Comprehensive Analysis of Indoor Handover using Real-World Experimentation

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Abstract

When exploring the optimisation of mobile telecommunications, achieving a smooth transition of mobile connections between base stations, known as handover, is critical for maintaining uninterrupted and high-quality mobile service. While 5G is expected to provide ubiquitous indoor coverage in the coming years, a comprehensive analysis of indoor handover using real-world experimentation is not found in the literature.

This dissertation comprehensively examines indoor handover processes within LTE networks, utilising real-world experimental setups to explore the dynamics and challenges inherent to indoor signal transition. Utilising the findings from a series of experiments conducted within an LTE testbed designed to reenact the nuances of indoor environments, we analyse the efficacy of existing indoor handover algorithms and propose the need for more robust approaches.

This research's findings highlight the extent to which environmental factors impact handover efficacy. Substantial fluctuations in signal quality challenge the reliability of conventional handover mechanisms. Specifically, this dissertation found that increasing the hysteresis margin significantly reduced the rate of unnecessary handovers without adversely affecting the user experience regarding latency or throughput.

Whilst the findings of this dissertation were somewhat limited by a lack of diversity within the utilised testing environments, they continue to highlight the requirement for future research into the specifics of this domain. This dissertation, therefore, concludes. This dissertation concludes with recommendations for network designers, operators, and future researchers, emphasizing the need for a nuanced approach to configuring handover parameters in indoor environments.

Research Ethics Approval

This project was planned in accordance with the Informatics Research Ethics policy. It did not involve any aspects that required approval from the Informatics Research Ethics committee.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(*William Moolman*)

Acknowledgements

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Chapter 1

Introduction

Over the past two decades, mobile operators have predominantly focused on increasing bandwidth and reducing the latency of mobile networks. This is reflected in the shift from 4G to 5G networks, which was implemented to meet the increasing consumer appetite for high-bandwidth technologies such as high-resolution streaming, video conferencing, virtual and augmented reality, and increasingly cloud-based AI processing [3]. To date, this 5G transition has been focused on improving the capabilities of existing mobile networks; however, as consumer demand grows, it is expected that 5G networks will begin to be deployed within indoor environments. Thus far, indoor deployment has been limited to research facilities, however public deployment is expected in the next decade [19].

Whilst extensive research has been performed on the performance of mobile networks in outdoor environments, there is currently a gap in the literature when exploring the performance of mobile networks within indoor environments, particularly when analysing the handover process. The handover process attempts to connect each mobile cell to the optimum radio base station (eNB), primarily determined by the signal strength measured by RSRP or RSRQ. By switching a mobile cell once its connection degrades, the handover process maintains user experience as per Quality of Service (QoS) and Quality of Experience (QoE) metrics; however, a throughput and latency penalty is simultaneously incurred.

The aims of this dissertation include:

1. To propose and deploy a testbed to study handover to be used to analyse handover.
2. To better understand the handover process within indoor settings and quantify the impact of a handover on user throughput and latency.
3. To propose adjustments or new algorithms to enhance the user experience in indoor 5G networks.

A robust testbed is essential to conducting a reliable analysis of the handover process, forming our initial aim. This paper will conduct simulations alongside real-world experiments in various indoor settings to collect network usage data to better achieve the proceeding aims. For much of the literature, simulations are used instead of real-world setups due to the complexity of maintaining a radio network, as well as the relatively high costs of equipment. This paper will initially utilise simulations but will use real-world experiments once the limitations inherent to simulations are reached. Simulations can be used in outdoor environments, as modelling the radio characteristics in a free-air space is straightforward using propagation loss algorithms such as log-distance log loss [13]. Indoor environments require modelling the radio absorption and reflection of walls, obstacles and dynamic objects such as human movement, which will deviate significantly from reality. However, a testbed using real-world hardware is essential, during which network operating data, such as RSRP, throughput and latency, must be captured for the analysis to be reliable.

Our second aim for the paper is the crux of the paper, as the understanding and calibration of the handover process is critical as it affects user experience significantly, especially with the increased demand for high-bandwidth applications. This paper aims to explore the impact of handovers on throughput and connectivity, as well as the frequency of handovers, and to determine whether all occurring handovers are necessary.

Our final aim is to use the insights gathered from our experimentation to propose adjustments to existing handover algorithms, suggest possible new techniques, and highlight how network design influences the handover process.

This dissertation's findings highlight the need for more careful setup and handling of indoor handovers and layout recommendations for more extensive real-world research. They also pave the way for subsequent exploratory studies that analyse other aspects of indoor cellular network performance. Ultimately, this work aims to enhance connectivity and service reliability in indoor environments, addressing the evolving needs of mobile network users. Through simulation, we examined the limitations of existing simulation models for indoor scenarios and confirmed the relationship between the hysteresis parameter and ping-pong rates. Through real-world experimentation, we have shown the inherent instability of indoor signals and demonstrated the considerable impact of environmental factors on network performance and reliability. Furthermore, our work examines the effects of handovers on network resilience, proposing a minimisation of handover rates to improve network robustness. However, acknowledging the limitations of our current methodologies, we present future research avenues for inquiry that span more complex simulation frameworks, diverse testing environments, and the exploration of predictive handover strategies using machine learning.

In conclusion, this paper significantly contributes to understanding and improving handover processes in indoor networks by providing a practical foundation and motivation for further research on development in this unexplored field to prepare for the upcoming 5G deployments.

Chapter 2

Background

2.1 Handover

Handover is when an active cell connection (data or cellular) is transferred from a source base station to a target base station to maintain continuous connectivity for mobile devices. Handover is a crucial technique in radio communication networks for mobility management and load balancing.

A UE [1] will have an active connection to a single base station (BS) at one time, with its signal strength being measured by the UE in terms of its Received Signal Reference Power (RSRP), which is used in handover triggering. RSRP can be affected by several different factors. Still, the two main influences are the distance to the base station (as propagation loss is logarithmically proportional to distance) and line of sight (LOS) blockages (as direct waves have higher power than reflected waves). RSRP is correlated with data throughput, and we want to maximise RSRP to maximise quality of services (QoS). A cell connection will also become unstable or drop at low RSRP strength.

2.1.1 Handover Procedure

1. A UE will measure the RSRP of all BSs in range and send the report to the connected (source) BS.
2. The source BS will compare the measured RSRP metrics and decide whether to initiate a handover. This decision is made with various algorithms discussed in 2.2, but all focus on maximising the UE's QoS by handing the connection over to a BS with a higher RSRP (or RSRQ).
3. If the BS initiates handover, it will determine which neighbouring BS to transfer the connection to. Various protocols determine how a connection is transferred; however, this is outside this paper's scope. Regardless of the protocol used, there will be a drop in connectivity and throughput.

[1] User Equipment - any device that can connect to a cell network, for instance, a mobile phone

4. The connection between a UE and the source BS can drop if the handover is not triggered before the RSRP drops below a level where communication is possible. This is termed handover failure (HOF), which has a much greater impact on connectivity, so the frequency of these failures must be minimised.

5. Handover decisions are not always optimal; a UE transferred to a neighbouring BS could be transferred back to the source BS if the RSRP values are unstable. This results in two unneeded handovers, decreasing QoS and increasing server load. This is termed Handover Ping Pong (HOPP), as it must be minimised.

2.1.2 Indoor Environments

The challenge of handover is relatively simple in outdoor environments, and with it being the main target of literature on the subject, many solutions exist to its various challenges. 5G, however, will be ubiquitously deployed in indoor environments. The indoor wireless channel is much harder to model, as LOS blockages are much more common due to the constrained environment. Furthermore, indoor deployments lend themselves towards much smaller cells (the area a BS serves); therefore, handovers will occur much more frequently in these high-density deployments.

Therefore, this paper's primary motivation and focus is on understanding, modelling, and predicting handover in indoor environments to maintain a high level of connection quality.

2.2 Handover Algorithms

This paper focuses on understanding the effects of handover and designing and testing various strategies to minimise the adverse effects. We, therefore, need to understand the different methods used to initiate handover and classify the multiple algorithms.

2.2.1 Classical Approach

The standard approach towards handover uses two parameters, *Hysteresis* and *Time to Trigger*, to determine when to trigger handover. When a neighbour cell has an RSRP greater than the current cell by a set margin, i.e. the Hysteresis, for a given period, i.e. time to trigger, the handover is triggered, and the UE is transferred to the neighbour cell. This process is illustrated in Figure 2.1. Alternative heuristics are often needed, as the standard approach is not robust enough for dynamic environments.

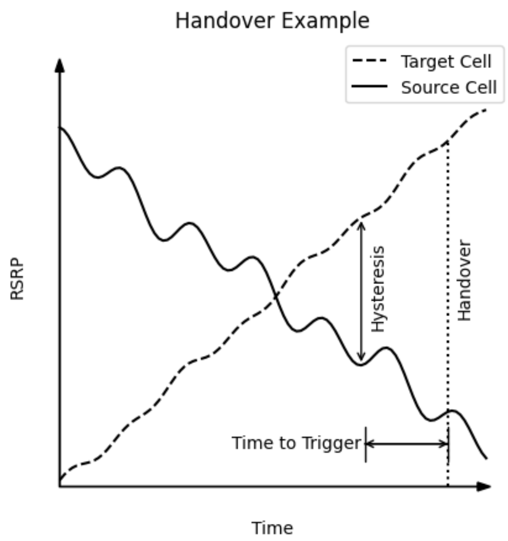


Figure 2.1: handover based on Hysteresis and TTT

2.2.2 Alternative Heuristics

Most existing handover algorithms use relative RSRPs (such as Hysteresis) with some delay (such as Time to Trigger). The literature suggests and models other parameters, including throughput, UE location, load balancing, user velocity, service delay, and distance. [10].

Hatipoğlu et al. [5] presented a handover-based load balancing algorithm for HetNets. The paper utilised UE speeds in determining handover, which is an unrealistic metric to obtain in practice. The algorithm itself is pretty simplistic, and while the paper showed promising results, the algorithm does not consider critical metrics such as RSRP or connection speed.

2.2.3 Machine Learning

Seeing handover as an optimization problem, using machine learning (ML) to solve it is natural. ML techniques are appealing because they offer potential performance improvements in complex domains where heuristic approaches struggle. As ML techniques do not require a model of the environment, this is especially applicable to indoor environments, where modelling proves difficult.

