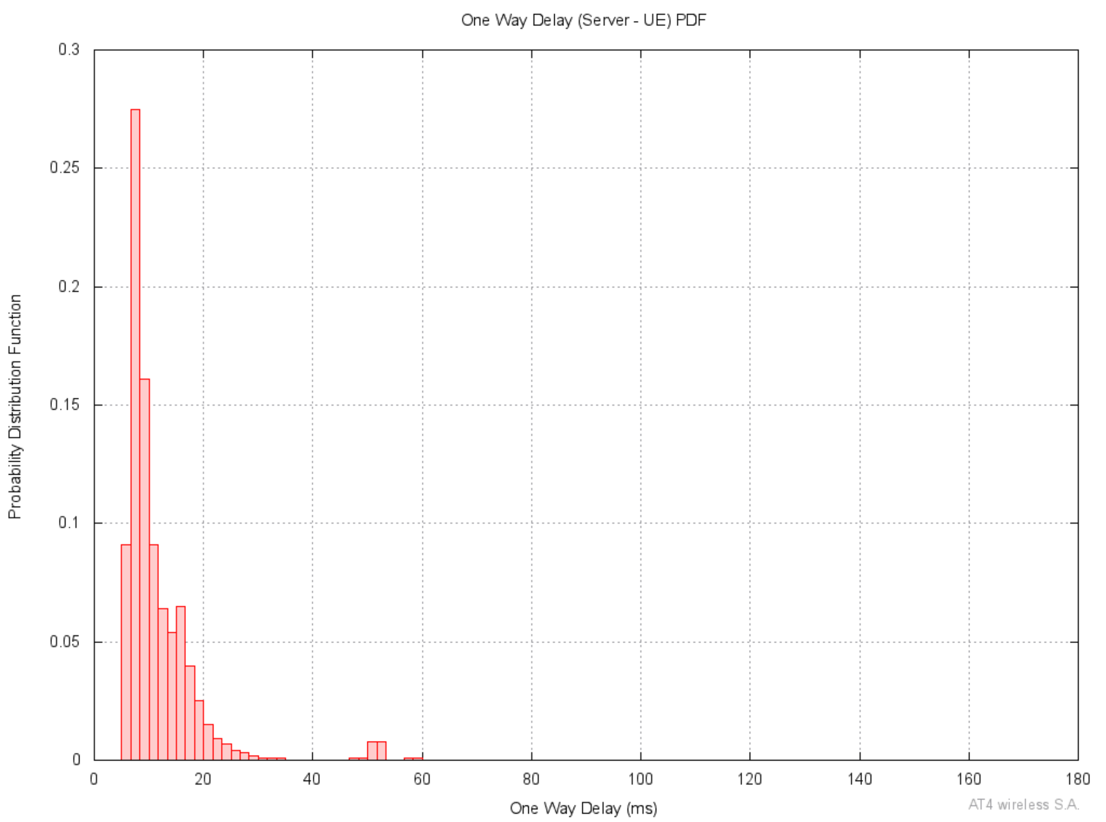

Figure 34: Test Campaign 2 – FDD_5_2 CQI reduction 1 histogram

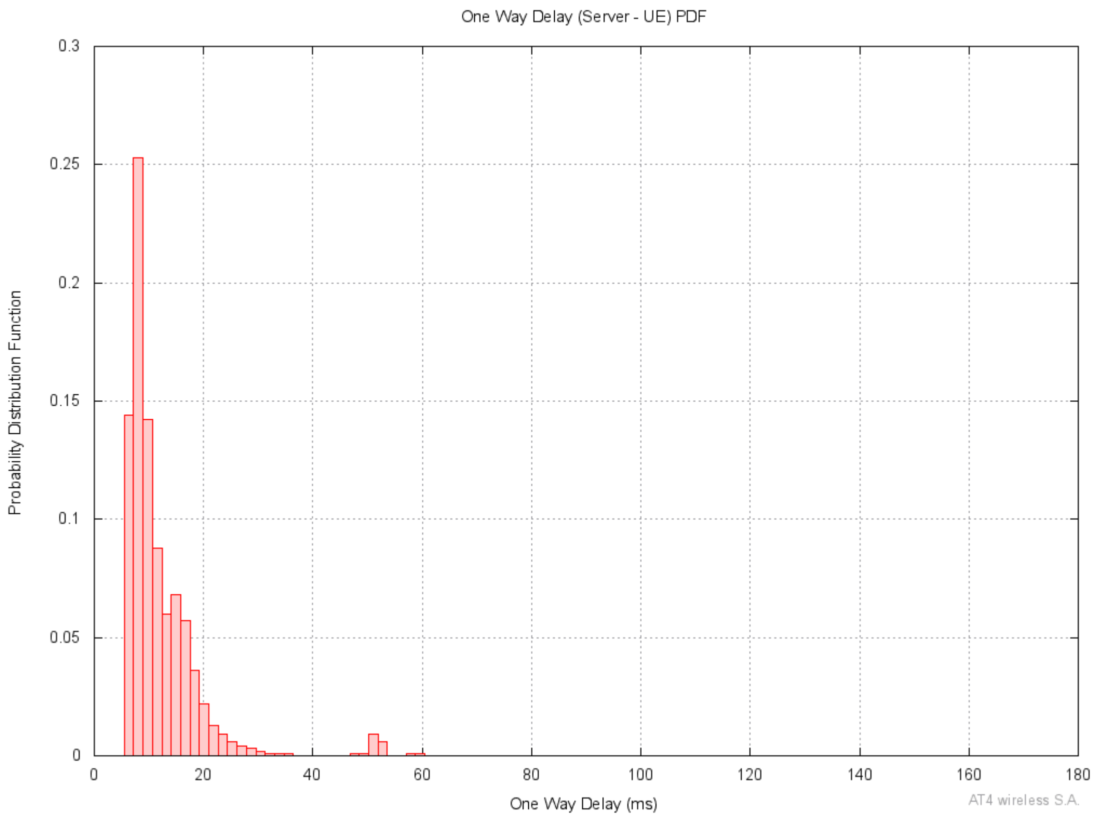

Figure 35: Test Campaign 2 – FDD_5_2 CQI reduction 2 histogram

Figure 33, Figure 34 and Figure 35 show OWD histograms for the three algorithms evaluated when SNR = 3 dB. No significant differences are observed except for a slight increase in the amount of packets that are transmitted with an OWD of 10 ms and less when the “more robust MCS for retransmissions” technique is used.

Additional L2 statistics were computed at the AT4LP to understand if the technique “more robust MCS for retransmissions” achieved at least the purpose of reducing the number of retransmissions. Results for Block Error Rate (BLER) and percentage of L2 NACKs are compiled in Table 8.

SNR (dB)	DL BLER (%)			DL NACK (%)		
	CQI-a	Robust 1	Robust 2	CQI-a	Robust 1	Robust 2
20	1,62	1,74	1,7	1,48	1,55	1,53
10	1,62	1,07	1,6	1,47	0,91	1,43
7	1,04	1,28	1,13	0,88	1,14	0,98
5	2,39	1,59	1,65	2,12	1,43	1,49

Table 8: Test Campaign 2 – FDD_4_2 vs FDD_5_2 L2 statistics

BLER and L2 NACK performance for medium and high SNR values seem to be very similar among the three strategies. Only for low SNR values (5 dB) there seems to be a reduction, around 1%, in BLER and NACK when the technique “more robust MCS for retransmissions” is used.

