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Optimisation of Spectrum Utilisation for Backhaul Networks in the 7–8 GHz Band

Modelling and Replanning of Microwave Fixed Services in Canada

Master's thesis in Information and Communication Technology

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Abstract

In the electromagnetic spectrum, the 7–8 GHz frequency band has long been used for wireless communication due to the favourably low rain attenuation. Today, in Canada and many other countries, incumbent use of this band includes microwave backhaul links, also referred to as Fixed Services (FS). However, the band's future is under discussion, with FS preparing for a possible increase in network capacity and other services investigating whether the band can be shared. This thesis investigated whether the current FS network could be replanned to optimise spectrum utilisation, thereby providing a baseline for discussions on opportunities to increase microwave link capacity and utilisation in the band.

Each FS link in Toronto, Montreal, and Vancouver was modelled using public Canadian data from Innovation, Science and Economic Development of Canada (ISED). While preserving link properties, a greedy heuristic algorithm was applied to optimise spectrum utilisation.

The results of the optimisation algorithm show that fixed services can use a smaller interval of carrier frequencies both within channel allocation subplans and across the frequency band. In Toronto, Montreal and Vancouver, all FS links could be concentrated within a 550 MHz interval, leaving approximately 600 MHz of continuous spectrum available. For future capacity increase, the results indicate that additional capacity may be possible within the 550 MHz interval, although a comprehensive study is left for future work.

In Vancouver, the spectral footprint could only be reduced for the mainland urban area, mainly due to multi-link hops limiting further compression. Overall, the results are promising and indicate that spectrum utilisation in the Canadian 7–8 GHz FS band can be improved through replanning, while also highlighting topology-dependent constraints that should be considered in future studies.

Keywords: Fixed Services, Microwave Backhaul, 7–8 GHz, spectrum optimisation, spectrum utilisation, spectrum sharing, replanning.

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Finally, I would like to thank my family for always supporting me and my friends for making my time at Chalmers unforgettable; *Avancez, ensemble.*

Ella Dahlström, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ATPC	Automatic Transmit Power Control
EESS	Earth Exploration-Satellite Service
ETSI	European Telecommunications Standard Institute
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FS	Fixed Service
FSS	Fixed-Satellite Service
IMT	International Mobile Telecommunications
ISED	Innovation, Science and Economic Development of Canada
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radiocommunication Sector
LNA	Low Noise Amplifier
LOS	Line-of-sight
NLOS	Non-line-of-sight
NSMA	National Spectrum Management Association
NTIA	National Telecommunications and Information Administration
P2P	Point-to-point microwave backhaul link
PSD	Power Spectral Density
QoS	Quality of Service
RPE	Radiation Pattern Envelope
Rx	Receiver
SNR	Signal-to-Noise Ratio
Tx	Transmitter
WRC	World Radiocommunication Conference
XPD	Cross-polar Discrimination
XPIC	Cross-polar Interference Cancellation

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1
Introduction

The 7–8 GHz spectrum for wireless communications is considered one of the “golden frequency bands” due to its favourable combination of coverage and propagation properties. Compared to higher frequencies, the band is less affected by rain-induced atmospheric attenuation, which is especially advantageous for long-distance transmission.

For these reasons, the band is already widely used by incumbent systems, with Fixed Service (FS) links among the primary services. Fixed Service microwave point-to-point backhaul links provide critical wireless communication infrastructure, serving both as cellular backhaul and for privately owned network nodes. Long-haul links are typically a cheaper, more rapidly deployed alternative to optical fibre [1].

The services supported by FS via cellular backhaul are typically International Mobile Telecommunications (IMT), including 4G, 5G, and potentially 6G after 2030 [2]. Given the properties of the 7–8 GHz band, it is also currently being considered for IMT identification, with ongoing feasibility studies in preparation for the World Radiocommunication Conference (WRC) in 2027 [3].

In the United States of America, the National Telecommunications and Information Administration (NTIA) is investigating the possibility of replanning the federal incumbents to clear parts of the band for 6G [4], [5]. With this large initiative, ITU-R is also investigating replanning of the lower band [6], [2], further highlighting the interest for spectrum in the 7–8 GHz band.

IMT is, however, not the only service seeking to utilise or increase its share of the band. For example, the band is also used by many primary satellite services, such as Fixed-Satellite Service (FSS), Earth Exploration-Satellite Service (EESS), and military satellite systems. As the space segment rapidly develops, new coexistence studies have started [7] to assess interference levels and investigate the feasibility of spectrum sharing between services.

Meanwhile, the capacity of the FS network is expected to increase [8] to sustain new data demands driven by the introduction of 6G. To serve as cellular backhaul, the FS would therefore require more deployed spectrum to support either more frequency channels per physical transmission hop or new link deployments.

It is important to note that the FS links currently operating in the band are protected and regulated. These links form critical infrastructure by providing connectivity for societies and critical services, and must therefore be protected from harmful interference caused by spectrum-sharing services or nearby links. This raises a complex question regarding the future use of the band, as FS may require additional spectrum at the same time as new services emerge, all competing for interference-free access to a limited spectral resource.

