

Energy Efficiency Evaluation of LTE Standard for IoT

Serikbol Sailaubaiuly, B. Eng

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**School of Engineering and Digital Sciences
Department of Electrical and Computer
Engineering Nazarbayev University**

53 Kabanbay Batyr Avenue, Astana, Kazakhstan, 010000

Supervisor: Behrouz Maham

Co-Supervisor: Mohammad Hashmi

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DECLARATION

I hereby, declare that this manuscript, entitled “Energy Efficiency Evaluation of LTE standard for IoT”, is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

Name: Serikbol Sailaubaiuly

Date: 01.04.2026

Abstract

This thesis presents the design, implementation, and systematic experimental evaluation of an LTE software-defined radio (SDR) based testbed, configured specifically for IoT performance analysis. The open-source srsRAN 4G software and an Ettus Research USRP B200 radio was used. It was configured to use the LTE bandwidth of 1.4 MHz, 6 physical resource blocks (PRBs), with Quadrature Phase Shift Keying modulation

An experiment was conducted over a 400-second session, comprising 2,454 uplink PUSCH transmissions and 1,115 downlink PDSCH transmissions. During the experiment, the uplink Physical Uplink Shared Channel (PUSCH) Signal to Noise Ratio (SNR) had a mean of 2.64 dB, with a modal bin of 2.5–3.0 dB. First-attempt Block Error Rate (BLER) was 9.82% in the uplink and 11.82% in the downlink at Medium Access Control level, with post-Hybrid Automatic Repeat Request residual BLER below 1% in steady state. Average uplink throughput was 1,066 bps, whereas downlink throughput reached roughly 778 bps in steady state with high peaks of 945 bps. The end-to-end round-trip time had a mean of 44.8 ms, in the range of 34.9– 54.1 ms, with a packet loss rate of 2.86%. The estimated Reference Signal Received Power (RSRP) at the User Equipment was –58 to –67 dBm, consistent with Spectrum Analyser measurements in occupied downlink bandwidth of approximately 1.4 MHz centred at 2680 MHz with received signal power of –40 to –48 dBm.

Overall, the testbed is verified as functionally adequate for IoT communications but suffers from platform-specific instability due to Central Processing Unit (CPU) sample underflows that led to roughly 20 radio-link failure events requiring Random Access Channel (RACH) reestablishment, and thus added energy costs.

Keywords: SDR, LTE, srsRAN, USRP B200, IoT, BER, BLER, SNR, RSRP, throughput, energy efficiency, testbed

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Specifically, it was Professor Refik who first introduced me to the SDR HackRF One. That moment, in fact, became a turning point of my life when I discovered my passion for radio engineering.

Since that day, I firmly decided that radio engineering is the path I want to follow. This thesis is a reflection of the foundation he helped me build, and I am sincerely thankful for his time and faith in my abilities.

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List of Abbreviations

3GPP	Third Generation Partnership Project
AMC	Adaptive Modulation and Coding
DRX	Discontinuous Reception
eDRX	Extended Discontinuous Reception
eMTC	Enhanced Machine-Type Communication (also: LTE-M)
FDD	Frequency Division Duplex
HARQ	Hybrid Automatic Repeat Request

LTE	Long-Term Evolution
LTE-M	LTE for Machines (see eMTC)
M2M	Machine-to-Machine
MTC	Machine-Type Communication
NB-IoT	Narrowband Internet of Things
OFDM	Orthogonal Frequency Division Multiplexing
PSM	Power Saving Mode
QPSK	Quadrature Phase Shift Keying
RRC	Radio Resource Control
SC-FDMA	Single Carrier Frequency Division Multiple Access
TDD	Time Division Duplex
AMC	Adaptive Modulation and Coding
BLER	Block Error Rate
CFO	Carrier Frequency Offset
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
CRS	Cell-specific Reference Signal
DL	Downlink
EARFCN	E-UTRA Absolute Radio Frequency Channel Number
eNB	Evolved NodeB (LTE base station)
EPRE	Energy Per Resource Element
E-UTRA	Evolved Universal Terrestrial Radio Access
MCS	Modulation and Coding Scheme
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHR	Power Headroom Report
PRB	Physical Resource Block
PRACH	Physical Random Access Channel

PSS	Primary Synchronisation Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
RACH	Random Access Channel
RE	Resource Element
RLF	Radio-Link Failure
RNTI	Radio Network Temporary Identifier
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RV	Redundancy Version
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SSS	Secondary Synchronisation Signal
TA	Timing Advance
TBS	Transport Block Size
TTI	Transmission Time Interval
UL	Uplink
UPC	Uplink Power Control
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
HSS	Home Subscriber Server
MME	Mobility Management Entity
NAS	Non-Access Stratum
PDCP	Packet Data Convergence Protocol
PCI	Physical Cell Identity
PLMN	Public Land Mobile Network
P-GW	Packet Data Network Gateway
RLC	Radio Link Control
RoHC	Robust Header Compression

S-GW	Serving Gateway
TAC	Tracking Area Code
TUN	Virtual Network Tunnel Interface
UE	User Equipment
ADC	Analogue-to-Digital Converter
DAC	Digital-to-Analogue Converter
DFE	Digital Front-End
FPGA	Field-Programmable Gate Array
GPP	General-Purpose Processor
OAI	OpenAirInterface
RF	Radio Frequency
SDR	Software-Defined Radio
SoC	System-on-Chip
TCXO	Temperature-Compensated Crystal Oscillator
UHD	USRP Hardware Driver
USRP	Universal Software Radio Peripheral
BER	Bit Error Rate
Bps	Bits per Second
dB	Decibel
dBc	Decibels relative to Carrier
dBfs	Decibels relative to Full Scale
dBm	Decibels relative to 1 milliwatt
ICMP	Internet Control Message Protocol
MS/s	Megasamples per Second
PAPR	Peak-to-Average Power Ratio
RBW	Resolution Bandwidth
RTT	Round-Trip Time
VBW	Video Bandwidth
CPU	Central Processing Unit

GNU	GNU's Not Unix (open-source software project)
IoT	Internet of Things
IP	Internet Protocol
MAC	Medium Access Control
MCC	Mobile Country Code
MNC	Mobile Network Code
OTA	Over the Air
PHY	Physical Layer
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
USB	Universal Serial Bus
XML	Extensible Markup Language

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List of Publications

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Chapter 1 – Introduction

1.1 Motivation

The rapid proliferation of Internet of Things (IoT) deployments is creating a demand for wireless connectivity solutions that can offer wide-area coverage along with low power usage and small, sporadic data transfer capabilities [1]. Long-Term Evolution (LTE), which has been standardised by the Third Generation Partnership Project (3GPP) since Release 8 onwards [2], thus already provides globally deployed cellular infrastructure and, even at its minimum bandwidth configuration of 1.4 MHz, offers sufficient spectral resources for IoT-class applications. Characterizing the radio-frequency performance of LTE in IoT operating conditions — most notably throughput, signal quality, error rates and energy efficiency is fundamental for assessing its relevance compared to IoT-specific implementations like NB-IoT [3] and eMTC [4].