ML algorithms can be subdivided into supervised, unsupervised and reinforcement learning. Supervised and unsupervised algorithms perform regression or classification on a set of inputs. Reinforcement learning is based on the idea that the algorithm will learn to maximise its rewards in a given environment by learning the optimal policy. In our case, the optimal policy is a sequence of handover decisions that maximise throughput while minimising HOF and HOPP. The use of reinforcement learning has been surveyed in [8].

Reinforcement learning is a broad grouping of algorithms. These include Multi-Armed Bandits, Monte Carlo methods, and Deep Q-learning.

Yajnanarayana et al. [18] presented a handover algorithm using Contextual Multi-Armed Bandit reinforcement learning. This ML model provided modest improvements (0.3dB) in the average RSRP of devices. The authors also built their custom network simulator, which used sophisticated propagation models like log-shadowing and the WINNER UMa Model. The code used to simulate it was not released, providing very little reproducibility of the paper. The improvements were relatively minor, and better results could be obtained with a deep-learning-based Reinforcement model.

Mollel et al. [8] further introduces and surveys an alternative machine learning method. The pure network-based models operate only on radio data, such as RSRP and base station states. However, an alternative heuristic uses optical information, such as camera feeds, to predict handover better. This is done by tracking UE movement through object detection and predicting when LOS will be obstructed. While this tool can prove very useful, it introduces many limitations, as the models trained will be very location-dependent and have the most significant impact in indoor environments due to the greater LOS blockage rate.

2.3 Handover Testbeds

To evaluate experimental algorithms, we need some way to emulate a network. Many authors run custom simulations using propagation algorithms to model path loss and simulate the network devices. A better method is using a software radio suite as a testbed. This allows us to emulate UEs, base stations (BSs), and the core network (CN).

A few options are available, with the significant software being srsRAN, OpenAirInterface, and Aether. This paper chose srsRAN due to its clear open-source code and extensive tutorials. While a fully custom testbed allows for greater flexibility, the realistic nature of using software radio suites will give results that much better reflect how the algorithms would perform in a real-world scenario and, so, arguably, provide more useful results.

Powell et al. [11] presented a testing framework for 4G experiments using srsRAN and performed basic experiments. The framework was presented clearly, and we were able to replicate the results of their simulation. The experiments they performed, however, were limited as signal strength was arbitrarily introduced by attenuating a signal and did not utilise signal propagation algorithms.

2.4 Previous Work

Tayyab et al. [14] explores the effect of cell size on various handover metrics, such as HOPP and HOF. This paper tackles handover in ultra-small cell deployments, which have similarities to indoor settings. The paper's results show a highly significant increase in ping-pong rates and HOF for cells with a smaller than 200m Inter-Site Distance (ISD) - the distance between two eNBs- leading us to conclude similar problems in our indoor scenario. However, the results were achieved through simulation, which does not account for the various secondary effects of indoor scenarios mentioned above.

Bertolini and Maman [2] presents a real-world experimental setup using OpenAirInterface and conducts various experiments to understand handover impact. However, this paper does not translate well to our domain, as physical cabling connects to each cell instead of a radio transceiver. This limits the results of their experiment, as no second-order effects are seen (LOS blockage, signal reflection and open-air propagation loss). The paper also outlines the handover protocol in an easy-to-understand way, which aids us in our understanding. This paper finds both a constant latency penalty in handover experiments and a drop in throughput when handover occurs.

Zhang et al. [20] presents an in-depth study on the impact of handover on TCP and UDP traffic. Their experiments used a similar cabled setup as [2] for their first experiments but used an outdoor testbed for the latter. The paper found a clear relationship between the hysteresis value and HO rate; however, it found no impact on TCP traffic. It further measured the latency introduced by a handover to be 80ms, a value we reproduce in Section 4.3.4.

2.5 Further Technologies

When examining the directions for this paper, three possible technologies should be reviewed as they strongly relate to either handover performance or experimentation.

2.5.1 Reactive vs Predictive Handover

There are two main strategies when dealing with handover. We can either react to degraded quality and handover to improve it, or we can predict when quality is about to degrade and handover to maintain the quality of the connection.

Reactive Handover

This is the traditional handover mechanism where the decision to switch a UE from one eNB to another is made based on the current signal strength and quality. This relies on a more static environment where no sudden drops in signal connection occur; if a connection falls below a certain threshold, the UE cannot communicate the degraded connection to the eNB base station and must perform a reconnection to the network – which incurs a more significant penalty. This also relies on real-time signal metrics, as a delayed response to a falling signal strength could result in an HOF. While drawbacks exist when there is not a long enough window to react, it is a much simpler algorithm to implement. It is chosen for most outdoor handover scenarios, with a notable exception in high-speed movement applications such as railways [7] and other dynamic environments.

Predictive Handover

Predictive handover instead attempts to predict when signal quality is about to drop and initiates handover before the signal quality drops below a certain threshold. It aims to minimize disruption and enhance the user experience by anticipating network conditions [1]. This avoids HOF, as seen in reactive handovers, but relies on accurate predictions. Prediction misses could instead lead to more unnecessary handovers, some of which may be classified as Ping Pong Handovers. Many predictive handovers utilise UE movement speed to estimate when to initiate a handover. However, many now leverage machine learning algorithms to predict the need for handover. This requires accurate historical data and real-time analysis for prediction, and signal processing techniques are incorporated to analyze patterns and predict future signal degradation.

2.5.2 Large Scale Emulators

We can fully simulate network environments in software; however, this is limited in its ability to extract valuable insights for new environments. There is an alternative, however, in the form of large-scale network emulators, the largest of which are the Platforms for Advanced Wireless Research (PAWR). These do not rely on software simulation but consist of real-world software-defined radio testbeds. Specifically, their POWDER platform is a city-wide testbed in Utah, United States.

POWDER allows researchers to run experiments without maintaining and deploying networks themselves. This removes many barriers to entry in the research of 4G/5G networks, as equipment costs can be high. It also enables researchers to test machine learning models for predictive handover and assess signal processing algorithms in a controlled environment [12].

For this paper, POWDER was not used as the group already had a working testbed; however, this remains a viable route for larger-scale experiments for an extension to this project. However, the drawback is the inability to perform mobility experiments, as radio attenuation is software-defined. This inherently limits us from performing our indoor experiments, where open-air radio propagation is what we are interested in.

2.5.3 O-RAN

Open Radio Access Network (O-RAN) architecture is a new software standard for interoperability and flexibility in 5G networks. It defines standardised interfaces (E2) for modular radio network components to communicate over and includes the RAN Intelligent Controller (RIC), a software-defined component responsible for controlling and optimising RAN functions [16].

This enables the integration of machine learning directly into the radio access network for smarter handover decisions and innovation and customization in handover strategies by allowing third-party applications and services within the RAN [9].

Chapter 3

Exploratory Research Design

3.1 Overview of Approach

Due to the iterative nature of exploratory work, this paper is not structured by methodology, results, and discussion but progresses iteratively. For our results to be meaningful and progress efficiently, the paper's research is structured into multiple experimentation cycles. Each cycle is comprised of:

1. Determining Objective(s) and Defining Hypotheses
2. Build Approach
3. Present Results
4. Immediate Discussion

This structure allows for a more flexible approach to the research. It allows us to adapt as new insights are gained and form new hypotheses without compromising the experiment. This supports the dynamic nature of exploratory research, where learning and adaptation are essential.

Determining Objective(s)

The first step in each experimentation cycle is clearly defining what objective we are trying to achieve. This objective, or objectives, guide the research for the cycle, determining which hypotheses are chosen and how to approach the research. Objectives may be refined or adjusted as data is gathered and new insights are formed.

Defining Hypotheses

As objectives are chosen, we can begin formulating hypotheses we aim to test or explore. We will test these predictions and provide a clear direction for the experimentation and analysis phases. Hypotheses should be specific and should not change as new data is gathered – for that, we can note down the new questions that arise, which will inform the next research cycle.

Build Approach

With our objectives and hypotheses defined, this stage will focus on designing and planning our experimentation process. This includes selecting methodologies, defining which data to collect and how, and outlining the analysis techniques to be employed. This approach should be designed to efficiently test and answer the stated hypotheses, achieving the cycle's objectives.

Present Results

This section presents all results from the experimentation and analysis of said data. The results should be detailed for clear analysis and focused on transparency and reproducibility to support the next discussion phase and future research.

Immediate Discussion

This final phase is an immediate critical discussion of the derived results. The data provides insights and discusses the implications for the paper's broader research goals. These insights and results feed directly into the design of the next cycle, and the learning gained, in turn, informs how we structure the following objective and approach.

3.2 Initial Hypotheses

In this paper, we aim to test four main hypotheses. We discuss the reason for their inclusion, what proving the hypotheses means regarding our research goals, and what contradicting them would indicate.

3.2.1 RSRP will be unstable

RSRP values will be less stable due to a more dynamic environment induced by the movement of persons and greater signal reflection from walls, doors, and obstacles.

- **Expectation:** Fluctuations in RSRP (Reference Signal Received Power) greater than expected due to the aforementioned reasons. We expect these to arise from the more constrained environment, providing greater signal reflection and the higher likelihood of LOS blockage due to the lower relative transmitter height.
- **Implication:** Unstable RSRP values may necessitate adjustments in network configuration and signal optimization strategies to ensure consistent user experience. Care must be taken regarding possibly dampening signal gain.
- **Consideration:** If RSRP values are more stable than expected, it could point towards an inherent robustness in the network's design against indoor environmental variables. Signal reflections could be overstated, and LOS blockage may not play a large role in lower-frequency transmission.

3.2.2 Ping Pong Handover will be prevalent

Ping Pong Handover will be much more prevalent due to the denser configuration of indoor networks and the nature of the indoor channel, which produces rapid changes in signal quality.

- **Expectation:** Increased Ping Pong Handovers are anticipated due to the closer proximity of access points and the resulting signal overlap. Small signal fluctuations could result in a handover to a neighbour cell and then immediately back again.
- **Implication:** A higher incidence of Ping Pong Handovers could indicate a need for more careful tuning of handover parameters or even more sophisticated handover algorithms tailored to dense environments - such as a Machine Learning based one.
- **Consideration:** Contradicting this hypothesis may suggest existing handover mechanisms are more effective in dense configurations than anticipated or that signal management techniques are mitigating expected issues.

