MIMO techniques in 5G/6G
Technical Milestone Report

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Abstract

The evolution of telecommunication systems, to meet increasing demands, has led to the fifth-generation (5G), which introduces key concepts such as millimeter-wave communcation, network slicing, and massive Multi-Input Multi-Output (MIMO). As the focus shifts to the next generation 6G, further development in MIMO techniques is anticipated to play a more critical role. This technical milestone report explores the evolution of MIMO techniques from LTE, 5G, and to ongoing development to understand their significance through a literature review. This review aims to deepen the understanding of MIMO techniques in order to interpret the channel responses from simulations, using the MathWorks 5G toolbox, of Tapped Delay Line (TDL) and Cluster Delay Line (CDL) propagation models. Future directions for the project include simulating present-day 5G New Radio (NR) end-to-end communication links to measure a quantifiable performance index, PDSCH throughput, and simulate ray tracing propagation models to compare with TDL and CDL models.

1 Introduction

The rapid development of cutting-edge technology over the past few decades has increased demands for higher data rates, enhanced reliability, and massive connectivity within the telecommunications landscape. Long-Term Evolution (LTE) within the fourth-generation (4G) has played a pivotal role in meeting demands by introducing concepts such as Orthogonal Frequency-Division Multiplexing (OFDM), scalable bandwidths, and support for Multi-Input Multi-Output (MIMO) antenna systems.

Building on the success of LTE, the fifth-generation (5G) networks have been designed to address a broader spectrum of use cases. This includes enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and massive Machine-Type Communication (mMTC). To achieve this, 5G introduced key concepts such as millimeter-wave communication, network slicing, and massive MIMO. Massive MIMO is particularly significant in enhancing spectral efficiency, system capacity, and energy efficiency by utilising large antenna arrays and advanced beamforming techniques.

As telecommunication systems now transition from 5G to 6G networks, new challenges to improve data rates, reliability, and connectivity emerges. The role of MIMO antenna systems is expected to expand further, evolving from traditional to adaptive configurations based on different channel models. This report aims to provide a literature review of these systems, exploring foundational concepts and current development, and highlighting key challenges. For this project, I intend to provide deeper insights within current MIMO systems by optimising antenna configurations to different channel models as well as different channel conditions.

2 Literature Review

The development of 5G and 6G networks is driven by the collaborative efforts of global standardisation bodies, research institutions, and industry leaders known as the 3rd Generation Partnership Project (3GPP). 3GPP releases defines technical standards and lays a foundation for 5G and beyond, introducing key concepts like massive MIMO as discussed before. Alongside 3GPP, major telecommunication companies - such as Qualcomm, Ericsson, Nokia, Huawei, Samsung and Apple - cooperate actively by contributing technical solutions and sharing research findings. On the other hand, operators like Vodafone, O2, Three, and EE in the UK contribute to real-world deployments and feedback for standardisation. This relationship between major companies and 3GPP offers a neutral forum for collaboration, fostering innovation and driving a global, unified ecosystem for telecommunication.

In this literature review, we will primarily be focusing on books, websites, and 3GPP specifications rather than exclusively relying on academic papers as for the advantage of understanding the commercial development of 5G and 6G. Below is a short summary of the physical layer side of 5G networks.