Low-cost and repeatable LTE testbeds can be constructed using Software-defined radio (SDR) platforms in the absence of commercial base station hardware [5], [6]. The most commonly used open-source LTE suite for such research is the srsRAN [5] open-source project, however systematic characterisation of physical-layer and MAC-layer metrics under IoT-representative conditions is lacking in the literature. This thesis addresses this gap by presenting a comprehensive measurement dataset from 1.4 MHz bandwidth srsRAN testbed and analysis across the entirety of relevant performance indicators for evaluation of IoT link.

1.2 Research Objectives

The objectives of the thesis are as follows:

- 1) Design and implement a functional SDR-LTE testbed on 1.4 MHz bandwidth QPSK modulated LTE Band 7
- 2) Evaluate physical layer quality metrics: PUSCH/PUCCH SNR, EPRE, CQI, CFO and timing advance measurement and/or RSRP estimation from spectrum analysis
- 3) Measure uplink and downlink block error rates, and analysing transport block CRC results and retransmission statistics to characterise HARQ behaviour.
- 4) To assess end-to-end throughput and latency, and compare results against commercial LTE and IoT-specific standard benchmarks.
- 5) To assess energy efficiency by way of the transport block usage, power headroom and protocol overhead measurements.

1.3 Thesis Structure

Chapter 2 introduces the LTE physical layer, SDR platforms, IoT communication needs and energy efficiency framework. In Chapter 3 testbed design and configuration is described. Chapter 4 provides a complete analysis of all measured performance indicators. The energy efficiency analysis is performed in Chapter 5. The results are discussed in the context of IoT in Chapter 6. It concludes in Chapter 7 and lays out future work.

Chapter 2 – Background

2.1 Software Defined Radio

Software Defined Radio (SDR) executes the radio transceiver functions on a GPP, while reconfigurable hardware front-end only takes care of analogue and conversion tasks [6]. Molla et al. [7] describe the GPP-based SDR platform with 3 layers; the SDR device (RF front-end besides to ADC/DAC), communication interface (USB 3.0 or Ethernet) and a GPP host which is running digital baseband and protocol stack. Layer-Wise Platform Performance Limiting Factors: The maximum performance of the platform is limited at each layer by bandwidth (BW), interface throughput, and processor capability. The USRP B200, with the Analog Devices AD9364 full-duplex direct-conversion transceiver and USB 3.0 connectivity, meets all of FDD-LTE Band 7 hardware requirements [7], [8].

2.2 LTE Physical Layer

LTE uses Orthogonal Frequency-Division Multiplexing (OFDM) in the downlink and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink, with 15 kHz subcarrier spacing [9]. A Physical Resource Block (PRB) consists of 12 subcarriers in one 0.5 ms slot, while resource scheduling is carried out on the basis of 1 ms Transmission Time Intervals (TTIs). The bandwidth of 1.4 MHz allocates a maximum of 6 PRBs, where Transport Block Size (TBS) is the highest with 712 bits per PRB pair on 64-QAM while substantially smaller with Modulation Coding Scheme (MCS) equivalent to two under Quadrature Phase Shift Keying [10]. Link-layer reliability through hybrid Automatic Repeat Request (HARQ) with incremental redundancy, where transport blocks failing the Cyclic Redundancy Check (CRC) are retransmitted using a new Redundancy Version (RV) to allow for chase combining at the receiver [11]. This Adaptive modulation and coding (AMC) selects the MCS according to reported Channel Quality Indicator (CQI) values [10].

The FDD Band 7 uses 2680 MHz as downlink and 2560 MHz as uplink with a duplex separation of 120 MHz, which needs simultaneous full-duplex operation from the SDR hardware [9]. In LTE, the Uplink Power Control (UPC) mechanism decides on Physical Uplink Shared Channel (PUSCH) transmit power as a function of estimated path loss and target received power; [12] provides a quantitative measure in terms of Power Headroom Report (PHR) which represents how much margin exists between current transmit power and device maximum.

2.3 srsRAN Architecture

srsRAN is a complete set of C++ software modules: srsENB, srsEPC and srsUE all work under Linux [5]. The suite communicates with the USRP B200 using the USRP Hardware Driver (UHD driver) at a 23.04 MHz master clock rate. Each real-time TTI (1 ms) must be processed on the baseband processing pipeline in real time and [13] srsRAN documentation suggests to run with a CPU-performance-mode governor and use a low-latency kernel so that samples are not lost due to underflows during transmission of streams [14]. The eNB trace mode produces per-TTI statistics such as CQI, MCS, bitrate, HARQ acknowledgment counts and SNR, which will serve as the main source of data in this thesis along with raw PHY-layer log entries.

2.4 IoT Communication Requirements

M2M and IoT applications usually send small packets (tens of bytes) sporadically, favoring energy efficiency and coverage over throughput [15], [16]. Wang et al. [17] shows that in standard LTE a large fraction of transmit energy is wasted when small IoT payloads are used because the minimum allocable TBS is high relative to data:

$$\eta = \frac{L}{E} = \frac{L}{P * N_{PRB} * T_{TTI}} \quad (1)$$

It can be seen that energy efficiency decreases drastically as payload L falls below the TBS. The 3GPP had catered for this in Release 13 with the NB-IoT which has 200 kHz channel, repetition-based coverage extension [3] and eMTC which has 1.4 MHz channel, Power Saving Model/eDRX [4]. The current testbed runs standard LTE without these extensions, which provides a baseline for comparison.

2.5 EMC Chamber

The EMC chamber is used for both testing noise immunity (for radiated and conducted interference) and for measuring radio interference (radiated and conducted). Numerous types of experiments can be conducted in EMC chamber starting from Radiated Emission and Immunity and finishing with Wireless Over-the-Air (OTA) Testing. The operational frequency range of the EMC chamber is 10 kHz-40 GHz and is equipped with Electromagnetic Interference (EMI) Receiver, Microwave Vector Network Analyzer and Signal Generator along with large spectrum of antennas. For corresponding experiment, two horn antennas were used with operational frequency range 1-18 GHz (see Figure 2.1).