Test results obtained in this campaign are not sufficient to ensure that the technique “more robust MCS for retransmissions” provides latency gains for scenarios with IP video surveillance camera traffic. Reasons why results are not as expected (see simulation results in section 7.2 of D4.3) may fall on two facts:

1. Multi-user diversity gain is not exploited in test bed 2
2. Retransmissions are not frequent during tests

1. The first reason is related to the fact that the AT4LP supports one UE at a time only while simulations carried out in D4.3 were provided for multiple users, where the benefits of a multiple-user scheduler such like this are better exploited. It is difficult to emulate a scenario similar to that of D4.3 simulations with test bed 2 and therefore results between simulations and tests in test bed 2 are not necessarily comparable.

2. The second reason becomes evident from results in Table Y3. Even at the lowest SNR value evaluated (5 dB) BLER is slightly above 2% for the baseline case and 1% when retransmissions are treated with a more robust MCS. With such low retransmission percentage values it is difficult to observe latency gains as the technique is focused on reducing the probability of successive retransmissions after the first one.

4.2.2.4. Test Campaign 3: TDD_1 vs TDD_2

This test campaign is intended to evaluate the performance improvement achieved with the technique “more robust MCS for retransmissions” for TDD. The baseline technique that has been used for comparisons is the Enhanced CQI-adaptive scheduler version TDD_1 (see section 4.2.1 for further details).
In this case, the CQI reduction value applied to retransmissions has been 1 in all cases, which is the one that seems to achieve better performance based on Test Campaign 2 results.
Test Setup #1 with WP3 traffic generation tool is used for all tests in this test campaign, test conditions are slightly different from those used in Test Campaign 2 (and compiled in Table 5). The UE used is a TDD reference platform hereinafter referred to as UE #5 (name kept confidential).

Cell parameters	
Duplex mode	TDD
Band	41
TDD UL-DL configuration	1, 2, 5 and 6
Bandwidth	10 MHz
Cyclic Prefix	Normal
SNR	0 dB – 5 dB
Cell power EPRE	-102,8 dBm/15kHz
Transmission mode	TM1 (SISO)
CQI reporting mode	Aperiodic 3-0
CSI request	Every 2 and 1 subframes
Nº symbols PDCCH	2
Max nº HARQ retx DL	3
Channel conditions	AWGN

Table 9: Cell parameters in Test Campaign 3 – TDD_1 vs TDD_2

Performance has been evaluated for different SNR values. Focus was put on low SNR values to increase the probability of retransmissions so that the technique “more robust MCS for retransmissions” can have its influence. TDD UL-DL configuration 1 was chosen for the first set of tests.

The traffic source used for this test campaign is an IP video surveillance camera. Packets are generated at a fixed rate every 40 ms and packet size follows the distribution shown in the Figure 30.

Results for UDP metrics such as OWD, IPDV (jitter), packet loss and throughput have been compiled in Table 10. Results in columns denoted by “CQI-a” correspond to the CQI-adaptive technique and results in columns denoted by “Robust” correspond to the “more robust MCS for retransmissions”. Figure 36 shows an OWD comparative between the two techniques.

SNR (dB)	OWD (ms)		IPDV (ms)		PER (%)	
	CQI-a	Robust 1	CQI-a	Robust 1	CQI-a	Robust 1
5	35,268	35,014	9,579	9,563	0,498	0,462
4	66,768	69,839	10,736	11,056	1,725	1,786
3	94,641	102,577	11,700	11,854	7,467	8,139