This spectrum is in high demand while it is inherently limited. Therefore, this thesis investigates the potential to optimise the spectrum utilisation for FS links, leveraging existing deployment data from the Canadian database.

1.1 Aim

This thesis aims to investigate the possibility of optimising the spectral utilisation of fixed services in the 7–8 GHz band through replanning of frequency channel allocations.

1.2 Limitations

Due to the fixed service networks being a critical infrastructure, the country-specific public databases vary with regional laws. Since the Canadian office of Ericsson had sourced sufficient public data for an analysis of Canada, the thesis is limited to Canada. Canada is, however, a country which actively works with spectrum optimisation [9], and can therefore be seen as an already leading baseline. Furthermore, the geographical difference of the studied cities, Toronto, Montreal and Vancouver, also covers different types of deployment strategies which may be found in other countries.

The thesis limits the analysis to three densely populated cities: Toronto, Montreal, and Vancouver. These urban areas and their surroundings have a higher link density, which leads to an increased risk of interference and, consequently, a more challenging optimisation problem.

1.3 Related Works

As discussed above, a significant number of studies are currently and have previously investigated coexistence and interference between services in the 7–8 GHz band. These studies mainly investigate technical and regulatory constraints, as well as solutions for spectrum sharing with the deployed FS network. However, these studies generally assume the FS network as static.

Investigating whether the FS incumbents could be replanned to optimise the spectrum utilisation has received little academic attention. One reason may be that the microwave backhaul network is a specialised domain, where access to realistic network modelling and practical constraints typically requires close collaboration with industry.

This gap motivates the aim of this thesis.

2
Theory

This chapter aims to explain some fundamental concepts and their interpretation for this thesis. The chapter is split into two parts: the theory of interference calculations, which is later used for replanning purposes by the optimisation algorithm, and then the theory behind licensing and frequency channel allocations, which backhaul licensing uses and must be adhered to when replanning a network.

2.1 Interference and link budgets

There are many contributing factors to interference at a receiver. This chapter aims to explain which factors have been included and how they have affected the magnitude of the calculated interference level between a victim receiver and an interfering transmitter.

2.1.1 The interference formula

The interference power I can be calculated with the logarithmic formula in equation 2.1.

$$I = P_{Tx} + G_{Tx}(\theta) - L_{PL} + G_{Rx}(\varphi) - L_{XPD} - L_{HW} \tag{2.1}$$

The interference power is thus the sum of the transmitting antenna gain $G_{Tx}(\theta)$ (dBi), the receiving antenna gain $G_{Rx}(\varphi)$ (dBi), the transmitting power P_{Tx} (dBm/MHz), and the losses which attenuate the interfering signal. These are the path loss L_{PL} (dB), the cross-polarisation loss for circular polarised interference L_{XPD} (dB) and feeder losses L_{HW} (dB).

The formula for interference is close to identical to the common link budget for an active link between an intended transmitter and receiver, where the received signal is the intended data link. In this case, as seen in equation 2.2, the received power is denoted P_{Rx}.

$$P_{Rx} = P_{Tx} + G_{Tx}(\theta) - L_{PL} + G_{Rx}(\varphi) - L_{XPD} - L_{HW} \tag{2.2}$$

The equations can be expanded to include a multitude of attenuating factors; however, due to the magnitude of smaller losses and modelling sensitivity, this thesis uses the formulation in 2.1. The included losses were mentioned above as the path loss L_{PL}, cross-polar discrimination of circular polarised signals L_{XPD}, and the loss between antenna and radio, often called feeder loss L_{HW}.

2.1.2 Antenna gains

Antenna gains, written as $G_{Tx}(\theta)$ and $G_{Rx}(\varphi)$ in formula 2.1, are the direction-dependent amplification of signal strength compared to the isotropic reference antenna and vary over the three-dimensional space around the antenna. The gain is visualised in antenna patterns, where the gain is represented as three-dimensional radiation patterns around the antenna. Antenna patterns are commonly described over the angular interval $[-180, 180]$ degrees around the boresight axis, where the gain is the strongest in the boresight direction, $[0°]$, then with decreasing gain as the angular offset from the boresight direction increases. If the angular offset lies outside of the mainlobe, the gain is defined by the antenna's sidelobes.

The transmit antenna gain $G_{Tx}(\theta)$, is defined as the gain in the angular direction θ. This emitting angle is θ, and is the angular offset from the transmitter's boresight to the direction of the receiver. Similarly, the received gain $G_{Rx}(\varphi)$, is the antenna gain at its incidence angle φ. The respective gains can be calculated by finding their respective offset angle, knowing the maximum gain in boresight and then using the antenna pattern to find the modelled gain at this angle.

Due to the highly directional dish antennas in the backhaul network, the three-dimensional antenna pattern can be approximated as circularly symmetric around the boresight axis [10], [11]. The offset angle to the boresight axis (called ϕ below, but could be either θ or φ) may therefore be described by two orthogonal components:

$$\phi \approx \sqrt{\Delta x^2 + \Delta y^2} \quad , \tag{2.3}$$

where the orthogonal components describe the angular offset to the boresight direction for azimuth (Δx) and elevation (Δy). Operating still under the circular symmetry assumption, the found offset angle can then be used to find the modelled antenna gain.