3.2.3 Unnecessary Handovers will dominate

The number of unnecessary handovers will be very high - independent of the change in QoS/QoE and level of throughput. Unnecessary handovers are defined as those that do not improve user experience and partially overlap with the Ping Pong metric.

- **Expectation:** A significant volume of handovers may occur without corresponding benefits regarding improved signal quality or throughput, indicating inefficiencies in the handover process.
- **Implication:** High rates of unnecessary handovers could lead to network resource wastage and degraded user experiences, highlighting areas for optimization.
- **Consideration:** Should this hypothesis be contradicted, it might reveal that current handover criteria are more effective than predicted at minimizing unnecessary transitions.

3.2.4 Impact on Total Throughput and End-to-End Latency will be high

The total throughput will be lowered due to the frequent handovers, and each handover will exhibit high latency penalties.

- **Expectation:** Frequent handovers are presumed to disrupt data flows, thereby reducing the overall network throughput.
- **Implication:** A drop in throughput due to handovers suggests a need for balancing handover triggers with throughput preservation, possibly by refining handover algorithms.

- **Consideration:** If throughput is not adversely affected by handover frequency as hypothesized, it could indicate that the network efficiently manages handovers to minimize the impact on data transmission.

3.3 Research Lab Layout

The testbed used to run the experiments is set up in one of the labs used by the Edinburgh NetSys Group. It consists of a node cluster, which hosts the network core, and four Intel NUCs, each connected to an Ettus Research B210 USRP, which acts as the base stations. These USRPs are Software-Defined Radios that act as radio front ends, allowing a network simulator to use them to send and receive radio signals at a specific frequency.

Below is a top-down view of the testbed used by the Edinburgh NetSys Group. Units are in centimetres, and the boxes with a cross through them represent the locations of the B210 USRPs. The USRPs on the top of the image are on a shelf 127cm above the ground, and the 2 USRPs on the bottom are on a desk 80cm above the ground.

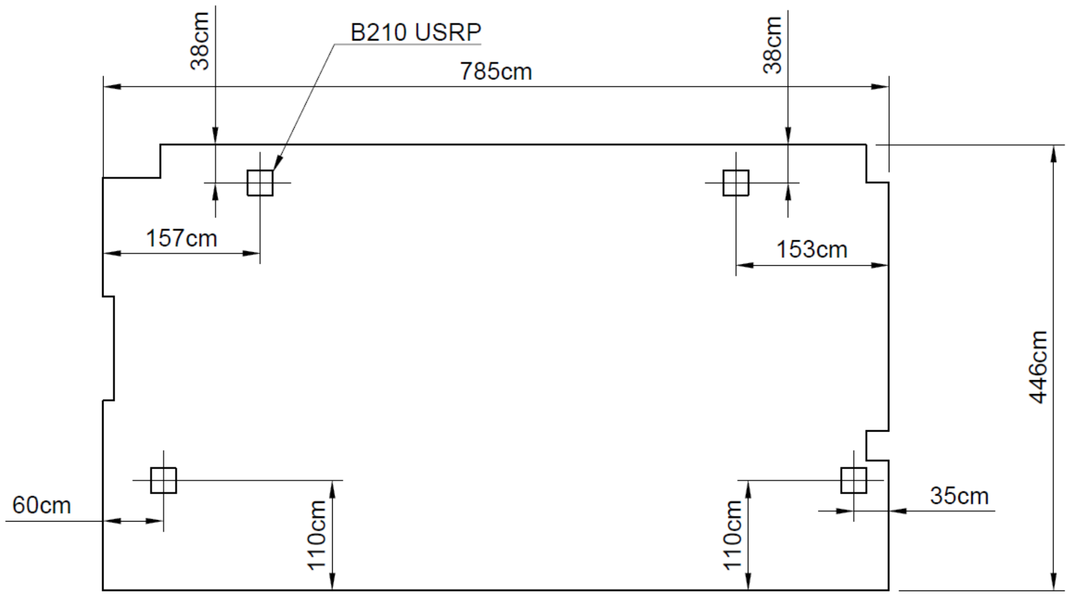


Figure 3.1: Radio Testbed Layout

3.4 Software Stack

There are multiple software artefacts needed to run the testbed. To run the base stations, srsRAN's eNB code controls the USRPs that host the radio layer of the network. Due to its ease of deployment and high compatibility with srsRAN, we use Open5GS to run the network core, which is responsible for authenticating users, orchestrating the network and providing a control flow. A Kubernetes deployment runs all these simultaneously, nominating the base stations and core network as pods and the physical NUCs and clusters as the nodes.

- The testbed consists of 4 NUCs, each connected to an Ettus Research B210 USRP.
- Each NUC runs a modified srsENB process, enabled with an E2 RIC interface to be ORAN compatible.
- Open5GS is running on another server and is connected using the S1 interface
- The entire setup is orchestrated using an in-house Kubernetes deployment framework for ORAN.
- We run an instance of srsRAN for the UE on a separate machine we can move, connected to another B210 USRP.
- The logs of the UE are saved to disk, with RRC logs set to DEBUG

Chapter 4

Experimentation

This chapter details our experimentation work to answer our key research questions. Each experiment contains an associated objective, approach, results and discussion section. We start our experimentation with our simulation-based experiments, detailing our testing of the LTE standard, and work to understand the link between the handover triggers and the ping-pong rate. We continue our work on the real-world LTE testbed, examining the radio characteristics in various mobility modes and the latency and throughput impacts of a handover event. We compare the changes in response for different cell densities and finally show the relationship between the hysteresis parameter and the handover rate in an indoor setting.

4.1 ZMQ-based Handover in srsRAN

4.1.1 Objective

The first phase aims to understand the basics of handover using srsRAN in a controlled simulation. We can use ZMQ and GNU radio to emulate the radio layer.

4.1.2 Approach

Following Powell et al. [11], we started with a pure simulation-based experiment of inducing a handover event. This is accomplished using ZMQ and GNU Radio to simulate the radio layer.

ZMQ[6], or ZeroMQ, is an asynchronous messaging library that emulates radio transmission. GNU radio[4] is a software development toolkit that uses ZMQ to interface the various srsRAN components. It also provides signal processing blocks to emulate attenuation between specific radio devices.

- We set up the experiment by running an Open5GS network core (EPC), two eNBs, and a UE; the latter two are binaries provided by srsRAN.
- The eNBs are connected to the EPC over the S1AP interface over TCP on our local machine.

- The eNBs connect to the UE using GNU radio and ZMQ, communicating over various TCP ports.
- To emulate propagation loss, we add `multiply` blocks provided by GNU radio (that amplify or attenuate a signal by some constant) on the send and receive channels from each UE to eNB connection, initially setting it to 1 for the eNB we designate as the source cell and 0 for the "target" cell.
- We must additionally add a `throttle` processing block, which keeps the sampling rate consistent with what srsRAN expects.
- On the srsUE process, we collect the measurement logs, fetching the RSRP for both cells.
- We gradually increase the multiply for the target cell, reducing attenuation until the RSRP is over the hysteresis threshold and the UE is handed over to the target cell.

Our GNU radio flowchart is displayed in Figure 4.1. TX is the radio transmission channel, and RX is the receiving channel. The multiply constant blocks are variable and are adjusted during simulation.

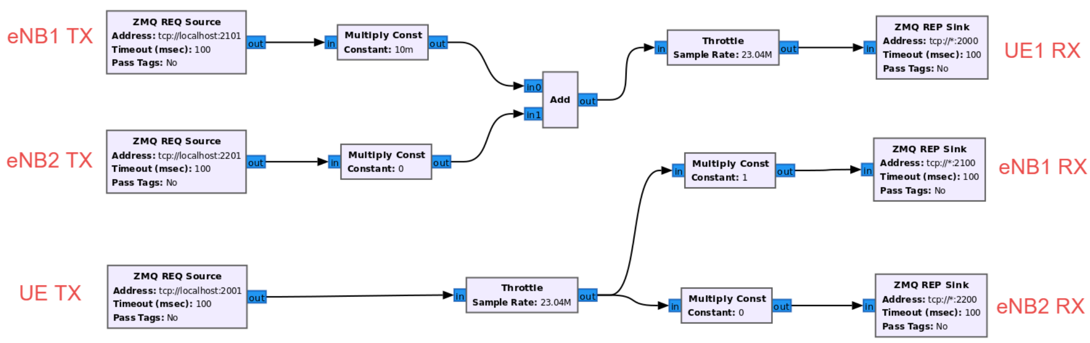


Figure 4.1: GNU Radio Handover Flowchart

4.1.3 Results

Figure 4.2 shows the experiment's results, with the y-axis representing signal strength and the x-axis being a dimensionless attenuation constant. We see handover occurring at -67dBm, 3dBm higher than the connection strength to our source eNB (eNB1). From this, we can see that the hysteresis value in this experiment was 3dBm.