Table 10: Test Campaign 3 – TDD UL-DL 1 UDP statistics

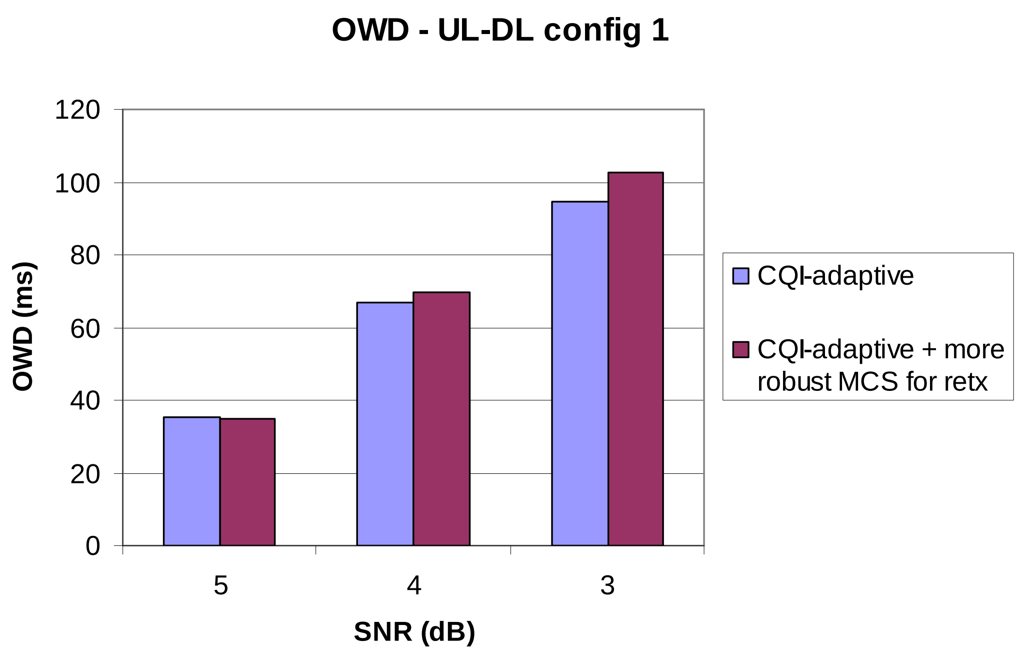

Figure 36: Test Campaign 3 – TDD_1 vs TDD_2 OWD results

Additional tests were carried out for UL-DL configurations 2, 5 and 6. Test results are presented below.

UL-DL config	OWD (ms)		IPDV (ms)		PER (%)	
	CQI-a	Robust 1	CQI-a	Robust 1	CQI-a	Robust 1
2	14,431	15,623	6,888	7,334	0,353	0,566
5	15,953	12,651	8,659	5,626	0,196	0,161
6	221,927	216,069	13,421	13,075	0,671	0,772