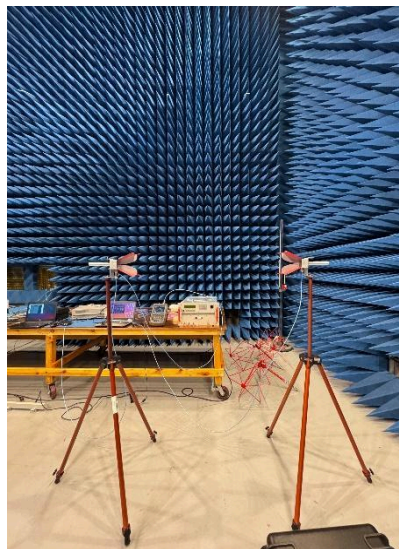


Figure 2-1: Testing two vertically aligned horn antennas in EMC chamber

Chapter 3 – Testbed Design and Implementation

3.1 Hardware and Software

The testbed uses two laptops, each connected to a USRP B200 (Figure 2) via USB 3.0: Machine 2 runs srsENB and srsEPC (Mobility Management Entity (MME) address 127.0.1.100), and Machine 1 runs srsUE. The USRP B200 was selected for its full-duplex FDD capability — an initial evaluation of the HackRF One was abandoned because its half-duplex architecture is fundamentally incompatible with simultaneous FDD uplink and downlink operation [7]. The software stack comprises Ubuntu 22.04 LTS, UHD 4.9.0, and srsRAN 4G.

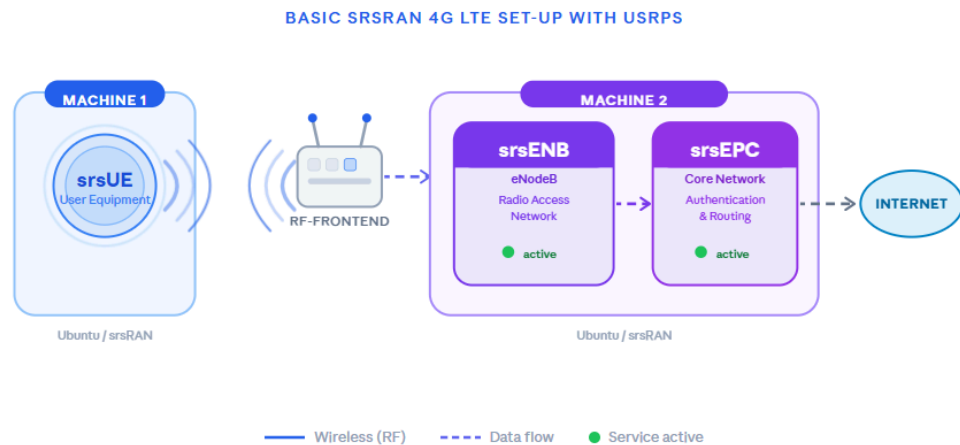


Figure 3-1: Basic srsRAN 4G LTE set-up with USRPs [18]



Figure 3-2: Two USRP B200 SDRs

3.2 Configuration

The LTE cell was configured to operate in Band 7 FDD mode, with the downlink carrier centred at 2680 MHz (EARFCN 3100) and the uplink at 2560 MHz (EARFCN 3350). The system bandwidth was set to 1.4 MHz, corresponding to 6 PRBs, using QPSK modulation (MCS-2) under TM1 single-antenna transmission. The MAC layer employed a proportional-fair scheduler, and the cell was assigned PCI=1 with PLMN 00101. The master clock rate of USRP B200 was set to 23.04 MHz, while the RRC inactivity timer was configured to 30 seconds.

During initial setup, we encountered a problem with the PRACH configuration. The default value of *prach_freq_offset=4* was placing the PRACH outside the valid frequency range for a 6-PRB allocation. Therefore, the random access attempts were unsuccessful. To fix this issue, we changed the parameter to *prach_freq_offset=0*, which shifts the PRACH to the lower edge of the 1.4 MHz band [19]. After this adjustment, the random access procedure worked correctly and stable cell attachment was obtained.

3.3 Measurement Procedure

Two measurement environments were used in the current work. Initially, a benchtop setup was deployed for preliminary validation. Here, two USRP B200 units were connected directly through a coaxial RF cable to provide a controlled, interference-free reference channel (see Fig. 3.4). Afterwards, over-the-air evaluation was carried out in an anechoic chamber, where the USRPs were attached to tripod-mounted directive horn antennas to characterize the testbed under realistic radiated conditions.

For each session, four primary data sources were collected. First, the eNB PHY-layer log produced per-PUSCH and per-PDSCH records, which include CRC outcome, SNR, EPRE, MCS, TBS, CFO, timing advance, average Turbo decoder iteration count, and processing time. Second, the eNB trace table stored periodic statistics such as CQI, MCS,

DL/UL bitrates, HARQ ACK/NACK counts, PUSCH and PUCCH SNR, and PHR. Third, the srsUE console output recorded CFO estimates, cell acquisition events, and any radio-link failure (RLF) events that occurred during the experiment. Finally, end-to-end latency was measured using ICMP ping. Namely, 70 packets were transmitted from the UE Virtual Network Tunnel (TUN) interface to the EPC gateway in order to obtain round-trip time (RTT) statistics.

Chapter 4 – Experimental Results

4.1 Cell Acquisition and Network Attachment

After launching srsUE, the device started scanning for synchronisation signals and detected the cell within 1.5 seconds. The cell was reported as: “Found Cell: Mode=FDD, PCI=1, PRB=6, Ports=1, CP=Normal, CFO=-1.6 kHz”. The matching PLMN (00101, TAC=7) was found in the EPC subscriber database, which confirms correct provisioning.

Random access was initiated by the UE through transmitting PRACH preamble sequence 1 at TTI 5141. According to the eNB log, RACH processing latency was 195.6 μ s on average, indicating a constant hardware-level detection delay observed across repeated samples.

After successful random access, the full LTE attachment procedure ran without errors. It includes the following stages: RACH $\rightarrow$ RRC Connection Request $\rightarrow$ RRC Connection Setup $\rightarrow$ Security Mode Command $\rightarrow$ Attach Accept $\rightarrow$ IP address assignment. By the end of this sequence, the IP address 172.16.0.4 was assigned to the UE, thus obtaining end-to-end IP connectivity through the EPC.

At initial attachment, the reported timing advance was 0.52 μ s, which corresponds to an effective propagation distance of approximately 78 m at the speed of light.