2.1 Physical Layer Overview

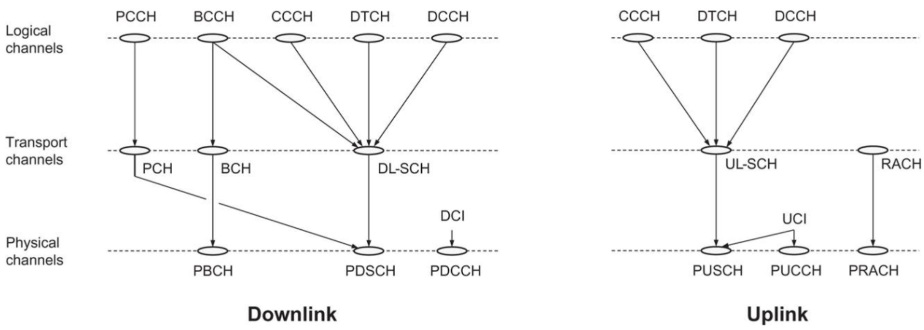


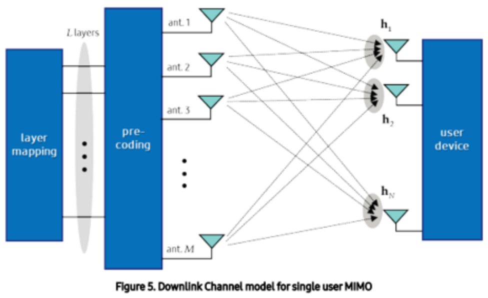
Figure 1: Mapping between logical, transport, and physical channels in 5G NR, illustrating the downlink and uplink flows from higher-layer logical channels to transport and physical layer channels. (Dahlman et al., 2018, Fig 6.11)

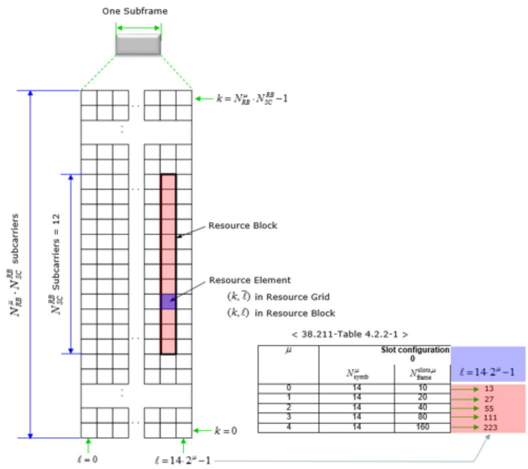
Above, shows the physical layer aspect of 5G New Radio (NR). It manages the transmission and reception of data across the air interface using a range of physical channels and signals. The physical layer is divided into downlink (DL) and uplink (UL) transmissions. The downlink refers to information being transmitted from the Base Station and received from the User Equipment (UE) whereas the uplink refers to vice versa. The downlink employs signals such as synchronisation signals for initial access and broadcast channels for system information dissemination, whilst uplink employs channels such as the Random Access Channel (PRACH) for connection establishment.

Key physical channels include the Physical Downlink Shared Channel (PDSCH), Physical Downlink Control Channel (PDCCH), Physical Uplink Shared Channel (PUSCH), and Physical Uplink Control Channel (PUCCH). These channels facilitate the transmission of data and control information, mapped from transport and logical channels.

2.2 Multi-Input Multi-Output (MIMO)

MIMO, or Multiple-Input Multiple-Output, uses multiple antennae at both the transmitter and receiver to send and receive multiple data streams simultaneously.Figures 2(a) shows how Single User (SU)-MIMO uses multiple antennae at the base station to transmit parallel data streams to a single user. The process starts with layer mapping, where the user's data, organized into layers, is prepared for transmission. These layers are then passed through precoding, which applies weights to optimise the transmission for the channel conditions, ensuring the data streams can be separated effectively at the receiver. Finally, the precoded data is transmitted via multiple antennae, and the user device receives it, using spatial separation to reconstruct the original data streams.





(a) Downlink channel model for single-user MIMO, showing layer mapping, precoding, and the transmission from multiple antennae to a user device via distinct channel paths

(b) 5G NR resource grid illustrating resource elements, blocks, and slot configurations for different numerologies as defined in (3GPP, 2020 Table 4.2-2-1)

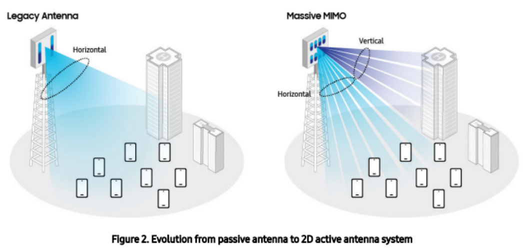
Figure 2: Figures from (Samsung, 2020) and (ShareTechnote, n.d.) respectively