4.1.4 Immediate Discussion

srsRAN's default hysteresis parameter (the A3 offset) used in our configuration was 3dBm. On a static source analysis of the srsRAN source code, we see the handover occurs when the following condition is met:

$$\mathrm{RSRP}_{\mathrm{Target}} - \mathrm{RSRP}_{\mathrm{Source}} > \mathrm{Hysteresis} + \mathrm{A3\ Offset} + \mathrm{Of} + \mathrm{Oc} \tag{4.1}$$

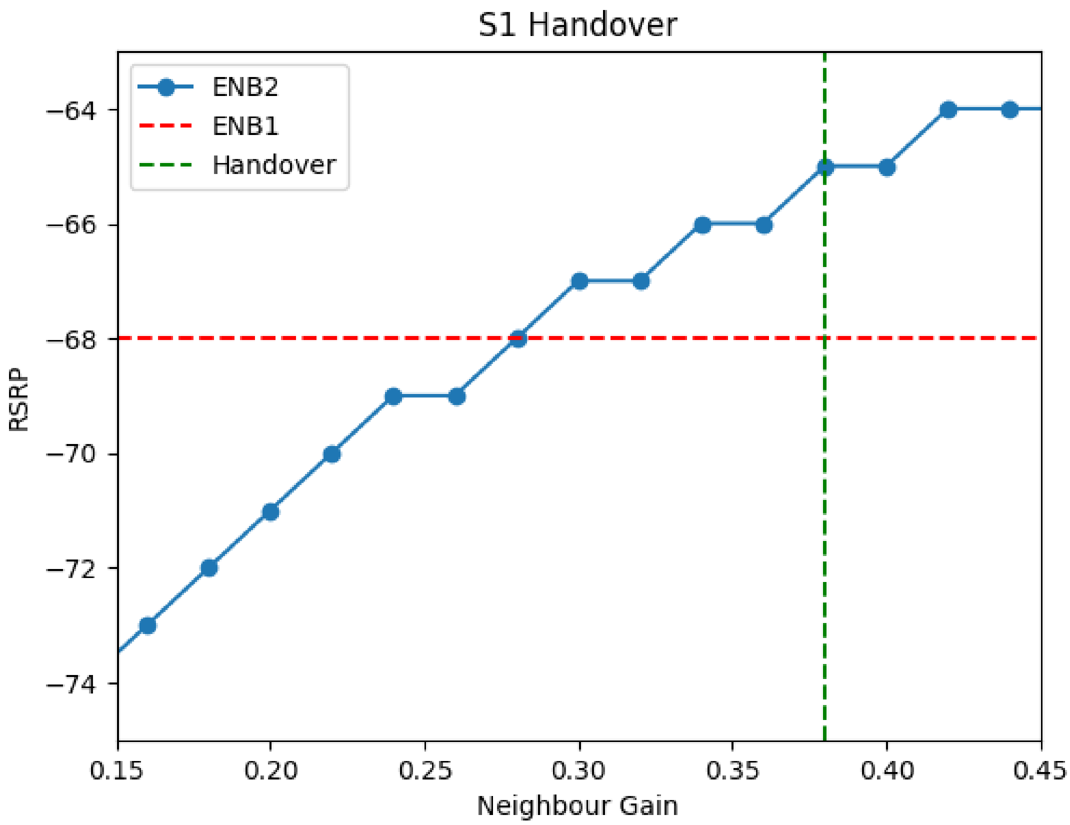


Figure 4.2: S1 Handover occurring in srsRAN with simulated UE over ZMQ/GNU Radio

where

$$\begin{aligned} \text{Of} &= \text{Frequency Offset}_{\text{Target}} - \text{Frequency Offset}_{\text{Source}} \\ \text{Oc} &= \text{Cell Offset}_{\text{Target}} - \text{Cell Offset}_{\text{Source}} \end{aligned} \tag{4.2}$$

where in the default setup, Of $= 0$ and Oc $= 0$.

The hysteresis in this equation should not be confused with the hysteresis mentioned in this paper. Instead, it is an additional threshold parameter provided by srsRAN. Together with the A3 offset, this parameter forms the hysteresis trigger parameter discussed in this paper. By default, this parameter is 0dBm, giving us a combined hysteresis value of 3dBm.

This phase confirmed srsRAN's adherence to the LTE standard, and a handover was successfully performed in a simulated environment. This phase was limited by the simplistic nature of the simulated radio network, as constants purely dictated network strength. The limited nature of the simulated environment prompted questions about how handovers would occur in more complex environments.

4.2 Custom Network Simulator for Large Scale Handovers

4.2.1 Objective

Building on the initial findings, this phase was focused on understanding the ping-pong metric and the associated triggers, employing a custom large-scale simulator for analysis.

4.2.2 Approach

Inspired by Hatipoğlu et al. [5], we reconstructed their non-disclosed tool to simulate large-scale handovers. This allows us to understand better how large-scale handovers are conducted. We can then attempt to replicate their findings to understand what causes ping-pong.

To model handover, we can simplify the modelling to the 2D domain, as vertical propagation loss can be discounted compared to the horizontal propagation between a UE and an eNB. This propagation loss is modelled using the log-distance path loss model[13]:

$$L = L_{\text{Tx}} - L_{\text{Rx}} = L_0 + 10\gamma\log_{10}\frac{d}{d_0} + X_{\text{g}} \tag{4.3}$$

Where L is the path loss in decibels, L_{TX} is the transmission power level, L_{RX} is the received power level, L_0 is the path loss at the reference distance d_0, d is the length of the path, d_0 is the reference distance, γ is the path loss exponent and X_g is a normal random variable representing the attenuation due to shadow fading (where obstacles

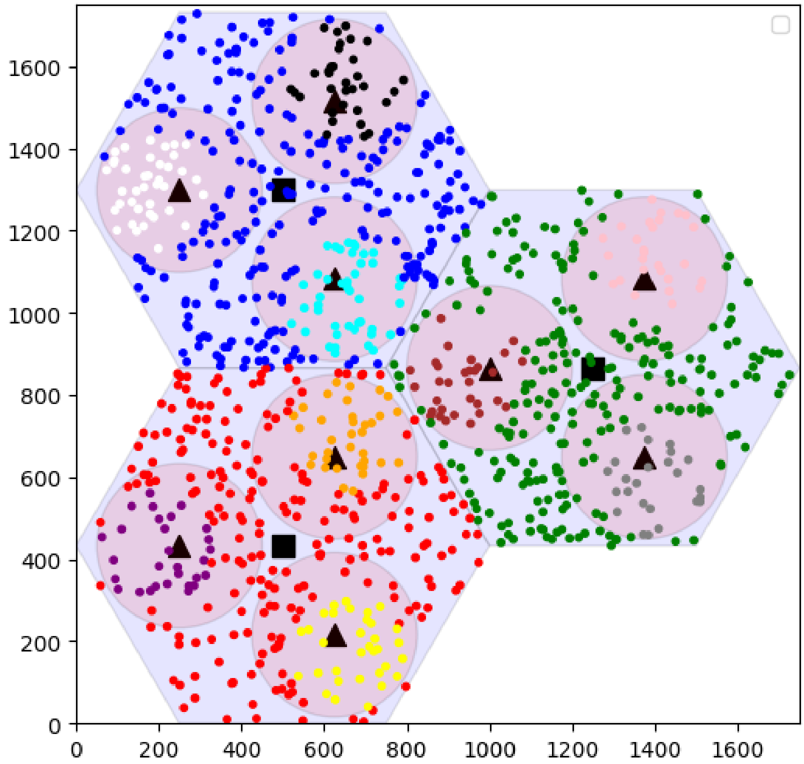


Figure 4.3: An overview of the 2D simulator

affect wave propagation). The values of L_0, γ, d_0 and X_g depend entirely on the specific deployment environment, carrier frequency and height of the antenna. We must choose a set of reference values to conduct our experiment.

We reconstruct the same environment as Hatipoğlu et al. [5] in Figure 4.3 to simulate a radio network. The three hexagons represent the movable area, the black squares represent macro-eNBs (lower frequency and higher range), and the black triangles represent the micro-eNBs (higher frequency but lower range). Each coloured dot represents a UE, with the colour representing which eNB it is connected to. The axes units are in meters.

We can simulate UE movement by categorising each UE as a pedestrian, a stationary person, or a vehicle, each of which moves at different speeds. The movement is simulated in timesteps, where at each timestep, a UE can change its heading by a random angle from -10 to 10 degrees.

Handover is calculated using the standard hysteresis and TTT parameters. We simulate different parameters and calculate the percentage of handovers classified as ping-pong, which we define for this experiment as if a handover occurs back to the source cell within 1 second.

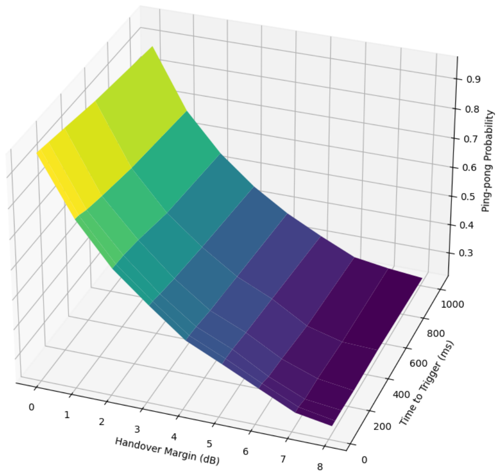


Figure 4.4: Ping Pong vs Hysteresis and TTT

4.2.3 Results

We run the experiment with various handover parameters in Figure 4.4. This graph shows an apparent exponential increase in ping-pong probabilities for a decreasing hysteresis (handover margin). At the same time, the TTT parameter does not provide a noticeable change to the ping-pong probabilities. At a 0dBm hysteresis value, the ping-pong probability reaches 90%.

4.2.4 Immediate Discussion

The simulator offered some insights into the conditions that cause ping-pong handovers; however, this was majorly limited by the rudimentary nature of the loss propagation function and highly approximate human movement. This reiterates the need for real-world testing to validate these findings, leading to our next experimentation phase.

4.3 Real-world Network Testbed Implementation

4.3.1 Objective

After performing the initial experiments in a simulator, we move on to testing in the real world to validate our simulation insights and provide real insight into indoor scenarios. We use a network of radio-enabled NUCs running as srsENBs to examine handover behaviour in a physical environment.

4.3.2 Approach

We plan on performing a range of experiments using the setup described in Sections 3.3 and 3.4. These experiments are outlined in the following subsections.

4.3.3 Mobility Tests

4.3.3.1 Objective

We wish to examine the performance of the indoor handover in various mobility settings.

4.3.3.2 Approach

To reduce confounding variables, we start the network with only two eNBs for this experiment. We examine four different mobility settings:

Stationary We set up this experiment by placing the UE machine between the two eNBs and taking care of the environment remaining entirely static; the UE remained stationary, and no persons moved during the experiment. Here, we expect no handover and that the radio signal (as measured by RSRP) remains constant.

Walking We set up this experiment by initially starting the data recording when the UE is near one eNB and then walking towards the other side of the room with the second eNB. Once we reach the eNB, we return to our initial position. To eliminate external factors, no other person was in the lab, and the movement speed was kept roughly constant. We expect the signal strength of the UE to vary proportionally to the distance we are from them and expect a handover to occur once we have moved beyond halfway between the UEs. We expect a second handover on the way back.

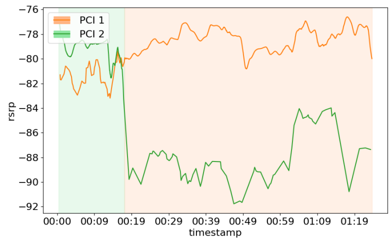
Rotating This experiment was devised to determine the impact of the angle of UE on the corresponding signal strength. We enable two eNBs on the same wall and place the UE halfway between the eNBs in the centre of the room. We slowly rotate the USRP between the two eNBs, back and forth. We expect no significant change in the signal quality, as LOS is not lost, and the distance between the UE and eNBs does not change.