2.1.3 Path loss, Propagation Attenuation and Fade Margins

The path loss factor in Formula 2.1 accounts for free space path loss (FSPL) according to Friis Formula [12]:

$$L_{FSPL} = 20 \cdot \log_{10}(\frac{4\pi d}{\lambda}) \quad , \tag{2.4}$$

where d is the link distance and λ is the wavelength. The FSPL is thus scaled mainly by transmission distance and carrier frequency. As an example, the FSPL for a 1 km long backhaul link at 7 GHz is approximately 109.3 dB, while for 8 GHz it is 110.5 dB.

For deployment, a link budget is planned to ensure that the wireless link can support the required data for the required availability needs. This is known as quality and availability requirements, or quality-of-service (QoS). In practice, this means that when planning a new link, the link budget in Equation 2.2 is expanded to include atmospheric attenuation such as rain fading, polarisation coupling loss, multipath fading, and other attenuating factors [13]. To account for rare but performance-limiting propagation conditions, like weather storms, the link may be planned conservatively, meaning that the link uses more advanced hardware or a higher transmit power than the average situation requires. This is known as the fade margin.

However, for an interference study, the clear-sky assumption is viable as the interfering signals are the strongest with fewer attenuating factors. For this reason, the interference equation 2.1 uses the approximation $L_{PL} = L_{FSPL}$. This means that clutter assumptions and other modelling of the environment, such as topology, are not included, which creates a conservative assumption.

While discussing propagation factors, it is important to note that the Earth's curvature is included as an angular offset contribution for the antenna gain. However, attenuating losses due to Earth's curvature, such as tropospheric scatter, are not accounted for. Neither are diffraction losses caused by the topology or environment in Non-Line-of-Sight (NLOS) systems.

These factors may be affecting the intended active links in the case of a NLOS system, but also the possible interfering power. This further demonstrates that the approximation $L_{PL} = L_{FSPL}$ is a conservative assumption that is likely to overestimate real-life interference levels.

2.1.4 Cross-polar discrimination

A co-polarised signal is a signal with the same polarisation as the receiver, while a cross-polarised signal has an orthogonal polarisation compared to the receiver, i.e. a vertically polarised signal but a receiver for horizontally polarised signals. The polarisation is a link property selected during link planning, and the most common types in Canada are linear vertical and horizontal (Appendix C.1).

However, due to propagation effects like rain and multipath and hardware like the antennas, the signal may become depolarised. This means that even a radiated co-polarised signal may contain cross-polarised components at the receiver, which causes further polarisation losses.

Cross-polar discrimination (XPD) is the system's ability to discriminate between a co-polarised and a cross-polarised signal, and it is an essential parameter for interference studies [14]. The total isolation is enhanced in many ways, and the receiver algorithm cross-polarisation interference cancellation (XPIC) is one. This thesis, however, only includes the XPD of the hardware.

The XPD varies with antenna models and is included in antenna radiation patterns. Because of this, the XPD is a factor which is directly modelled into the antenna gains. However, if the radiated signal is cross-polarised to the receiver, a correct radiation pattern for the antenna model must be chosen to account for the correct XPD.

To provide insight, a general minimum value for cross-polar discrimination in high-performance systems can range from 27-40 dB, according to minimum requirements from regulatory bodies such as ETSI [14]. However, a real system's XPD can exceed these values.

If the XPD factor can be accounted for using the antenna gain, as described above, the cross-polarisation loss L_{XPD} in Equation 2.1 equals 0 dB. This factor is instead used for circular polarised signals.

When a linear polarised receiver is interfered with by a circular polarised signal, the XPD can be simplified as co-polarised antenna gain and a loss of $L_{XPD} = 3$ dB. This is caused by the circular polarisation consisting of a vertical and a horizontal component of equal amplitude, so the receiver will have co-polarised interference from half of the radiated circular polarised signal. This half-power behaviour is included by the $L_{XPD} = 3$ dB loss.

2.1.5 Feeder Loss

The feeder loss L_{HW} models losses caused by the transmission cables, known as feeders, between the antenna and the radio. The feeder loss is essential because FS may use split mounting, which refers to mounting radios and antennas at separate locations. Given a transmission cable, the antenna can be mounted outdoors at an elevated height, while the radio can be installed indoors and at ground level.

As deployment techniques and mounting heights vary within the FS network, the feeder losses can vary and be significant for high-mounted, split-mounted systems. The feeder loss is applied to each receiver to establish a common reference point before the Low Noise Amplifier (LNA) of the system.

2.1.6 The long-term interference threshold

For long-term FS-to-FS interference, an aggregate interference-to-noise criterion of $\frac{I}{N} = -10$ dB is used. This corresponds to an interference level 10 dB below the receiver noise floor, which is consistent with the long-term interference considerations given by ITU-R for fixed services [15].