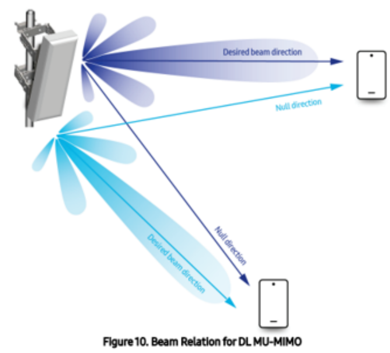
Figure 2(b) shows the resource grid, which represents the time-frequency resources available for transmission in an OFDM system. Each cell in the grid corresponds to a resource element, defined by one subcarrier in frequency and one OFDM symbol in time. Resource grids play a crucial role in organizing and allocating resources for each transmission. In SU-MIMO, data from different layers is mapped to these resource elements, enabling efficient parallel transmission over the same time and frequency while leveraging the spatial domain.

2.3 Massive MIMO and Beamforming

Figure 3(a) below highlights the transition from legacy antennae to Massive MIMO systems and the significance of beamforming in modern wireless networks. On the left, legacy antennae broadcast signals omnidirectionally, leading to inefficiencies and interference. In contrast, Massive MIMO employs a 2D active antenna array to transmit highly directional beams, both horizontally and vertically, significantly improving coverage and capacity.

Figure 3(b) illustrates how beamforming enables targeted signal transmission, directing beams toward desired users while nullifying interference for others. This is especially critical in Multi-User MIMO (MU-MIMO), where multiple users are served simultaneously with precise beams, enhancing spectral efficiency and network performance.



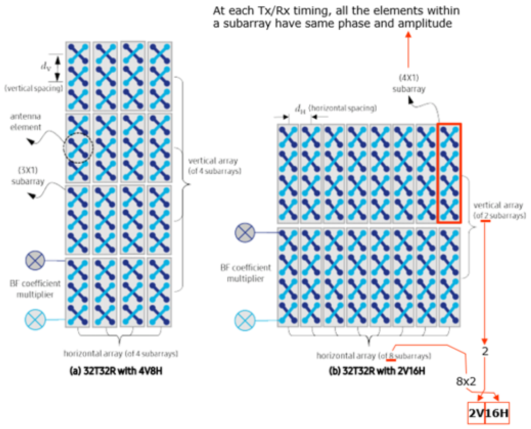


(a) Evolution from legacy passive antenna systems with horizontal beam coverage to 2D active antenna systems using massive MIMO

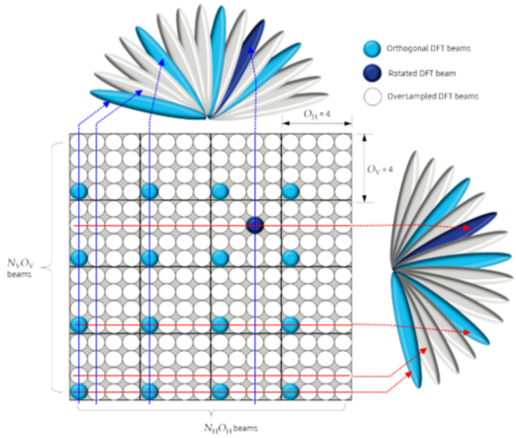
(b) Beam relation for downlink multi-user MIMO (DL MU-MIMO)

Figure 3: Figures from (Samsung, 2020)

2.4 Beamforming Process



(a) 32T32R antenna configurations illustrating 4V8H and 2V16H subarray structures



(b) Visualization of orthogonal, rotated, and oversampled DFT beams in a beamforming grid

Figure 4: Figures from (Samsung, 2020)

Figure 4(a) illustrates the structures of the 32T32R antenna array with 4V8H and 2V16H subarrays. Each element in the array transmits signals with specific phases and amplitudes, controlled by beamforming coefficients. The array is organised into subarrays—each with elements working together to form beams in both the horizontal and vertical planes.