Dynamic Environment In this experiment, we aim to test the network's response to a more dynamic environment. The UE is placed in the same position as the **Rotating** experiment, facing towards the eNBs' midpoint. During the experiment, a person walks in front of the UE and back again, simulating people walking around in a room. We expect some small drop in the signal strength as LOS with the corresponding eNBs is lost, but we believe that signal reflections contribute a sufficient proportion of the signal strength.

4.3.3.3 Results

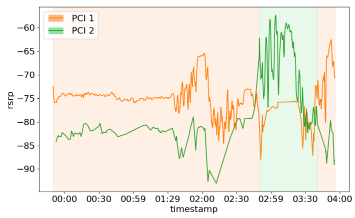
The real-world experiments and the description of the experiment are set out in Figure 4.5. Here, the plots have an x-axis representing time and a y-axis with the signal strength (RSRP) measured in dBm. Each line plot represents the signal quality between the UE and a specific eNB; in this case, we have two line plots as we have two eNBs. The background colour of the plot represents the eNB to which the UE is currently connected. We have matched the colour palettes (darker shade for the signal quality and pastel shade for the connection) to make the plot more intuitive.

Figure 4.5: Real-world Network Testbed Implementation: A series of experiments illustrating various aspects of handover behaviour in a real-world setup.



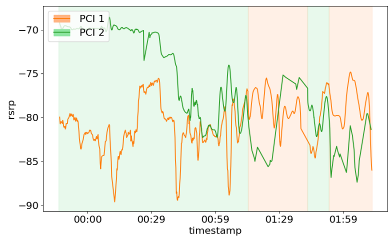
(a) Stationary

Figure 4.5a: Shows the effect of no movement on RSRP measurements, indicating the presence of environmental noise and its potential impact on handover decisions.



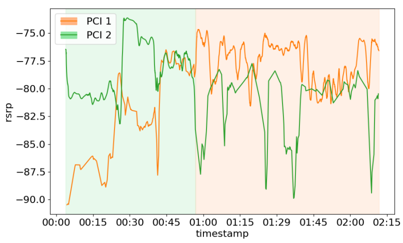
(b) Walking back and forth

Figure 4.5b: Demonstrates the RSRP and connected cell for a walking back and forth episode. This experiment showcases the dynamic RSRP changes as the UE moves closer or further from each eNB.



(c) Rotating UE

Figure 4.5c: Illustrates the impact of rotating the UE on RSRP fluctuations and handover events, highlighting the sensitivity of handover mechanisms to device orientation.



(d) LOS Blockage by walking around

Figure 4.5d: Examines the effects of line-of-sight (LOS) blockage by simulating movement around the UE. This scenario reflects real-world dynamics where human movement can influence signal quality and handover behaviour.

4.3.3.4 Immediate Discussion

These findings underscored the complexity of indoor scenarios.

Figure 4.5a shows the high impact of environmental noise even in stationary situations. We expected the RSRP values to remain constant, as the distances between the eNBs and the UE were unchanged, but this was not the case. We observe that even in stationary environments, RSRP can have significant changes, which can trigger handover, as seen at 00:17. The large drop in RSRP at 00:17 for PCI 2 causes PCI 1 to have a greater signal strength over the hysteresis value, causing the eNB to trigger a handover command. We can hypothesise that there are additional second-order effects on signal quality indoors, including environmental noise.

Figure 4.5b shows the network's response as a UE moves linearly between two eNBs. We expect the RSRP to scale smoothly as the UE reduces the distance to a new eNB and reduces as a UE moves away proportionally. We see the expected change in RSRP, including the expected handovers when we moved between the eNBs. There is a handover once the UE approaches the second eNB and another once it returns to the initial eNB. However, the large noise spikes were not accounted for in the expectations of the experiment, where the RSRP does not necessarily scale proportionally. Instead, we see a very noisy, erratic response.

This is partially explained by Figure 4.5c, where we seek to highlight this possible disparity by rotating the UE back and forth to determine if the angle of the UE would additionally impact the results, causing significant disturbances to RSRP. We indeed see this, as in the figure, the RSRP values fluctuate as we rotate the UE back and forth. This does not change the distance between the network devices. Additionally, this impact on RSRP is significant enough that we see multiple handovers occurring at 01:11, 01:42 and 01:51.

For the final figure, Figure 4.5d, we investigate whether LOS blockage could also be an extenuating factor in our previous results. Indeed, we see very large RSRP drops as we move between the UE and the eNB.

The four experiments together highlight the high difficulty of indoor handover. The RSRP values change very quickly and do not behave as expected. We see the relationship between RSRP and distance. However, we see greater than-expected influences from the angle of the UE and the impact of LOS blockage. These combine to form a challenging environment for indoor handover to be controlled and calibrated.

4.3.4 Handover Impact on Latency

4.3.4.1 Objective

To understand the severity of the issues found in the previous experiment must be mitigated, we must understand the impact on metrics such as throughput and latency of the connection during a handover event. This experiment focuses on the latency introduced by an individual handover.

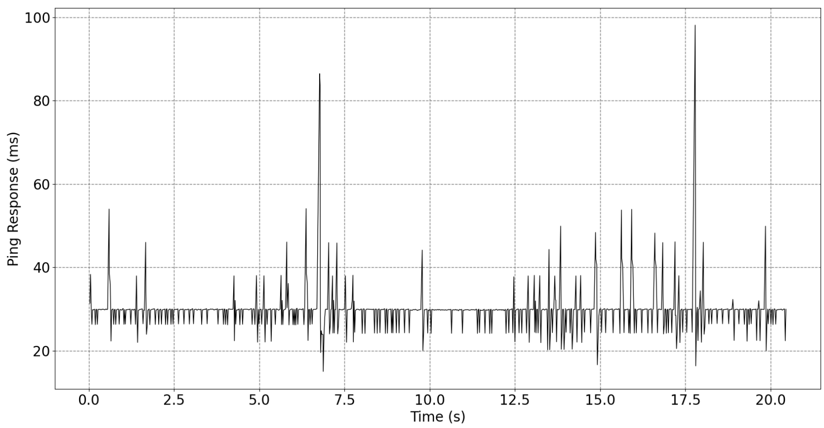


Figure 4.6: Ping latency during a handover event

4.3.4.2 Approach

To determine the latency impact of a handover event, we utilise ICMP `ping` messages. We set up the UE to send ping messages to the EPC every 10ms. We simultaneously use `tcpdump`[15] to capture all incoming and outgoing packets. We then can use Wireshark[17] to analyse the return trip time (RTT). We use Wireshark's inbuild graphing tool to produce a time series of the maximum RTT.

To capture a handover event, we set up the experiment similarly to Section 4.3.3's walking experiment, walking from one eNB to the other.

4.3.4.3 Results

The results are shown in Figure 4.6. We see a significant latency spike during both handover events; however, no packets were dropped due to the EPC/eNB buffering of any packets received during HO. We can see that the latency spike reaches 95ms.

4.3.4.4 Immediate Discussion

This result is consistent with Zhang et al. [20]. We understand that the UE will experience a latency penalty for each handover event. This spike in latency does not last long, though, minimising the total impact on the network performance.

4.3.5 Throughput Analysis in Indoor Environments

4.3.5.1 Objective

To further understand the impact of handover in indoor environments, we must also examine the throughput drop due to handover. This section focuses on repeating the mobility tests in Section 4.3.3 while measuring throughput.

4.3.5.2 Approach

We must first determine an approach to measuring the impact on throughput during a handover event. We have two communication protocol options: UDP and TCP. UDP is a best-effort protocol that does not contain rate limiting or reliable message delivery; however, it can deliver the highest throughput. Conversely, TCP ensures reliable message delivery and varies the transmission bandwidth depending on packet loss. It also accounts for the majority of internet traffic.

We can use the `iperf3` tool, which is the most popular network performance tester software. It also allows both UDP and TCP testing.

- We can set up the experiment by enabling all our eNBs and using our lab machine as a UE. We keep the environment and UE static during the experiment.
- We start an `iperf3` server on the EPC. Simultaneously, we begin a `tcpdump` process to capture all incoming packets
- For testing UDP throughput, we start a client on the UE in UDP mode. We set the bandwidth to 100Mbits/s to saturate the uplink.
- For TCP testing, we start the client in TCP mode. The TCP protocol automatically determines the bandwidth.
- We can then measure the throughput by examining the lengths of the incoming packets to the EPC.

4.3.5.3 Results

Figure 4.7 shows a 30-second capture of UDP throughput. The RSRP values remain constant, while the throughput is very erratic.

Figure 4.8 shows 30 seconds of TCP throughput capture. The RSRP values are slightly different. However, the connected eNB has a higher signal strength than the UDP. The throughput is much more constant - due to the TCP rate limiting the connection. However, it transmits at a much lower rate than the UDP connection. Furthermore, connection outages lasting more than 2.5 seconds are caused by the TCP backoff after a radio failure.

4.3.5.4 Immediate Discussion

Determining the best protocol to use for testing the network proves difficult. UDP provides a better understanding of the maximum throughput the connection can allow. However, due to its ubiquity, TCP better emulates how regular communication is affected by network performance. Due to the network's inherent instability, TCP becomes unviable when testing our network. As packet loss impacts TCP's communication ability, large outages appear during our throughput measurements. This would limit our understanding of the effect of HO on throughput. Furthermore, we wish to test the network's maximum capacity, so UDP provides a more granular view.

We, therefore, use UDP in our following experiments.