The interference threshold I can this way be calculated as:

$$I_{Th} = N_{floor} - 10 = -174 + 3 + 10\log(BW) - 10 \tag{2.5}$$

Where N_{floor} is the noise floor, where -174 dBm/Hz is the thermal noise power spectral density at room temperature, 3 dB is the approximated noise figure, and BW is the receiver bandwidth in Hz.

2.1.7 Automatic Transmit Power Control, ATPC

While some backhaul systems operate at a fixed transmit power, others employ automatic transmit power control (ATPC). ATPC is a radio algorithm that enables the transmitter to adjust its transmit power in response to current channel conditions for a given modulation and data rate. In poor channel conditions, the transmitter increases its transmit power to compensate for channel fading, whereas it may operate at a lower transmit power in clear-sky channel conditions. This may extend hardware lifetime and reduce energy consumption and interference with nearby receivers.

Additionally, ATPC is often used in modern systems in combination with adaptive modulation. Because of this, both the transmit power and the data rate may adapt from channel conditons. However, as only ATPC contributes to the transmit power

P_{Tx} and therefore the interference levels, only this is included in an interference study like this.

When deploying a link using ATPC, the link planning becomes slightly different since the maximum transmit power will rarely be used. However, in the ISED database, the use of ATPC is not noted. Additionally, the source data only contains the maximum allowed transmit power. From the source data alone, it can not be determined if a link utilises ATPC or fixed output power.

2.2 Frequency channels and Channel allocation plans in Canada

In wireless networks, a communication link must operate on one of the possible frequency channels which the regulatory service assigns licenses for. These licenses define the carrier, or centre, frequency (f_c) of the link and the maximum bandwidth the operator can use. On the regulatory side, these channel allocation plans define alternatives for which licenses might be granted and accompanying rules. The rules are defined by each regional regulatory service, but harmonisation is attempted over continents and internationally.

For a general frequency band for fixed services, the spectrum is normally split into two halves, the low and the high side. This is because the links are frequency division duplexed (FDD) and must then have one lower frequency for one direction of transmission, and a high frequency for transmission in the reverse direction, unless the link is unidirectional. Additionally, if a hop uses both a low and high channel (FDD), these will always differ by the fixed duplex spacing Δ_{duplex}. The difference makes the receiver less saturated by the transmitter in the same location. If the low channel $A1$ exists in the low band, then the high channel will always exist on the channel $A1'$, whose carrier frequency will always be:

$$f_{c,A1'} = f_{c,A1} + \Delta_{duplex} \tag{2.6}$$

In Canada, the 7–8 GHz band is split into three sub-bands with each an accompanying allocation plan [16], [17]. In this thesis, these are called subplan 1 (SP1) for 7125–7425 MHz, subplan 2 (SP2) for 7425–7725 MHz and the Upper band (UB) for 7725–8275 MHz. The subplans contain different licensing prioritizations, channel options, as well as different duplex spacing.

For subplan 1, only channels of the bandwidths 30, 20, 10, 7.5, 5 and 2.5 MHz may be assigned. The band allocates channels for the low half on 7125–7250 MHz and the high side on 7300–7425 MHz. This leaves a 50 MHz guardband around the midband frequency f_m with no channels. This subplan uses a duplex spacing of Δ_{duplex} = 175 MHz. The channels can be plotted for a better overview. In the following graph, the channels are plotted over the given subplan interval, displaced on the y-axis to show overlap capability. The circles define the carrier frequency of each channel, and the surrounding blocks the bandwidth it occupies in the spectrum.