Figure 4(b) shows how these subarrays generate Discrete Fourier Transform (DFT)-based beams. Orthogonal beams, represented in light blue, are used to cover the spatial domain efficiently. Oversampling and rotating these beams, as shown in darker blue, allow for finer control over beam directionality, ensuring maximum coverage and interference suppression.

2.5 Channel Modelling

Channel Modelling in 5G NR focuses on two key approaches: Tapped Delay Lines (TDL) and Clustered Delay Lines (CDL), which are essential for simulating realistic wireless propagation environments. TDL models use discrete delay taps to represent multipath components. Each tap corresponds to a specific delay and power level, simulating basic fading scenarios like Rayleigh or Rician fading. TDL is simple and suitable for evaluating basic channel effects but lacks spatial and angular precision. In contrast, CDL models group multipath components into clusters, offering detailed spatial and angular modeling. CDL incorporates advanced propagation characteristics like angular spread, Doppler shifts, and spatial correlation, making it ideal for modern MIMO and beamforming systems.

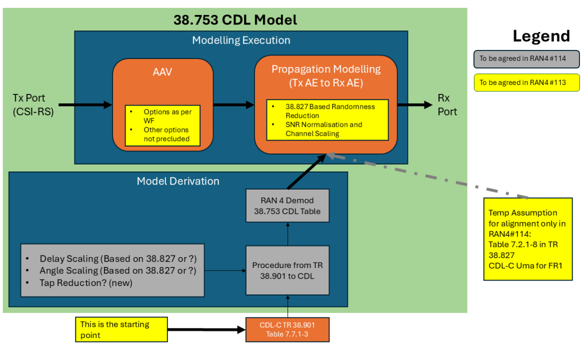


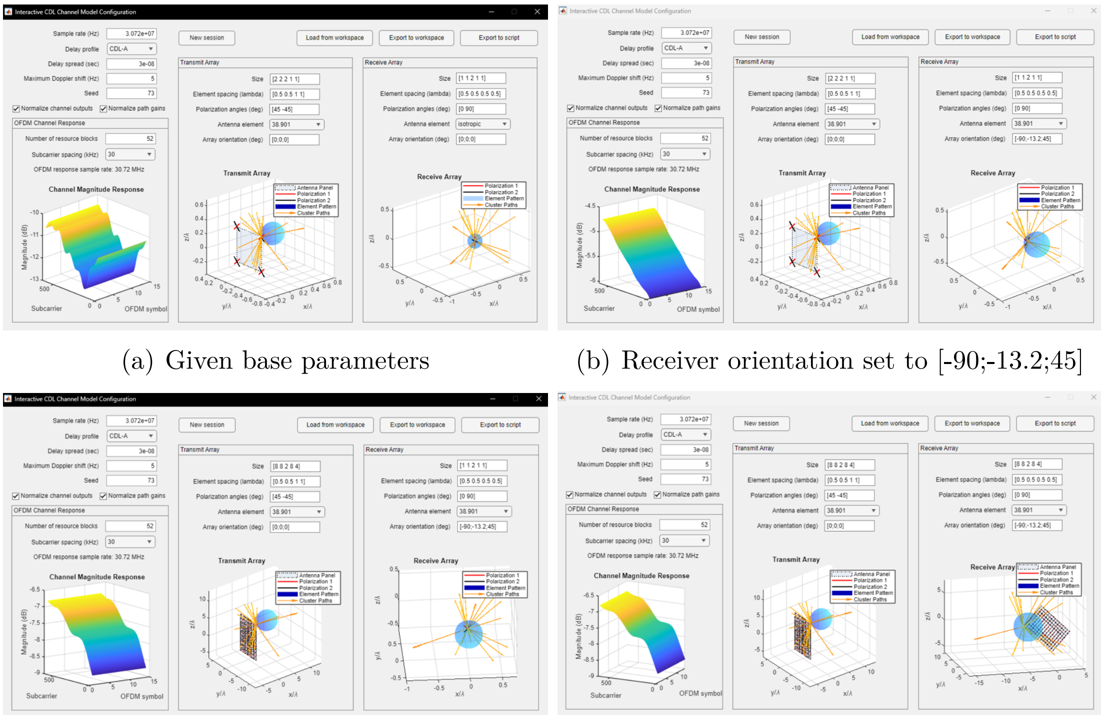
Figure 5: System Diagram of CDL model (3GPP, 2025)