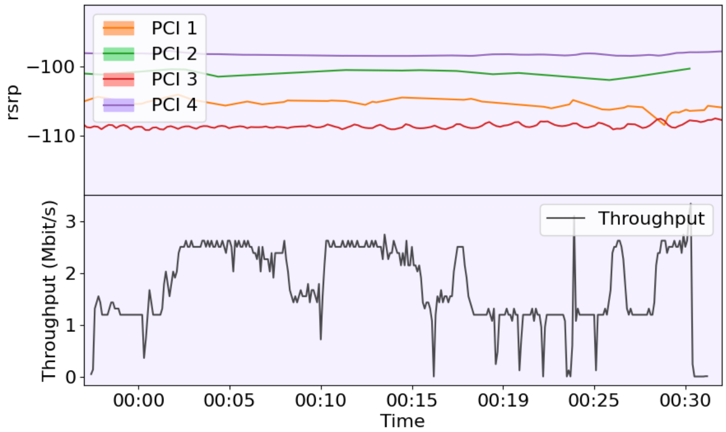


Figure 4.7: Stationary UDP Capture

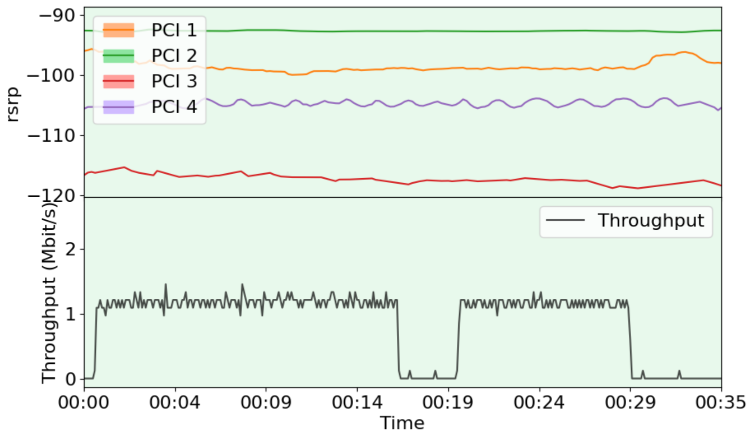


Figure 4.8: Stationary TCP Capture

4.3.6 Increasing cell density

4.3.6.1 Objective

The previous mobility tests were run with only two eNBs enabled. This does not fully represent planned indoor deployments; many will use higher cell density. This experiment focuses on the network's performance with more active cells. We can hypothesise that the handover rate will be much higher with increasing cell density (more eNBs enabled).

4.3.6.2 Approach

We reenact the walking mobility test from Experiment 4.3.3 over multiple captures. In this experiment, we enable all four eNBs. To generate a more natural data sample. we move around the lab without a specific path to emulate wandering around.

Considering our conclusion from the previous experiment, we enable UDP throughput capture.

4.3.6.3 Results

The experiment's results are shown in Figures 4.9 and 4.10. Here, we observed a set of figures without the expected clear throughput drop during a handover event; instead, the throughput was not steady enough to draw such conclusions.

Many handovers occur during each experiment, between 2 and 3 handovers per minute. Furthermore, we see the appearance of ping-pong handovers occurring in Figures 4.9a and 4.9b. In Figure 4.9a, the handover at 00:31 lasts 40ms, and the handover at 02:40 lasts 153ms. In Figure 4.9b the handover at 00:57 lasts 57ms.

To better understand the figures, we calculate Pearson's Correlation Coefficient between the RSRP of the connected cell and the throughput. We additionally calculate the mean throughput by eNB. These are presented in Table 4.1.

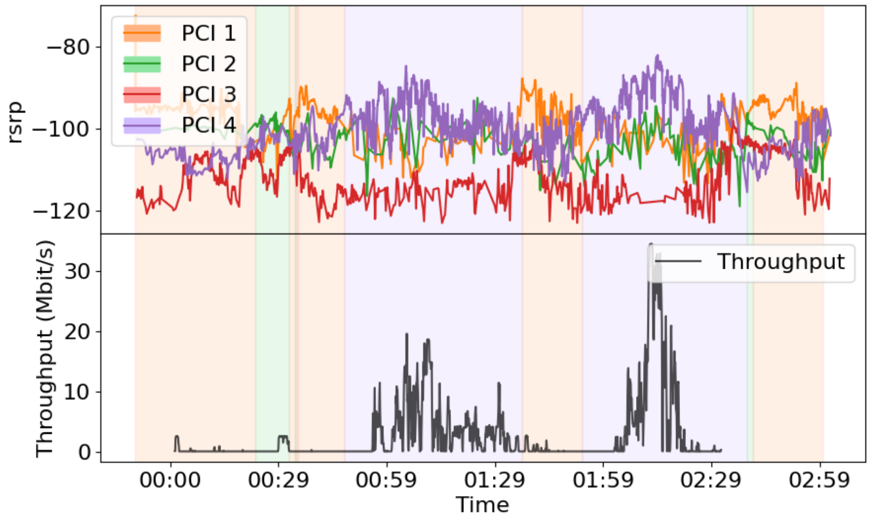
Table 4.1: Correlations and Throughputs of Experiment

	Pearson's Correlation	Mean Throughput (Mbits/s)			
		PCI 1	PCI 2	PCI 3	PCI 4
Figure 4.9a	0.55	0.12	0.50	0.00	4.56
Figure 4.9b	0.13	6.05	1.73	0.00	4.08
Figure 4.10a	0.04	0.00	2.47	9.21	3.52
Figure 4.10b	0.50	2.74	1.60	0.00	4.34

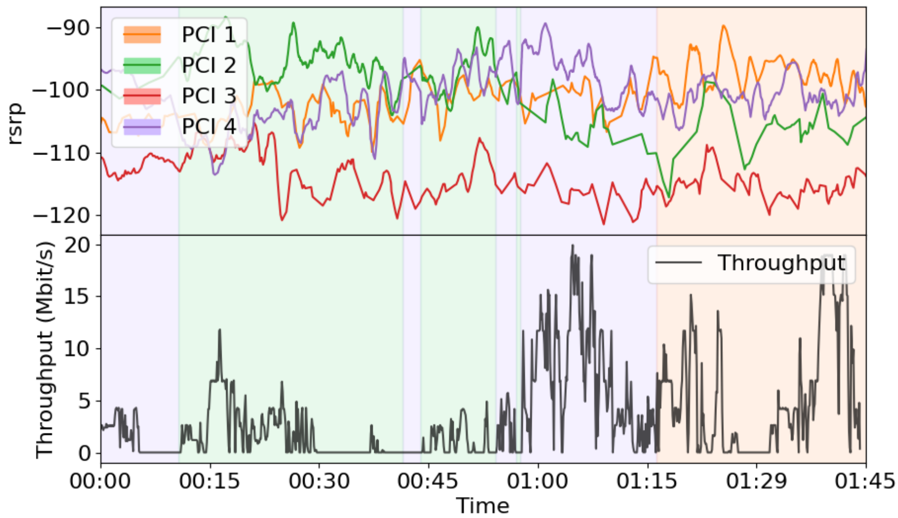
4.3.6.4 Immediate Discussion

In all four captures, we see a high rate of handover even when the signal quality has not significantly fallen. This observation is primarily due to the increased density of eNBs with similar signal strengths. Two of the captures have ping-pong handovers, where a handover occurs within a few seconds of the initial handover.

Figure 4.9: Moving Capture of Throughput (1)

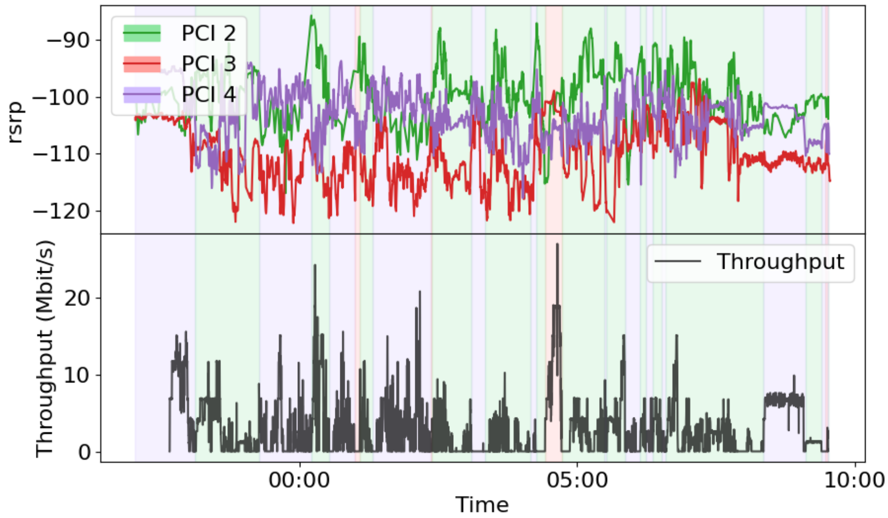


(a) Capture 1

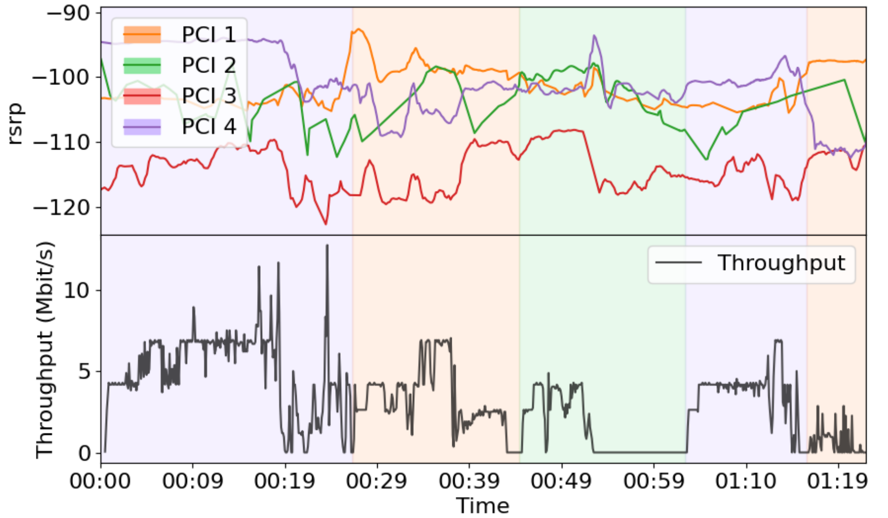


(b) Capture 2

Figure 4.10: Moving Capture of Throughput (2)



(a) Capture 3



(b) Capture 4

The throughput instability makes analysis very difficult. This is seen in Table 4.1, where there is a great disparity between the throughputs of the different eNBs. While there is a moderate correlation between the signal strength (RSRP) and the throughput in two of the experiments (0.55 and 0.50), the other two experiments do not present this relationship (0.13 and 0.04).