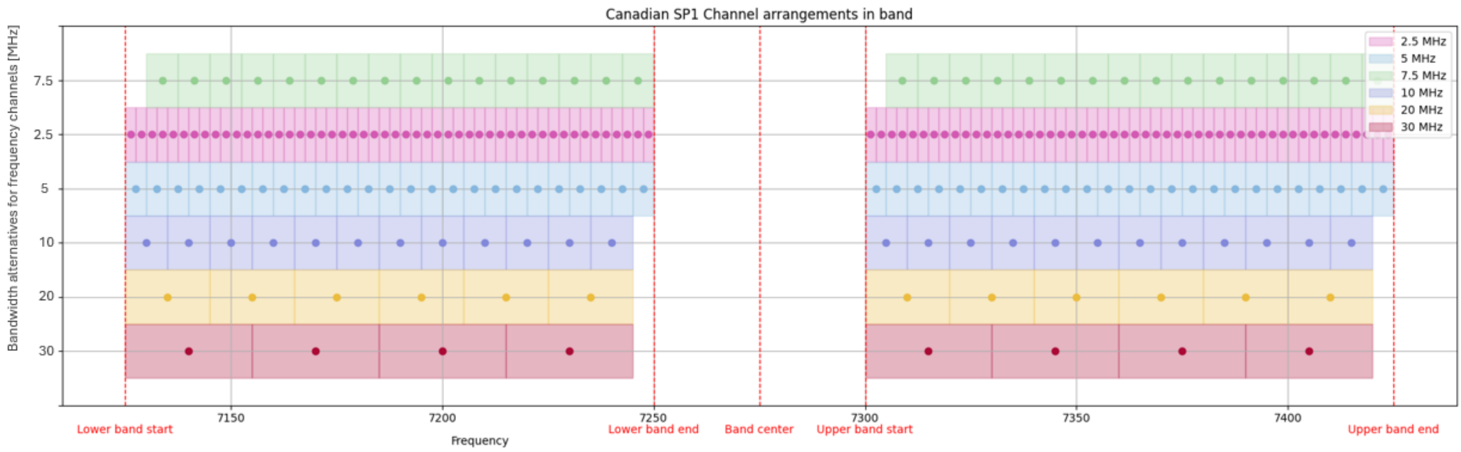

Figure 2.1: Channel arrangements in subplan 1. Each y-axis level represents one type of bandwidth within the spectrum plan, x-axis shows the spectrum each channel occupies.

As seen in Figure 2.1, a 30 MHz channel may overlap with up to three 10 MHz channels, and even more of the narrower channels. This means a single 30 MHz channel can be interfered with by all smaller channels covering this interval. This overlap and what it means for interference is further explained in the next section, where co-channel interference is explained.

For subplan 2, which occupies the band 7425–7725 MHz, the same channel bandwidths may be used as in SP1. In this band, there is no guard band around the midband, and the duplex spacing is $\Delta_{duplex} = 150$ MHz. An overview is seen Figure 2.2.

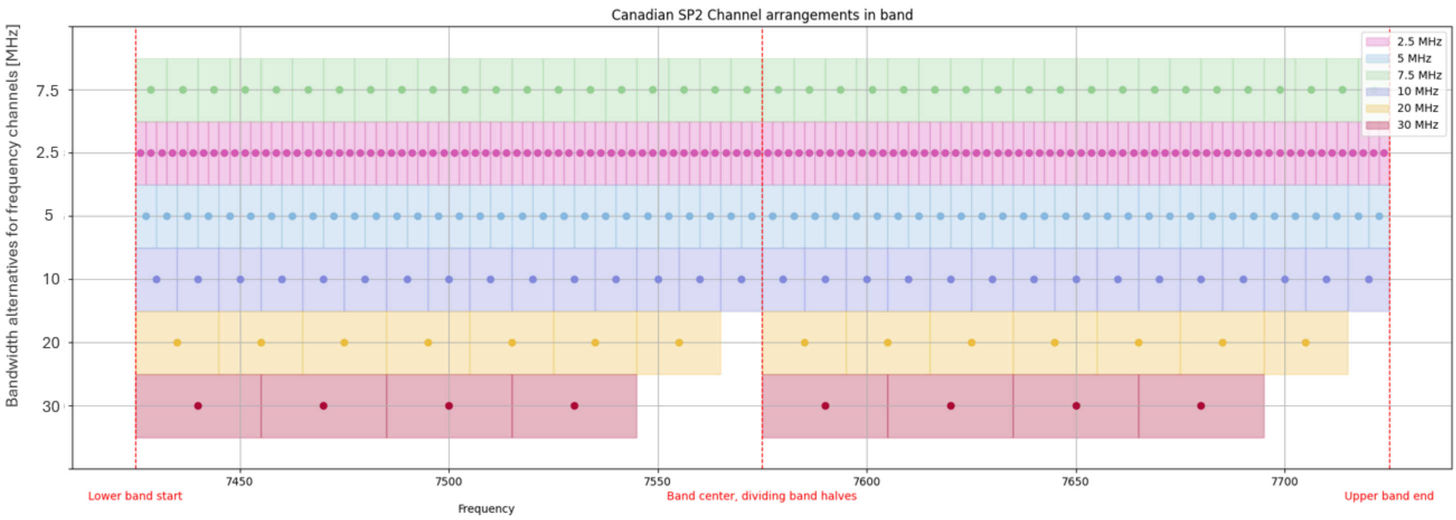

Figure 2.2: Channel arrangements in subplan 2. Each y-axis level represents one type of bandwidth within the spectrum plan, x-axis shows the spectrum each channel occupies.

For the upper part of the spectrum, UB, with the interval 7725–8275 MHz, the allowed channel sizes change slightly. The allowed bandwidths are 30, 20, 10, 5, 2.5 and 1.25 MHz and the duplex spacing is $\Delta_{duplex} = 300$ MHz. The channel arrangements can be seen in Figure 2.3.