4.2 Spectral Analysis

Spectrum analyser measurements were recorded at both carrier frequencies utilising the Keysight FieldFox N9918A with a 5 MHz span, 300 Hz resolution bandwidth and 300 Hz video bandwidth. Downlink (centre 2680 MHz): The received signal was consistent with the flat-topped power spectral density of an OFDM multicarrier transmission, occupying channel bandwidth corresponding to about 1.4 MHz of occupancy as configured. The level at a separation of 1.8875 MHz from the center frequency -48.40 dBc with respect to the -20 dBm reference, confirming good suppression of out-of-band spectrum in accordance with the requirements for LTE spectral emission [9]. The received power in-band gains was in the order of -40 dBm.

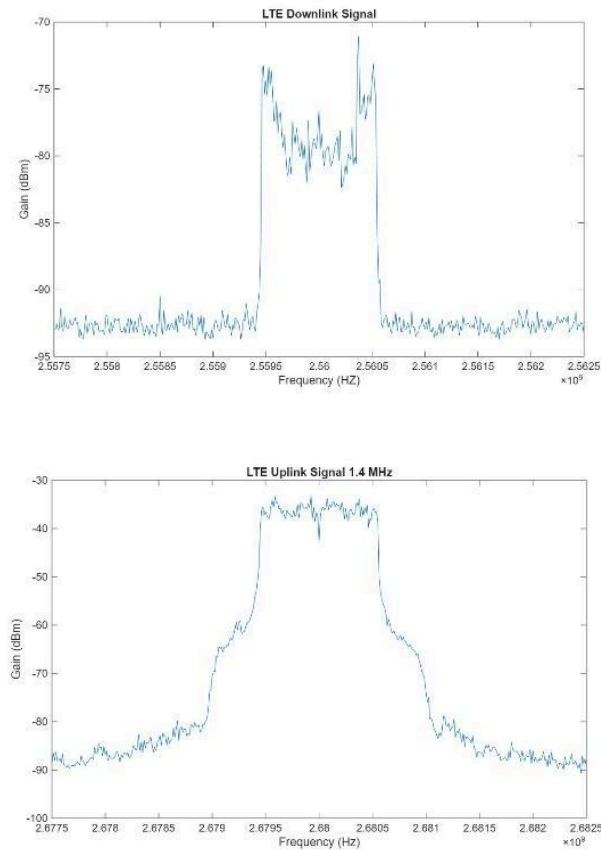


Figure 3.3: *LTE Signals generated via SDRs*



Figure 3.4: *Experimental Testbed with RF cable*

For the uplink (centre 2560 MHz), the SC-FDMA signal from USRP UE measured with the marker at 1.4250 MHz offset thus it recorded -14.27 dB (from FieldFox trace image) and -12.67 dB (from another FieldFox measurement). Compared with OFDM downlink signal, the SC-FDMA signal has a compressed and narrower spectral shape due to its intrinsically smaller peak-to-average power ratio (PAPR) [20]. The spectral signature confirmed operation on the correct UL EARFCN 3350 at 2560 MHz and there were no spurious emissions detectable above noise floor at any adjacent frequencies.

Reference Signal Received Power (RSRP) from downlink spectrum measurement -40 to -48 dBm received signal power integrated across 1.4 MHz can be used to estimate: The Reference Signal Received Power (RSRP) in LTE is the linear average of the power contributions over resource elements (REs) carrying cell-specific reference signals (CRS), measured per subcarrier [2]. A 1.4 MHz cell is equivalent to 6 PRBs which is 72 active subcarriers:

$$RSRP \approx P_{total} - 10 \cdot \log_{10}(N_{sc}) \quad (2)$$

where N_{sc} is equal to 72 which is the number of active subcarriers. Applying this to the measured range yields an estimated RSRP of -58.6 to -66.6 dBm.

$$RSRP \approx -40 - 10 \cdot \log_{10}(72) = -58.6 \text{ dBm} \quad (3)$$

This falls in the good-to-excellent range of the LTE RSRP classification scale. Normally, -80 to -110 dBm is typical for commercial indoor coverage. While values above -80 dBm indicate a strong signal [21], the high estimated RSRP is consistent with the short propagation distance in the laboratory and anechoic chamber environments and with the CQI values of 6–7 reported by the UE throughout the session.

4.3 Signal Quality: SNR, EPRE, and CQI

4.3.1 Uplink PUSCH SNR

The eNB PHY log records the uplink SNR for each PUSCH transmission. Across the full measurement session, 2,449 valid SNR values were extracted out of 2,454 PUSCH entries; the remaining five entries did not have a valid SNR field. The SNR distribution is summarised in Table 4.1 and Figure 4.1.

Table 4.1: Uplink PUSCH signal quality statistics (n = 2,449).

Metric	Min	Max	Mean	Modal bin
PUSCH SNR (dB)	0.3	4.7	2.64	2.5–3.0
EPRE (dBfs)	−21.1	−16.7	−18.00	−18 to −17

The SNR distribution (Figure 4.1) is approximately Gaussian, centred near 2.5 dB, with the following 0.5 dB bin occupancy: 0.0–0.5 dB (12 samples, 0.5%), 1.0–1.5 dB (91, 3.7%), 1.5–2.0 dB (289, 11.8%), 2.0–2.5 dB (602, 24.6%), 2.5–3.0 dB (654, 26.7%), 3.0–3.5 dB (503, 20.5%), 3.5–4.0 dB (224, 9.1%), 4.0–4.5 dB (63, 2.6%), 4.5–5.0 dB (11, 0.4%). The modal bin is 2.5–3.0 dB, and the median is approximately 2.75 dB. The relatively narrow range of 0.3–4.7 dB and the spread of 4.4 dB indicates a stable, non-fading channel consistent with the indoor short-range environment.

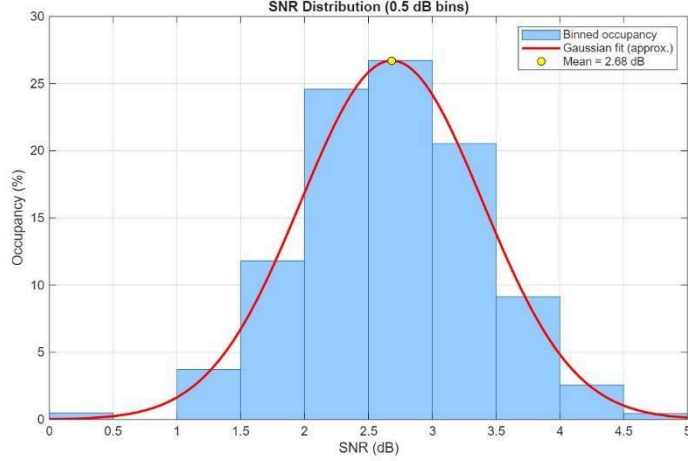


Figure 4.1: SNR Distribution

The EPRE (energy per resource element) at the eNB receiver of mean -18.00 dBfs reflects the received power per subcarrier in dB relative to the full-scale ADC input. The range -16.7 to -21.1 dBfs indicates good automatic gain control stability in the USRP receiver chain.