4.3.7 Hysteresis Impact

4.3.7.1 Objective

During the previous experiments, we saw a very high rate of handovers, even when throughput was not improved. We turn to our tuneable parameters of handover: TTT and hysteresis. Considering our results from Experiment 4.2, we can hypothesise that Hysteresis will most impact our ping-pong and handover rate.

4.3.7.2 Approach

To determine the effect of hysteresis on handover, we run a series of experiments adjusting the hysteresis value. We can set up the experiment with 4 eNBs enabled and the UE stationary, positioned so that the RSRP values of the eNBs are similar, where the chance of a ping-pong handover is high. We run the experiment with hysteresis values of 0, 3dBm, 6dBm and 9dBm.

4.3.7.3 Results

The experiment results are plotted in Figure 4.11. We see the rate of handover decrease for each increase in the threshold. We see a rate of 1.73 handovers/min for a 0dBm margin, 0.68 handovers/min for a 3dBm margin, 0.21 handovers/min for a 6dBm margin and 0.12 handovers/min for a 9dBm margin.

4.3.7.4 Immediate Discussion

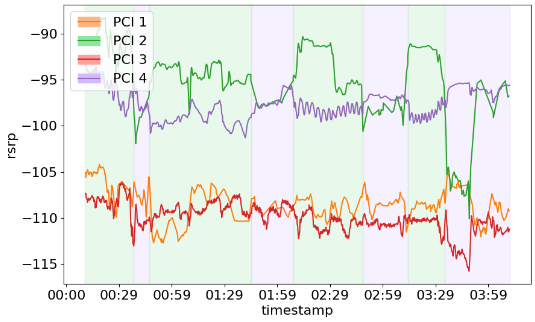
These results are in line with what we have expected. The hysteresis parameter is introduced in network systems to avoid ping-pong handovers specifically. We know from Equation 4.1 (simplified) that handover occurs when:

$$\mathrm{RSRP}_{\mathrm{Target}} - \mathrm{RSRP}_{\mathrm{Source}} > \mathrm{Hysteresis}$$

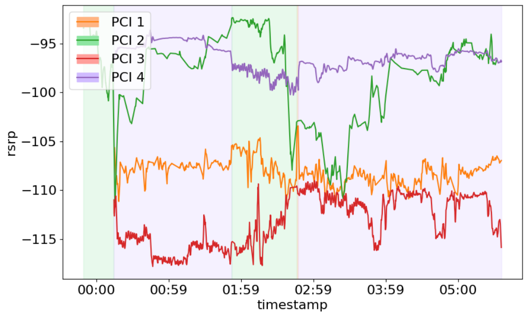
This equates to the two RSRP values being more distinct before the handover is triggered, leading to fewer cases where handover is triggered. Our experimental data supports this; we have a clear relationship between the rate of handover and the hysteresis value.

While a higher hysteresis value is desirable in this setting to reduce the number of handovers, it negatively impacts other mobility settings, as a higher margin means that handovers will be triggered later and may suffer a throughput penalty before connecting to an eNB with a stronger connection.

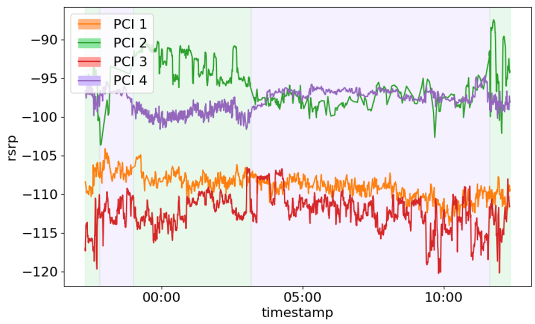
Figure 4.11: Hysteresis values effects on HO rate



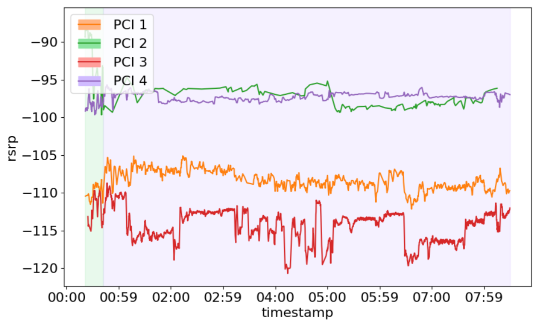
(a) Hysteresis Threshold: 0dBm



(b) Hysteresis Threshold: +3dBm



(c) Hysteresis Threshold: +6dBm



(d) Hysteresis Threshold: +9dBm

Chapter 5

Discussion

5.1 Interpretation of Findings

5.1.1 Adherence to LTE Standards and Simulation Limitations

Our study begins with a simulation of an LTE network using srsRAN, ZMQ and GNU Radio. Through this simulation, we confirmed srsRAN's adherence to the LTE standard during handover. We found that the hysteresis parameter behaves as expected, while TTT was not explored due to the limitations in data collection from the simulation. While useful for understanding handover, this simulation was limited in its insights on indoor environments due to the lack of realistic models for constrained environments. This prompted us to use an LTE testbed to gather real-world data for analysis.

5.1.2 Insights from Custom Network Simulator

While srsRAN provides a standards-conforming implementation of LTE, we can instead build a custom simulator that, while it cannot emulate a real network, can instead gather data on handover behaviour in large-scale systems. This allowed us to find a clear link between the hysteresis parameter and the ping-pong rate, with a minor relation to the TTT trigger. This result was expected from Hatipoğlu et al. [5] and further validated with our experiments later in our testbed; nevertheless, it reinforced our understanding and focused on real-world experimentation of testing different hysteresis parameters.

Similar to the srsRAN simulation, this network simulator was heavily limited by the simulation model; in this case, it used the log-distance path loss propagation model, which would not account for many of the indoor influences, such as LOS blockage, the rich multi-path environment, or increments in signal reflections due to furniture or angle of arrival. The approximation of human movement further limited it, so the experiment's results are only intended as a reference for further experimentation.

5.1.3 Real-World Network Testbed Observations

This paper focused on real-world network testbed observations to provide a realistic and comprehensive evaluation of indoor handover.

Our initial experimentation started with exploring UE mobility and examining possible human movement patterns in two eNB scenarios. We explored four different behaviours: stationary, walking, rotating and LOS-blocking movement. We only saw the expected behaviour in our walking scenario; RSRP decreased proportionally to the distance to the eNBs and the UE, which triggered a handover once a UE moved closer to another eNB. However, the other three experiments deviated from expectations. Our static setup showed large spikes in RSRP with no explainable cause, leading us to believe that indoor signals are inherently less stable than outdoor transmission. We can hypothesise that this is due to the highly constrained environment, which leads to a rich multi-path environment. We can also hypothesise that the proximity of the UE and the eNBs may influence this.

A rotating UE again deviated from expectations of a constant RSRP value, where RSRP had heavy fluctuations, causing multiple handovers, leading us to believe that the radiation was not omnidirectional; the angle of the UE impacted the signal strength. Our LOS blockage experiment also had greater-than-expected fluctuations in signal strength. From these experiments, we can hypothesise that further experiments will exhibit a high handover rate and that higher hysteresis values might be required to avoid unnecessary handovers – alongside increased difficulty interpreting our experimentation results.

We conducted further experiments on the latency and throughput impacts of handover. We chose UDP as a transmission protocol over TCP because it highlights our network's maximum throughput better. The latency induced by a handover was measured as a 95ms increase in RTT using the `ping` and `Wireshark` tools. Handover did not show the predicted drop in throughput. Instead, the network was characterised by handovers causing connection drops or reconnections. This indicates that the handovers, in scenarios with poor network resilience, should be minimised due to the risk of a connection failure.

Increasing the number of eNBs caused the issues encountered in two eNB setups to worsen drastically. There was a high handover rate even in stationary environments. From this, we conclude that indoor environments should try to minimise cell density, especially if the stationary signal fluctuations are reproduced in the deployment environment.

We finally performed an experiment examining the hysteresis threshold. This followed expectations, where increasing the hysteresis parameter monotonically reduced the number of handovers. Due to the instability of RSRP exhibited in earlier examinations, we can recommend higher hysteresis values be chosen for indoor environments at the cost of triggering handovers a bit late.

5.2 Implications and Applications

5.2.1 Impact on Network Design and Management

We can provide preliminary recommendations for network design and management from the experiments run in simulated environments and real-world testbeds. These recommendations should not be utilised naively—instead, they are meant to provide a starting point for further research and experimentation in both the field and individual deployments.

- Handover rate should be minimised in unreliable networks. As connections dropped often in our network during a handover event, the handover rate should be minimised to reduce the risk of a connection failure. Alternatively, the network robustness to handover failures must be prioritised to account for the high handover rate experienced due to RSRP fluctuations.
- High hysteresis values are preferred. A high hysteresis threshold can mitigate signal fluctuations, helping reduce handover. A hysteresis value that is too high could cause a device not to prioritise the closest eNB; however, in indoor deployments, the density of cells causes this to be less of an issue as we do not expect a UE to go out of range.
- Cell density should be minimised where possible. The RSRP fluctuations experienced cause the handover rate to scale with cell density. Increasing the distance between cells will lead to a lower handover rate.

5.3 Limitations of the Study

5.3.1 Simulation Constraints

As mentioned above, we experienced limitations in our simulation due to the environmental modelling. These limitations were, however, well understood and did not detract from the insights we gained. It did, however, limit the applicability of the results of both experiments, instead using the results to guide our real-world testing.

5.3.2 Controlled Environment in Real-World Testing

Our lab testbed provided realistic results; however, our experiments were limited due to the environment's controlled nature. We could only conduct experiments in a singular room configuration with fixed eNB positions. This highly limited the number of experiments that could be done, such as testing the impact of moving around corners indoors, moving through doorways and testing the effects of differing wall materials such as glass, wood and concrete. This limited our study to look at the effect of a constrained environment, albeit with the dynamic aspects induced by human movement.

5.3.3 Network reliability

The final limitation of the study was the lack of network resilience. Network failures were very common, as radio communication is inherently unreliable, requiring much more testing hours to extract meaningful data. This may also be a confounding factor in our results, where fluctuations in throughput and signal could be attributed to network instability rather than a product of the environment. To validate the results of this experiment, repeated testing on alternative hardware setups and different labs would be required.