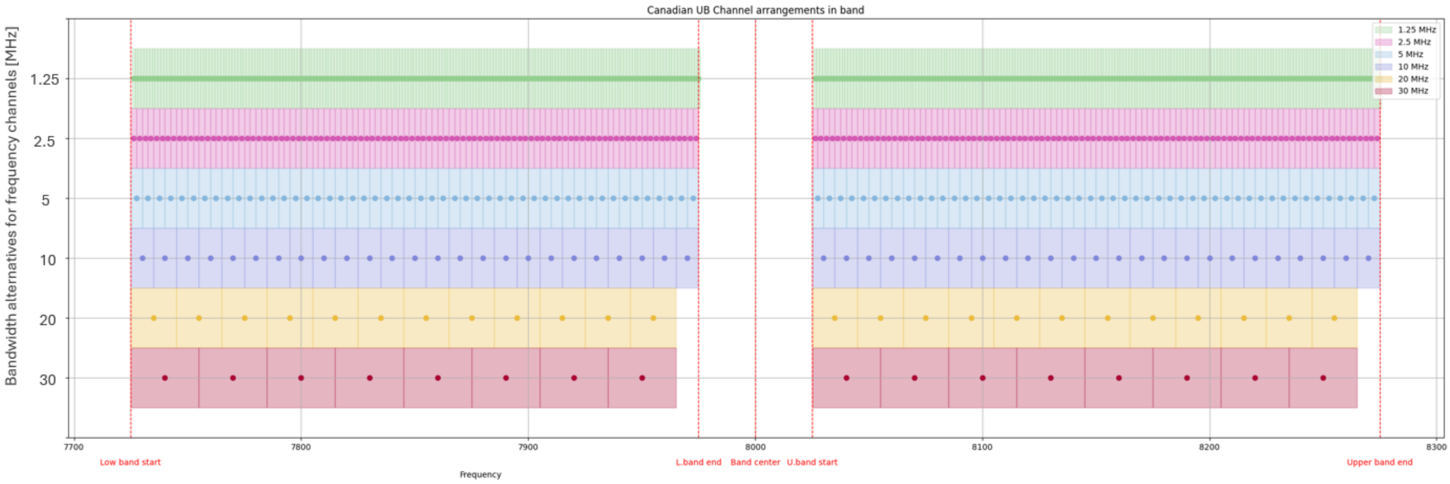

Figure 2.3: Channel arrangements in the upper band (UB, 7725-8275 MHz). Each y-axis level represents one type of bandwidth within the spectrum plan, x-axis shows the spectrum each channel occupies.

2.2.1 Co-Channel and Adjacent Channel Interference

As described briefly in the previous section, interference is only caused between links with overlapping channels as it is only these channels which carry power on a frequency of which the receiver is receiving on. This is what is called co-channel interference.

In reality, the transmitted signals' bandwidth in the channels is not perfectly aligned with the limits of the licensed channel. The Power Spectrum Density (PSD) defines the transmitter's power distribution around the carrier frequency. The PSD is regulated to comply with power spectral masks, which act as limits for the PSD to ensure resilient spectrum usage, but slight power may still appear outside of the defined channels [14]. Any interference caused by this type of leakage is called Adjacent Channel interference.

The transmitted power of a signal is thus changing over the bandwidth along the PSD curve. The better the radio, the flatter the PSD over the channel bandwidth while complying with maximum transmit power regulations and with as little as possible roll-off and leakage.

In this thesis, a flat mask assumption is made, which means that power is assumed constant over the bandwidth. The small contributions of adjacent channel interference are ignored. However, co-channel does not automatically mean that the channels fully overlap. As there are channels with different bandwidths, it may be only a part of the signal which is on the same frequency as the receiver. In such a case, only the share of the overlapping spectrum can be considered from the transmitted power, such that $P_{Tx} = P_{Tx.Max.} - BW_{Tx} + BW_{overlap}$ [dBm/MHz].

3
Methodology

This chapter aims to explain the methodology of how the source data was handled, how the optimisation algorithm operates and how the results could be achieved, as these were the three main steps in achieving the results.

3.1 Data sourcing and data cleaning

Public data from ISED, containing all fixed service links in Canada, was used for analysis in this project. The extensive data required both filtering and data cleaning to create a data format appropriate for processing. The next sections will explain each step where assumptions were made on the data.

However, before the assumptions and the data cleaning are expanded upon, the data columns that were available can be summarized as follows:

- License number
- Carrier frequency
- Bandwidth
- Antenna model
- Antenna constructor
- Longitude and latitude
- Site's elevation above sea level
- Mounting height of antenna
- Azimuth angle
- Elevation angle
- Polarisation
- Name of Owner
- Deployment date
- Maximum transmit power, P_{Tx}
- Feeder loss, L_{HW}
- Fade margin

3.1.1 Standby links

When studying the collected data, multiple entries had the exact same physical antenna and channel parameters, but with different license numbers. This means that all columns were identical apart from the license number. Manual verification of selected sites using Google Earth also confirmed that the hardware must be shared or spatially diversified horizontally. An assumption was thus made that these entries must be some type of standby links for protection purposes.

Standby links cover the same physical hop as the primary links but are only activated if the primary link fails [18]. It is sometimes referred to as 1+1 links. In a database, both links must be documented; however, in reality, only the primary link transmits until failure.

For this thesis, the assumption meant a data cleaning step which checks for "duplicates" of the same FDD link and reduces them to one, always-transmitting FDD link. If the results of this thesis were to be implemented, the service provider would apply the same protection standby solution again to regain the hop's true protection availability.