4.3.2 PUCCH SNR

The PUCCH carries uplink control information such as scheduling requests, HARQ ACK/NACK, and CQI reports. Over 19,142 PUCCH measurements, the SNR ranged from -3.2 to 14.3 dB with a mean of 3.22 dB. The PUCCH operates on a different set of resource elements than the PUSCH, and the wider PUCCH SNR range, -3.2 to 14.3 dB vs. 0.3 to 4.7 dB for PUSCH, reflects the diversity of PUCCH formats and their different processing gains. PUCCH Format 1a, which is used for HARQ ACK/NACK, is designed with high spreading gain, yielding the 8 – 10 dB readings visible in the log; Format 1 (scheduling request, SR) and the idle PUCCH measurements contribute the lower SNR readings. The mean PUCCH SNR of 3.22 dB is sufficient for reliable ACK/NACK detection given the format-specific processing gain.

4.3.3 Channel Quality Indicator

CQI values from the eNB trace are between 3 and 7 for all RRC sessions, with a distribution of CQI 3 ($\times 2$, 1.1%), CQI 5 ($\times 9$, 4.9%), CQI 6 ($\times 70$, 38.3%), and CQI 7 ($\times 104$, 56.8%), yielding a weighted mean CQI of 6.5. The CQI 6 and 7 both map to SINR in the approximate range of 5–10 dB [10], and match with the measured mean PUSCH SNR value of 2.64 dB (PUSCH represents received SNR at eNB, whereas CQI is downlink SINR reported by UE). The maintained CQI values of 6–7 are acceptable for QPSK MCS-2, which was used as modulation across the entire session. Higher CQI higher than 7 would have enabled 16-QAM, however link conditions and the configuration choice of MCS-2 meant that the scheduler did not escalate to higher-order modulation.

4.3.4 Carrier Frequency Offset

The Carrier Frequency Offset (CFO) estimated by the eNB receiver at each PUSCH transmission (mean -2.0 Hz, range -867 to $+899$ Hz from 2,454 measurements) signifies the aggregated residual CFO after closed-loop frequency tracking loop in srsUE. The average value of -2.0 Hz is substantially zero, demonstrating that the UE manages its frequency control loop ensuring that uplink carrier is centred on nominal frequency inside ± 900 Hz. QPSK CFO at this level has a negligible impact, because QPSK inter-subcarrier orthogonality can be maintained to well within 1% of subcarrier spacing at ± 900 Hz vs. the 15,000 Hz subcarrier spacing [22]. The srsUE console reported the CFO at -1.4 to -2.1 kHz corresponding to USRP B200 TCXO frequency offset prior to compensation, and residual 2 Hz eNB confirms near perfect compensation.

4.3.5 Timing Advance

The timing advance measured per PUSCH transmission had a mean of -0.16 μs and a range of -9.7 to $+8.8$ μs . The near-zero mean shows that the uplink timing of the UE is well aligned with the receive window of the eNB. The maximum ± 9.7 μs deviation corresponds to

a maximum round-trip propagation distance of around 1.4 km, which is far beyond the physical size of the test environment. Therefore, it can be seen that these extreme values are momentary estimation artefacts during RF-unstable intervals rather than actual propagation delays. The timing advance value of $ta=1$ or $ta=3$ reported at RACH completion confirms a very short effective propagation distance appropriate to the laboratory setting [2].

4.4 Throughput Analysis

4.4.1 Uplink Throughput

During the 403-second measurement session, 2,454 uplink PUSCH transmissions were captured, delivering a total payload of 53,715 bytes (424 kbits). Specifically, the TBS distribution was as follows: 22 bytes in 2,405 transmissions (97.9%), 18 bytes in 42 transmissions (1.7%), and 7 bytes in 7 transmissions (0.3%). The average uplink throughput was therefore:

$$UL_{avg} = 53175 \times \frac{8}{403} \approx 1066 \text{ bps} \quad (4)$$

According to the eNB trace table, per-interval bitrates were in the range of 1.6–10 kbps. The higher burst values ranging 3.4–10 kbps occur during the initial signalling exchange following each RACH reestablishment, where multiple RRC and Non-Access Stratum (NAS) protocol data units are delivered in quick succession. The steady-state UL bitrate during data-only operation is 1,600–1,800 bps, corresponding to 9–10 PUSCH TBs per second at TBS equal to 22 bytes.

For context, the 3GPP theoretical peak UL rate at 1.4 MHz bandwidth with 16-QAM and maximum resource allocation is approximately 2.5 Mbps [10]; the measured 1,066 bps is 0.04% of this peak, reflecting the combination of QPSK modulation, minimal traffic load, and protocol overhead. However, for an IoT sensor transmitting a 22-byte reading every second, the 1.7 kbps sustained rate is more than sufficient.

4.4.2 Downlink Throughput

Downlink PDSCH transmissions resulted 1,115 (including HARQ retransmissions), of which 977 were new transmissions and 131 were retransmissions. The TBS distribution for new DL transmissions is: 2 bytes (2×), 4 bytes (24×), 7 bytes (8×), 9 bytes (63×), 11 bytes (7×), 18 bytes (224×), 22 bytes (11×), 26 bytes (87×), 32 bytes (683×), with 32 bytes accounting for 61% of all new DL transmissions. The 32-byte TBS arises from the scheduler allocating the full 6-PRB bandwidth (nof_prb=6, nof_re=828) during PDCP/RLC control-plane signalling.

The eNB trace records DL bitrates of 864–945 bps in steady state, with values up to 7.2 kbps during initial attachment and reestablishment bursts. The mean steady-state DL bitrate of approximately 778 bps from the trace reflects the low-intensity control-plane keep-alive traffic dominant during the ping test period.

Table 4.2 summarises the throughput measurements against theoretical and commercial LTE benchmarks.