5.4 Discussion Summary

To wrap up, we observed an erratic behaviour of the signal quality, even in static settings, which leads to triggering handover many times. The hysteresis can be tuned to avoid unnecessary handover but might trigger handover a bit late. Once handover is triggered, we measured a latency of 95ms and detected many reconnections. Overall, sensitive applications to high latency or connection failures would suffer from detrimental performance in indoor scenarios. We conclude that indoor handover is significantly challenging, and more research is needed.

5.5 Future Work

Much is needed to be done to further the studies starting in this paper, as the results of this paper are intended as a starting point for further research. We suggest four different avenues of research for later works.

5.5.1 Improving Simulation Realism

Our paper improved the simulation accuracy using real-world hardware and over-the-air radio communication. However, there is still a strong use case for simulated environments: the volume of data generated. If machine learning is used, a large volume of data is required to train the requisite models. The feasibility of gathering this data manually using a setup similar to our papers is low, so our simulated environments need to be improved.

The first avenue is to utilise better simulation models. The WINNER UMa [18] model, in particular, was developed for dense urban environments and could be suited to emulate indoor environments with some modifications. Furthermore, human movement algorithms were developed to emulate outdoor movement, so they must be redeveloped to emulate indoor movement.

Finally, the custom simulator built uses an approximation of a mobility management unit, which will not necessarily conform to LTE standards and could deviate from a real handover process. We can account for this by integrating srsRAN into this simulator, using ZMQ to communicate between UEs, and controlling attenuation from the calculated propagation loss.

To further increase simulation accuracy, we can use real-world hardware, albeit with software-defined attenuation rather than over-the-air radio communication, by utilising the POWDER platform.

5.5.2 Extensive Real-World Experimentation

Our current real-world studies are done in a single environment with a single testbed. More extensive studies are required to explore diverse environments to comprehensively understand indoor network behaviour. We have devised a list of alternative environments we hope to test in further studies:

Non-convex Rooms Our testing was constrained to a rectangular room. To better understand the effects of LOS blockage due to the physical room, we would require testing in non-convex rooms, such as L-shaped rooms, alcoves or non-straight corridors. This would allow testing and contrasting different eNB placements.

Multi-room Deployments To better understand how moving through doorways impacts network performance, multi-room deployments are essential, i.e. have eNB based in multiple rooms. This is very important for indoor testing, as we can hypothesise that moving between rooms is a required handover event, which we do not want to suppress with our above strategies.

Material Impact As we have tested in a single environment, we wish to test in an environment with different floor, ceiling and wall materials. This would allow us to test whether specific materials impact the network quality more than others, e.g. is there less signal attenuation through glass or drywall rather than a brick wall, or whether specific wall materials reduce signal reflection.

5.5.3 Exploring Alternative Technologies and Protocols

Finally, although this paper was incepted due to the forecasted deployment of 5G in an indoor environment, the experiments performed were done using LTE networks. This choice was made as srsRAN, our software stack, has a much more mature LTE implementation. We, therefore, believe that while our results are applicable due to the shared utilisation of the open-air radio communication, repeating these experiments with a 5G stack could yield further insights. This is due to the higher frequency used by 5G networks having different radio properties, for instance higher frequencies experience much higher signal absorption, and propagation loss.

5.5.4 Predictive Handover

Predictive handover is a vital goal for indoor deployments, allowing handover to be triggered before signal quality degrades. This goal is out of scope for this project, but we believe it will be a key area of research in the future. Drawing from the extensive literature on using Machine Learning in outdoor handover, we believe this to be a powerful tool for developing robust indoor handover. Due to the noisy signals seen in experimentation, however, we believe this would require additional heuristics than the existing algorithms.

Chapter 6

Conclusion

Reflecting on the research in this paper, we aimed to develop a comprehensive understanding of the handover processes of 5G networks inside relatively unexplored indoor environments. This exploration was motivated by the increasing demand for seamless connectivity to support high-bandwidth applications, from high-resolution streaming to cloud-based AI processing. Through a series of real-world experiments and simulations, this paper has uncovered the complexities and difficulties of indoor deployment and handover and highlighted several future research pathways for enhancing network performance and user experience. In this chapter, we highlight the key finding of our research, their practical importance, and the avenues they open for future exploration.

6.1 Synthesis of Key Insights

- We validated the operational integrity of srsRAN within LTE standards, highlighting the predictability of the hysteresis parameter in the handover process.
- We highlighted the limitations of current simulation models in emulating indoor settings, focusing our attention on real-world testbeds for more granular insights.
- We identified a strong correlation between hysteresis values and ping-pong rates, and highlighted the need to optimize handover algorithms for indoor use.
- On experimentation, we encountered the inherent instability of indoor signals. This demonstrated the significant effect of environmental factors on handover rates and network stability.
- We quantified the latency and throughput impacts of handovers on network performance. This led to the recommendation of minimising handover frequency for a more resilient network.

6.2 Reflections on Network Design and Management

- We encounter the need for careful handover management, higher hysteresis values and reduced cell density to mitigate the difficulties posed by high signal fluctuation and excessive indoor handovers.

- We highlighted the need for increased network robustness against handover-induced disruptions, potentially through new handover algorithms or infrastructural enhancements.

6.3 Limitations and Horizons for Future Inquiry

- We acknowledged the constraints of simulation models and the controlled nature of our testbed experiments, laying the foundations for developing more sophisticated simulation frameworks and diversifying testing environments.
- We proposed a series of further indoor settings to extend this study to obtain a broader understanding of network behaviour, signalling the need to test environments that mimic the complexity and variability of real-world use cases.
- We further suggested the extension to using 5G transmission in our testbed, to better consider the distinct radio properties they have.
- Finally, we considered the usage of predictive handover strategies, leveraging machine learning to anticipate and mitigate potential service degradation before it compromises user experience.

6.4 Concluding Reflections

In alignment with the objectives at the outset of this paper, our findings underscore the importance of rethinking handover processes for the indoor deployment of 5G networks. By exploring the difficulties unique to indoor environments, from signal reflections to LOS blockages, this research challenges the naive understanding of indoor network performance. Furthermore, it lays the groundwork for more extensive, large-scale testing of the indoor environment to better develop strategies to improve the end-user experience.

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Appendix A

Glossary

Base Station A fixed point of communication within a mobile network that communicates with mobile devices. It serves as a hub for connections to the wider network and manages radio communications..

Channel Quality A measure of the performance of a communication channel, reflecting its capacity to convey signals without error. It is influenced by factors like signal strength, interference, and noise..

Handover The process of transferring an ongoing call or data session from one cell of the network to another as the user moves through the coverage area..

Latency The delay from the source sending a packet of data to the destination receiving it. Latency is measured in milliseconds and can be affected by various factors in the network..

Latency Reduction Efforts or technologies aimed at decreasing the time it takes for a data packet to travel from source to destination, critical for applications requiring real-time interaction..

Multipath Propagation The phenomenon that occurs when a wireless signal splits into multiple paths as it encounters obstructions like buildings or terrain, leading to multiple copies of the signal arriving at the receiver at slightly different times..

Network Core The central part of a telecommunications network that provides various services to customers who are connected by the access network..

Network Density Refers to the number of nodes (base stations, access points) within a given area in a network, affecting the network's capacity and performance, especially in densely populated urban areas or indoor environments..

Network Simulation The act of using a computer model to predict the performance of a network in order to understand how it behaves under different conditions..

Path Loss Model A mathematical model that predicts the path loss (attenuation of signal strength) as a function of distance and other conditions. Used to design and plan wireless communication systems..

Ping Pong Effect In wireless networks, a situation where a mobile device continuously switches between two base stations due to marginal differences in signal strength, causing inefficient use of network resources..

Propagation Loss The attenuation of signal strength that occurs as an electromagnetic wave propagates through space or a medium..

Quality of Service Management The process of prioritizing network traffic and ensuring that critical data receives the bandwidth it requires to maintain high-quality transmission, especially in networks supporting diverse applications and services..

Radio Access Network Part of a mobile telecommunication system. It implements a radio access technology. Conceptually, it resides between a device (such as a mobile phone, a computer, or any remotely controlled machine) and provides connection with its core network..

Radio Frequency The rate of oscillation within the range of about 3 kHz to 300 GHz, which corresponds to the frequency of radio waves, and the alternating currents which carry radio signals..

Signal Attenuation The reduction in strength of a signal as it travels through a medium or across distance, often due to loss factors such as absorption, reflection, and scattering..

Signal Reflection The phenomenon of a propagating electromagnetic wave (signal) bouncing off a surface. In telecommunications, reflections may cause multipath propagation, leading to interference..

Signal Strength A measure of the power level that an RF device, such as a wireless router or a mobile phone, receives from the signal source..

Signal-to-Noise Ratio A measure used in science and engineering to quantify how much a signal has been corrupted by noise. It is defined as the ratio of signal power to the noise power and is often expressed in decibels..

Software Defined Radio A radio communication system where components that have been typically implemented in hardware (e.g., mixers, filters, amplifiers, modulators/demodulators) are instead implemented by means of software on a personal computer or embedded system..

Throughput The rate of successful message delivery over a communication channel. This data may be delivered over a physical or logical link, or it can pass through a certain network node..

User Equipment Mobility Refers to the movement of the user equipment (such as smartphones or tablets) and its ability to maintain a continuous connection and service quality as it moves across different base stations or cell areas in a mobile network..

Appendix B

Acronyms

BS Base station, a radio transceiver that provides the radio connection to the UE.

CQI Channel Quality Indicator.

eNB An LTE base station, a radio transceiver that provides the radio connection to the UE.

EPC Evolved Packet Core - an LTE network core.

gNB A 5G base station.

HetNets Heterogeneous Networks (macro and micro cells).

HO Handover.

HOF Handover Failure.

HOPP Handover Ping Pong.

ICMP Internet Control Message Protocol.

LOS Line of Sight.

LTE Long Term Evolution.

ML Machine Learning.

ORAN Open Radio Access Network.

PCI Physical Cell Index - a value representing a physical cell.

QoE Quality of Experience.

QoS Quality of Service.

RSRP Reference Signal Receiver Power - a measure of signal quality.

RSRQ Reference Signal Receiver Quality - a measure of signal quality.

RTT Return Trip Time.

S1AP S1 Application Protocol.

SINR Signal-to-Interference-plus-Noise Ratio.

TCP Transmission Control Protocol.

TTT Time to Trigger.

UDP User Datagram Protocol.

UE Any mobile device that can connect to the mobile network as a client.