3.1.2 The ATPC assumption

After the previously described links had been reduced to a single data entry per physical antenna pair, an interference simulation was performed for the original network in each city. Although no changes to the transmitting antennas were made, the simulation indicated harmful interference in some cases.

To investigate these results, the simulator output was compared with Ericsson's MINI-LINK link-planning tool, which can model link-specific characteristics using more detailed information than is practical to include in the optimisation algorithm. This situation can occur when a radio tower has multiple receivers operating on the same channel but pointing in different directions. The situation is illustrated in Figure 3.1. Here, the black line indicates the intended hop between the radio towers, while the orange line indicates the interfering signal path. In this example, two links with small angular displacement appear to cause interference with each other unless ATPC is applied.

Figure 3.1: Example of how interference in the original network may appear. The red markers are receivers, the black line symbolises an active link, and an orange line symbolises the interfering path from an interfering transmitter.

Using the MINI-LINK tool, the interference could be confirmed as possibly real. But as the original network should not be operated with harmful interference, ATPC was investigated as a possible reason to why the links were deployed. It was confirmed by the MINI-LINK planning tool as the possible reason when interference dropped below the harmful threshold once ATPC was applied.

The link distances, maximum transmit powers, and fade margins for Canada were investigated and plotted to confirm that the data were reasonable. These plots can be seen in the appendix, B.1, A.1, D.1. As the links' maximum transmit powers resulted in unusually high signal-to-noise ratios (SNR) and the documented fade margins were consistent with ATPC deployment, ATPC was assumed to be active in the network. This helps explain interference in the original network and removes it when ATPC is applied to these interfering transmitters and their corresponding duplex return links. Note, however, that ATPC was only applied to the interfering links in the original network, which the MINI-LINK planning tool also confirmed.

For the interfering links in the original network, the maximum transmit power was edited like:

$$P_{Tx} = P_{Tx.Max.} - P_{FM} \quad [\text{dBm}] \tag{3.1}$$

For this reason, the results below contain two alternatives. Where ATPC has been applied to only the outliers from the original network, and where ATPC has been applied to every link in the network.

3.1.3 Antennas

The antenna gain for antenna 1 was found by calculating the relative angle from boresight to antenna 2 in both the horizontal and vertical planes. In the horizontal plane, this was done by finding the difference between the given azimuth angle and the bearing between the antenna coordinates. For the vertical angular shift, the antenna heights, elevation tilts, difference in site elevation above sea level, and slight curvature of the Earth were included, as the links may be long. The vertical and horizontal offset angles were then used to find the true incidence or emitting angle using Equation 2.3. This angle could then be mapped to the antenna pattern to determine the antenna gain.

Access to the measured antenna radiation pattern envelopes (RPE) for each antenna model provides a more realistic estimate of the antenna gain compared to a generic RPE from, e.g., ITU-R. This is partly because the sidelobe attenuation can differ greatly between a generic RPE for multiple antenna types and the measured envelopes.

In this thesis, access to the measured RPEs for each antenna model came from the National Spectrum Management Association (NSMA). With the off-boresight angle and the antenna RPE, each antenna gain could be determined.

Assuming the antenna model's RPE as a circularly symmetric antenna pattern, the offset angle was mapped to the antenna pattern's gain for this angle. For cross-polarised cases, the transmitter's gain was found by using the co-polar antenna pattern, and the receiver's gain would use the appropriate cross-polar pattern.

3.1.4 Reflectors

In Canada, there are some instances where the transmitting power is observed to be very small (A.1, A.4). In Toronto and Montreal, this is not the case, but in Vancouver, such types of entries appear. These entries all have antennas marked as "RF/Reflector" in the data set.

The geographical difference was investigated, and it was concluded that Vancouver has more mountains surrounding the city. A possible explanation is that they are used in non-line-of-sight systems (NLOS).

In NLOS systems, topology prevents a line-of-sight (LOS) solution and then uses a reflector (or repeater) to redirect the link over the obstacle. As mountains surround Vancouver, NLOS solutions with reflectors are probably needed.

The NSMA antenna pattern collection did not contain reflectors which could be used directly. Instead, these entries have been mapped to low-class (least directive) antennas with similar gain to the hardware-defined one in the NSMA database. The transmitted power was treated like a regular transmitter's power.

3.1.5 Area limitation and selection of antennas

Toronto, Montreal and Vancouver were picked for their population density. As Backhaul links have a median of over 20 km in Canada, as seen in Appendix B.1, B.2, B.3, B.4, a large land area was picked to cover the dense deployments of the backhaul network. Area selection took the central coordinate of each city and added a $\pm\Delta^{\circ}_{lat}$ in latitude and Δ°_{long} in longitude of the area selection around the coordinate. For the particular case of Vancouver, a smaller area was also selected to make an analysis for mainland links and exclude high-capacity coastal links from the optimisation algorithm.

Links with either a receiver, transmitter or both within the area are then considered in the optimisation algorithm. That means that even edge cases were included; however, as the selected area was big, the edge cases were far away from the urban cities.