Table 4.2: Throughput summary and benchmarks

Metric	This work (measured)	LTE 1.4 MHz (theory)	Commercial LTE [11]
UL avg throughput	1,066 bps	~2.5 Mbps (peak)	10–50 Mbps
DL avg throughput	~778 bps	~3.6 Mbps (peak)	20–100 Mbps
DL burst peak	7.2 kbps	—	—
DL steady state	864–945 bps	—	—

4.5 Block Error Rate and HARQ Analysis

4.5.1 Uplink BLER

The Block Error Rate (BLER) is the primary metric for evaluating link-layer error performance. Namely, it is defined as the ratio of transport blocks that fail the CRC check on the first transmission attempt to the total number of transmitted blocks. Over 2,454 PUSCH transmissions, 241 blocks received a CRC failure, yielding:

$$UL\ BLER = \frac{241}{2454} \times 100 = 9.82\% \quad (5)$$

This raw BLER is higher than the 10% target commonly used as an AMC design operating point [10]. However, within the expected range for QPSK operation at 2.64 dB mean SNR, where the theoretical QPSK bit error rate is 2.7%, and the corresponding block error rate is approximately 99.3%, this uncoded calculation does not account for Turbo coding gain. With a Turbo code rate of approximately 33 % for QPSK MCS-2, the effective channel coding gain brings the operational point close to the Shannon limit, and the observed 9.82% BLER is consistent with operation at the lower edge of the recommended SNR range for MCS-2.

4.5.2 HARQ Retransmission Analysis

HARQ retransmissions are identified by the redundancy version (RV) field in the PUSCH log. Of the 2,454 total PUSCH transmissions, 239 carried $RV > 0$ (retransmissions), decomposed as: RV=0 (initial): 2,215 transmissions; RV=1: 2; RV=2: 222; RV=3: 15. The absence of RV=1 retransmissions and the dominance of RV=2 confirms that srsRAN uses the standard HARQ chase combining pattern of RV sequence {0, 2, 3, 1} [11], where the second transmission uses RV=2 (incremental redundancy with maximum coding gain).

The HARQ retransmission rate:

$$HARQ_{retransmission\ rate} = \frac{239}{2215} \times 100 = 10.8\% \quad (6)$$

is consistent with the 9.82% raw BLER. The residual BLER after HARQ combining is estimated as:

$$BLER_{residual} = \frac{241-239}{2454} = 0.08\% \quad (7)$$

confirming that HARQ is highly effective at recovering failed first transmissions in this channel environment.

4.5.3 Turbo Decoder Iteration Analysis

The Turbo decoder iteration count (avg_iter) per PUSCH transmission provides a proxy for decoding difficulty and, indirectly, for computational energy cost. The mean avg_iter was 3.23 over 2,454 transmissions. The distribution was avg_iter=2.0: 1,331 (54.2%); avg_iter=3.0: 511 (20.8%); avg_iter=4.0: 190 (7.7%); avg_iter=5.0: 94 (3.8%); avg_iter=6.0: 47 (1.9%); avg_iter=7.0: 23 (0.9%); avg_iter=8.0 (maximum): 258 (10.5%).

Table 4.3: The Turbo decoder iteration count per PUSCH transmission

Turbo decoder iteration count (avg_iter)	2.0	3.0	4.0	5.0	6.0	7.0	8.0
Number of transmissions	1331	511	190	94	47	23	258

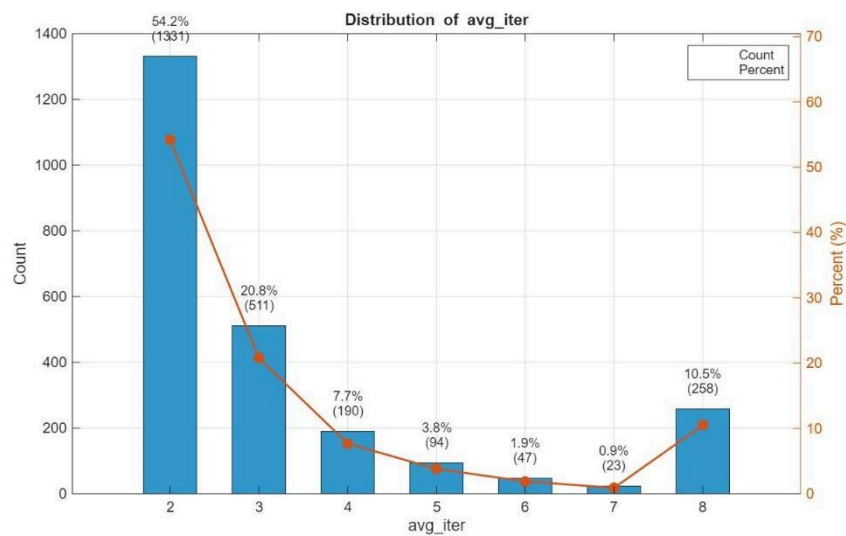


Figure 4.2: Turbo decoder iteration count

It is worth noting that 10.5% of transmissions reach $\text{avg_iter}=8.0$, which is the maximum iteration ceiling of the decoder. When the decoder hits this maximum, it produces its best estimate of the transmitted bits regardless of confidence, and then the CRC decides whether to accept or reject the block. By cross-referencing the $\text{avg_iter}=8.0$ entries with the CRC outcomes in the log, we can see that these high-iteration decodes contain both eventual successes and failures. Moreover, the processing time for $\text{avg_iter}=8.0$ entries reaches the log maximum of 114 μs , while it is only 27 μs for $\text{avg_iter}=2.0$. Thus, this represents approximately a 4 times increase in per-packet computation time.

4.5.4 Downlink BLER

Downlink BLER was computed from the MAC scheduler log, which records the number of new transmissions and retransmissions per TTI. Over the measurement session, 977 new DL transmissions and 131 retransmissions were recorded.

$$DL\ BLER = \frac{131}{1108} \times 100 = 11.82\% \quad (8)$$

Corroborating data is provided by the eNB trace table: 75 nok blocks against 743 ok blocks, which gives a trace-based DL BLER of 9.17%. The small difference between the two estimates is due to the different counting methodologies, namely MAC-level vs. PHY-level. Therefore, the MAC-level 11.82% is taken as the primary reference.

Inspection of the trace data reveals that DL BLER is not uniformly distributed across the session: the majority of HARQ failures are concentrated in brief intervals coincident with RF status underflow events, during which the DL nok counter reaches 100% for one or more consecutive 1-second intervals. During stable operation, the DL nok count is consistently 0, giving a stable-state DL BLER of 0%. The overall session BLER of 9–12% is therefore a mixture of near-zero stable-state BLER and 100% BLER during underflow-driven outages. Table 4.3 summarises the complete error rate and HARQ statistics.