Figure 5 outlines the 38.753 CDL model. It starts with the transmission of reference signals (e.g., CSI-RS) through the modelling execution, which includes propagation effects like randomness reduction, SNR normalisation, and channel scaling. These elements ensure realistic channel characteristics for testing advanced 5G features like massive MIMO.

3 Methodology

For this project, I aim to simulate these propagation models for both TDL and CDL; and measure a performance index based on spectral efficiency, coverage, and magnitude to provide deeper insights into TDL and CDL model behaviour. Then, I aim to vary antennae array configurations and parameters to find an optimisation scheme based for different spacial models (E.g. Rural, low traffic and Urban, high traffic areas). MathWorks 5G Toolbox has various, useful functions and prebuilt to simulate both TDL and CDL models.

3.1 MathWorks 5G Toolbox



(a) Given base parameters

(b) Receiver orientation set to [-90;-13.2;45]

(c) Transmitting array size set to [8;8;2;8;4]

(d) Receiving array size set to [8;8;2;8;4]

Figure 6: CDL channel interactive configuration app (MathWorks, n.d.[a]) with various parameters to visualise channel magnitude response

Figure 6 above visualises the channel magnitude response for a CDL channel for different parameters for antenna configurations. By using the standard parameters agreed within the 3GPP RAN4 R4-2419403 way forward document, we observe that for Figure 6(b), the shape of the channel response is more symmetrical than of Figure 6(a) and has a larger magnitude. This allows for a more stable and predictable framework for analysing and optimising wireless communication systems. Though, ideally a flat high magnitude response for all frequencies is desired. Figure 6(c) and (d) visualises the effect of adding more antenna sub array elements to the transmitter and receiving end. This causes the channel response to become imperfect due to several practical and physical factors.

3.2 Risk Assessment

As there is no need to any equipment other than a computer for the methodology above, there is minimal risk involved when working on this project. As the project progress, High Performance Computing (HPC) may need to be accessed to simulate more computationally expensive channel models such as Ray Tracing.

4 Project Direction

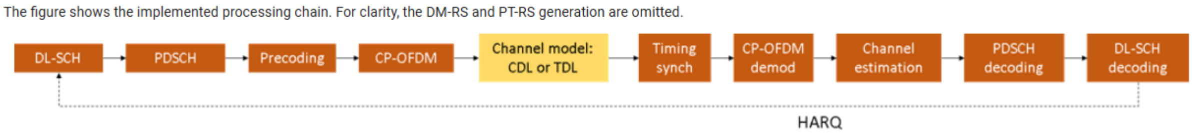


Figure 7: (MathWorks, n.d.[b])

Although this prebuilt interactive configuration app for a CDL channel is great for visualising the channel magnitude response with variance to transmitter and receiver antenna parameters, a quantifiable result to measure performance is preferred. Figure 7 above shows the processing chain to measure the physical downlink shared channel (PDSCH) throughput of a 5G (NR) end-to-end link (MathWorks, n.d.[b]). The way forward for this project would be to build an end-to-end simulator using standardised parameters set by 3GPP, for both TDL and CDL, to produce a performance graph of SNR in against PDSCH throughput percentage. Then, after ensuring performance requirements matches accordingly to the User Interface (UE) performance requirements in (3GPP, 2021) to up to +2.5dB, we can investigate the optimisation of antenna configurations. Further into this project, a ray tracing propagation model, like Sionna RT by NVIDIA, could also be investigated.

5 Appendices

References

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