Table 11: Test Campaign 3 – TDD UL-DL 2, 5, 6 UDP statistics

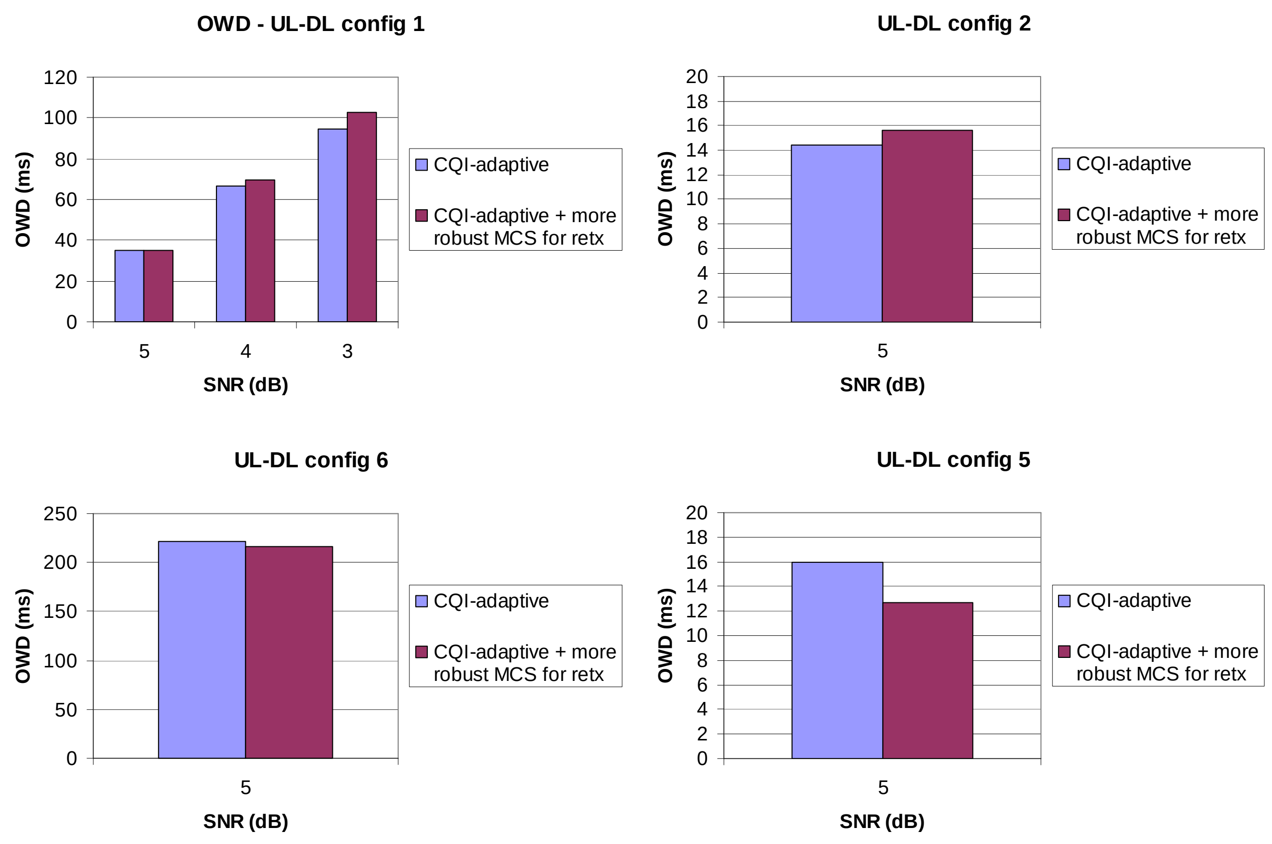

Figure 37: Test Campaign 3 – TDD_1 vs TDD_2 OWD results

Similarly as in Test Campaign 2, results presented above do not show a clear benefit in the use of the “more robust MCS for retransmissions” technique in terms of OWD. The reasons are again the same; on one hand test bed 2 has a limitation of operation with one single UE at a time, which basically removes the scheduler gain due to multi-user diversity. On the other hand, the number of retransmissions is again too low to observe significant latency gains.

5. ACRONYMS

Acronym	Defined as
3GPP	3rd Generation Partnership Project
AT4LP	AT4 wireless LOLA Platform
BLER	Block Error Rate
BSR	Buffer Status Report
CQI	Channel Quality Indicator
DL	Downlink
EARFCN	E-UTRA Absolute Radio Frequency Channel Number
eNB	Evolved Node B
EPRE	Energy Per Resource Element
E-UTRAN	Evolved-Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
IAT	Inter-Arrival Time
IOT	Interoperability
IP	Internet Protocol
IPDV	IP Delay Variation
KPI	Key Performance Indicator
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MTU	Maximum Transfer Unit
NACK	Negative Acknowledgement
OAI	Open Air Interface
OWD	One-Way Delay
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDF	Probability Density Function
PER	Packet Error Rate
PHY	Physical (layer)
PRB	Physical Resource Block
PS	Packet Size
PSA	Power Spectrum Analyzer
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RAP	Random Access Procedure
RAR	Random Access Response
RLC	Radio Link Control

RF	Radiofrequency
RRC	Radio Resource Control
SDK	Software Development Kit
SIB	System Information Block
SISO	Single-Input Single-Output
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
TB	Transport Block

6. REFERENCES

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[4] LOLA Project (Achieving Low-Latency in Wireless Communications), “D4.3 Adaptive Modulation and Coding Scheme and Hybrid ARQ Mechanism v3.0”. January, 2013.

[5] 3GPP TS 36.213 V11.2.0 (2013-03), “3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 11)”.

[6] 3GPP TS 36.211 V11.2.0 (2013-03), “3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (Release 11)”.