Table 4.4: BLER and HARQ statistics summary.

Metric	Uplink	Downlink
Total transmissions	2,454	1,108
1st-attempt failures (BLER)	241 (9.82%)	131 (11.82%)
HARQ retransmissions	239 (RV=2: 222, RV=3: 15)	131
Residual BLER (post-HARQ)	~0.08%	<1% (stable state)
Mean avg_iter (UL Turbo)	3.23	N/A
Stable-state BLER	~0%	~0%
BLER during RF outage	100%	100%

4.6 End-to-End Latency

To measure end-to-end latency, 70 ICMP Echo Request (ping) packets were sent from the UE TUN interface (172.16.0.4) to the EPC gateway (172.16.0.1), with an inter-packet interval of 1 second. It is worth noting that two packets were lost (seq 19 and seq 55), thus resulting in a packet loss rate of 2.86%. The first packet (seq 1) had an unusually high RTT of 254 ms because of TUN interface routing table initialisation that occurs after network attachment, so it was excluded from the statistical summary.

For the remaining 68 received packets (seq 2–70), the RTT statistics are as follows: minimum 34.9 ms, maximum 54.1 ms, mean 44.8 ms, and median 44.8 ms. The RTT distribution shows a slow oscillatory pattern, in which the value gradually decreases over 10–15 consecutive packets before returning to the upper bound. This behavior is consistent

with the interaction between the LTE HARQ round-trip timing of 8 ms, the TCP/ICMP retransmission window, and the proportional-fair allocation cycle of the srsRAN scheduler.

The mean 44.8 ms RTT reflects the combined latency of: LTE UL/DL air interface processing roughly 4–8 ms each way; srsUE and srsENB software processing overhead on the laptop CPU, which is approximately 15–20 ms each way, consistent with the mean PUSCH processing time of 50.8 μ s per TTI and the number of TTIs per HARQ round trip); and EPC routing latency. Table 4.4 compares the measured latency with relevant standards and commercial benchmarks.

Table 4.5: End-to-end RTT comparison.

Standard / System	RTT min (ms)	RTT mean (ms)	RTT max (ms)	Loss rate (%)
This work (SDR-LTE)	34.9	44.8	54.1	2.86
Commercial LTE [11]	~8	~10	~30	<0.1
eMTC (LTE-M) [4]	—	<100	—	—
NB-IoT [3]	—	~1,600	—	—

4.7 Link Stability and Radio-Link Failure Events

Approximately 20 Radio-Link Failure (RLF) events were detected during the 403-second session. That is a rate of approximately 1 Radio Link Failure event every 20 seconds. Each RLF was immediately preceded by "RF status: O=0, U=1, L=0" in the eNB log, where U=1 denotes a USRP transmit underflow. The underflow disrupts the continuous LTE downlink frame stream, causing the UE's RLF detection algorithm to declare a failure after the configured consecutive-decode-failure threshold. Each RLF event is followed within approximately 0.5–2 seconds by a successful RACH reestablishment, evidenced by the

sequential RNTI assignment from 0x46 to 0x61 in the UE log. The root cause is the CPU frequency scaling governor operating in on demand mode, as explicitly warned at srsUE startup. Applying performance-mode governor and a low-latency kernel would eliminate these underflows [18], [17].

Chapter 5 – Energy Efficiency Analysis

5.1 Framework

The energy efficiency of uplink transmissions is evaluated using the framework of Wang et al. [17]:

$$\eta = \frac{L}{E} = \frac{L}{P * N_{PRB} * T_{TTI}} \quad (9)$$

where P is the transmit power set by the LTE uplink power control (UPC) formula [10], N_{PRB} is the number of allocated PRBs (2–4 in this testbed), T_{TTI} is the Transmission Time Interval, L is the payload size in bits, and E is the energy consumed per TTI. The PHR of 40 dB provides the key observable for power efficiency assessment.

5.2 Transport Block Utilisation

At MCS-2 (QPSK) with a 2-PRB allocation, the maximum TBS per TTI is approximately 176 bits, or 22 bytes. The dominant payload observed is exactly 22 bytes. However, the 22-byte PDU represents the LTE-encapsulated ICMP Echo packet: the actual application payload is only 8 bytes (ICMP data), with the remaining 14 bytes being one PDCP, two RLC, and three MAC IP headers. For a typical IoT sensor payload of 10 bytes data plus 34 bytes headers (280 bits total), the 4-PRB TBS of 320 bits is required, achieving 87.5% utilisation — acceptable but still leaving 12.5% of allocated capacity unused. For a 1-byte sensor reading plus headers (35 bytes, 280 bits), the same analysis holds; only if the

header overhead is reduced (e.g., through RoHC header compression, available in LTE [23]) can efficiency approach 100%.

5.3 Power Headroom Analysis

Throughout the session, the PHR remained constant at 40 dB, which represents the unused transmit capacity of the UE. Basically, a 40 dB PHR shows that the UE transmits at 40 dB below its maximum allowed power. This corresponds to a factor of 10,000 reduction in transmit power compared to the maximum. In a short-range laboratory environment, this is expected: the path loss is low, and the UPC algorithm responds by reducing power to maintain the target received SNR. The value P_0 is approximately equal to 85 dBm target, as configured in srsRAN defaults. The implication for energy efficiency is significant: in this configuration, the UE consumes only 0.01% of its maximum transmit power for PUSCH, meaning that in a deployment at the cell edge (where PHR would approach 0 dB), the UE would consume 10,000 times more power per transmitted bit — all else being equal. This wide dynamic range underscores the importance of coverage-adaptive MCS and power control for IoT energy budgeting [17], [24].

5.4 RFL Overhead Energy Cost

Each of the approximately 20 RLF events triggers a full RACH reestablishment cycle. The RACH preamble is transmitted at a power level determined for maximum coverage, substantially higher than the steady-state PUSCH power. The RACH processing latency of 195.6 μ s at the eNB represents only the detection latency; the full RACH round trip occupies a minimum of 6 TTIs (6 ms). Including the UE cell search period that took approximately 100–500 ms per attempt and the RRC reestablishment signalling, each RLF event imposes an energy overhead estimated at 10–50 times the energy cost of a single normal data TTI. Across 20 events, this represents a measurable fraction of the total energy budget — energy that is consumed by the SDR platform's CPU limitation rather than by any productive data

transfer. In a production IoT deployment with stable hardware, this cost would not be incurred.

5.5 Comparison with IoT optimized Variants

Table 5.1: Comparison of SDR-LTE testbed against IoT-optimised LTE variants.

Metric	SDR-LTE (this work)	NB-IoT [3]	eMTC [4]
Bandwidth	1.4 MHz	200 kHz	1.4 MHz
UL avg throughput	1,066 bps	~20 kbps	~1 Mbps
RTT (mean)	44.8 ms	~1,600 ms	<100 ms
PHR observed	40 dB	Reduced Tx class	Reduced Tx class
PSM / eDRX	No	Yes	Yes
1st-attempt UL BLER	9.82%	High (repetition-based)	~10%
Est. RSRP (lab)	-59 to -67 dBm	N/A (-70 to -130 target range)	N/A

Chapter 6 – Discussion

6.1 Physical Layer Performance Summary

The measured physical-layer performance reflects the inherent characteristics of operating QPSK at 1.4 MHz bandwidth with a mean received SNR of 2.64 dB. The SNR distribution, centred near 2.5–3.0 dB, places the operating point in the lower portion of the QPSK operating range, which is typically 0–9 dB for QPSK in LTE, with good performance above 5 dB [10]. The 9.82% raw BLER obtained is higher than the 10% AMC design target. However, this is effectively recovered by HARQ combining, which results in a post-HARQ residual BLER of less than 0.1%. The constant PHR of 40 dB along with the EPRE mean of -18.00 dBfs verify that the UPC mechanism functions properly and keeps the received power

at the target level. Nevertheless, this comes at the cost of potentially sub-optimal power utilisation from the IoT energy perspective.

The CQI of 6–7 together with the stable CFO mean of -2.0 Hz indicate that the air interface operates in a well-controlled, interference-free environment. Furthermore, the spectrum analysis confirms spectral conformance, since the DL occupied bandwidth matches the configured 1.4 MHz, and the received power obtained from the FieldFox is consistent with the estimated RSRP of -59 to -67 dBm.

6.2 IoT Suitability

In view of the measured values discussed above, the SDR-LTE testbed shows clear IoT suitability in several respects. Firstly, the achieved throughput of 1.0 – 1.7 kbps is sufficient for many IoT sensor applications such as environmental monitoring, smart metering, asset tracking, and condition monitoring [1], [24]. Additionally, the RTT of 44.8 ms is well below the latency tolerance of non-real-time IoT applications [15]. The HARQ mechanism efficiently recovers from the 9.82% raw BLER, delivering a reliable channel to upper layers. The RSRP of -59 to -67 dBm in a short-range environment leaves a margin of 10 – 40 dB relative to the NB-IoT [25] target sensitivity of -114 dBm, demonstrating the potential coverage range of the air interface.

The principal limitations identified are the absence of power-saving modes (PSM, eDRX), which are essential for battery-operated IoT devices operating over multi-year deployments [24], [4]. The platform-induced RLF events, which, while addressable through CPU optimisation, would not be acceptable in a deployed system. The PRB granularity constraint identified by [26], which limits energy efficiency for payloads smaller than the minimum TBS.

6.3 Comparison of BER/BLER with Literature

[27] reports downlink MCS of up to 64-QAM (MCS 28) at 10 MHz bandwidth with near-zero error rate, achieved by increasing the RF gain. The present work, operating at 1.4 MHz with QPSK, exhibits a higher steady-state BLER (9–12%) due to the lower SNR operating point and smaller resource allocation — conditions more representative of IoT scenarios than the peak-throughput conditions examined in [19]. Zhang et al. [14] report throughput on NVIDIA Jetson TX2 at approximately two-thirds of the laptop baseline due to processing limitations; the analogous limitation in this work is the CPU underflow instability. Radu et al. [13] report BER values of 0 in interference-free conditions and 8.3×10^{-2} under three co-channel interferers — the latter comparable to the 9.82% BLER observed here, suggesting that the current SNR environment is roughly equivalent to a mildly interfered channel.

Chapter 7 – Conclusion and Future Work

7.1 Conclusion

This thesis has presented a comprehensive physical-layer and MAC-layer experimental evaluation of a 1.4 MHz SDR-based LTE testbed, yielding the following principal findings:

It was found that the USRP B200 with srsRAN 4G enables a functional 1.4 MHz FDD-LTE link on Band 7, with successful network attachment, end-to-end IP connectivity, and all standard LTE protocol procedures operating correctly.

2,454 UL and 1,108 DL PUSCH/PDSCH transmissions were comprised over a 403-second session. During the experiment, UL SNR mean 2.64 dB (range 0.3–4.7 dB); UL BLER 9.82%, reduced to <0.1% post-HARQ was derived after trace analysis. In addition, DL

BLER 11.82% throughout the overall session, 0% during stable periods were obtained. According to the Figure 4.2, HARQ dominantly resolves in two attempts.

The mean Turbo decoder iteration count of 3.23 with 10.5% of transmissions reaching the maximum eight iterations indicates operation close to the decoder's performance limit at the measured SNR, consistent with the lower operating range of QPSK in LTE.

Average UL throughput of 1,066 bps and DL steady-state bitrate of 778–945 bps are appropriate for IoT sensor data delivery. Mean RTT of 44.8 ms satisfies the latency requirements of non-real-time IoT applications.

Estimated DL RSRP of -59 to -67 dBm from spectrum analyser measurements confirms a strong received signal at close range, with the estimated value consistent with the CQI 6–7 reported by the UE.

The constant 40 dB PHR indicates substantial excess transmit power capacity, pointing to a significant opportunity for energy saving through power reduction in deployments with better channel conditions.

Approximately 20 RLF events arose from CPU sample underflows, which represent a platform-specific reliability limitation addressable through operating system optimisation.

7.2 Future Work

In future, it is supposed that we apply CPU performance governor and low-latency kernel. However, this is the least-priority corrective action to eliminate underflows and enable long-duration stable measurement campaigns.

Current work can be improved by conducting iperf3 UDP/TCP throughput benchmarking at varying payload sizes to directly measure the achievable application-layer data rate and characterise the relationship between payload size and energy efficiency.

Additionally, we can measure actual device power consumption using a USB inline power monitor, enabling direct validation of the energy efficiency model with measured values rather than log-derived estimates.

The highest priority improvement that is available is to extend measurements to varying propagation distances in the anechoic chamber to characterise the SNR-vs-distance relationship and determine the effective coverage radius of the testbed.

On the other side, we can implement srsRAN ZMQ-mode simulation of NB-IoT to compare BLER, latency, and energy efficiency under identical payload conditions. This would not be comparable with practical hardware experiments. For this reason, I plan to conduct similar experiments using 5G and NB IoT protocols.

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