The selected links within the area are optimised by using the algorithm described below. For each iteration, an interference calculation is run for each receiver, and each receiver considers all transmitters within a radius of d km of itself. This means that even transmitters outside of the selected area are considered, as interference levels are calculated for the receivers close to the area limit.

The inclusion radius variable d was chosen based on the maximum link distance in Canada as seen in Appendix B.1. A selection of d =200 km includes even the longest link in Canada and will include all relevant possible harmful transmitters.

Figure 3.2 shows an in-map example. Radio towers within the area are marked with a red marker, the physical hop with a coloured line, depending on the link's bandwidth and the area selection limit is marked in red. One receiver has been chosen for an interference calculation in this case, this receiver is highlighted by being the centre of blue arrows, which symbolise how the inclusion area spans around the receiver with radius $d = 200$ km. The area within the figure does not cover 200 km, as this would make the figure unreadable.

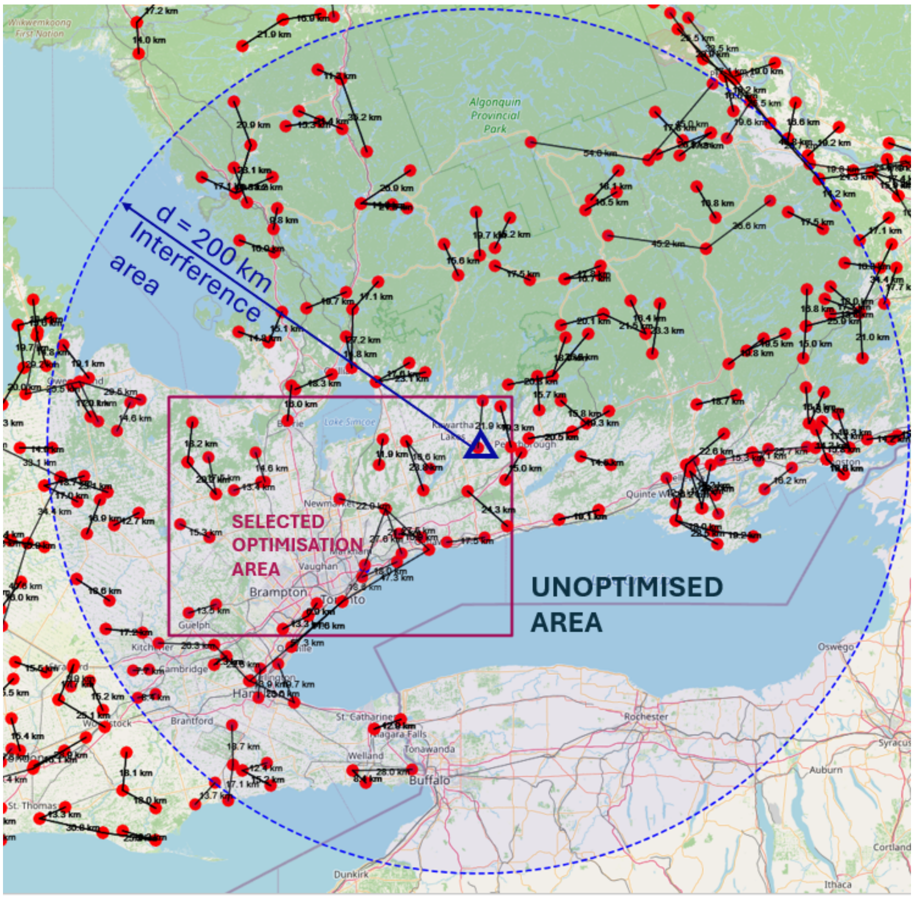

Figure 3.2: Example of how areas are defined. The currently analysed receiver is highlighted with a triangle. The area which contains all links to be optimised is within the pink rectangle, the unoptimised surrounding area where links remain untouched, and the inclusion area for interference calculation, which includes all transmitters within the radius d for interference calculation.

Furthermore, in Table 3.1, the coordinates used for each case are listed. As the results for Vancouver required further analysis, there is an additional case for a smaller area, which only covers the mainland city.

Table 3.1: Area parameters defining result area

City	Coordinates [°]	Δ_{lat}	Δ_{long}	d [km]
Toronto	44.00, -79.40	0.5	1	200
Montreal	45.50, -73.57	0.5	1	200
Vancouver (1)	49.21, -122.90	0.5	1	200
Vancouver (2)	49.21, -122.90	0.1	0.35	200

3.2 The Optimization Algorithm

The aim of this thesis was to investigate whether optimisation was possible and not to ensure the optimal network planning. However, at first, a comparison was made between algorithms using random seeding to escape local optima and a greedy heuristic algorithm. The result showed that the greedy algorithm gave the most concentrated spectrum utilisation results for these area selections, as randomness and seeding created a larger spectral footprint, which goes against the goal of optimising the spectrum utilisation. Thus, the greedy heuristic algorithm, as described below, was created:

Listing 3.1: Overview of the optimization algorithm

```
Input: Cleaned data set, ATPC applied and Ericsson Antenna
   models
Output: Optimised network

# Step one; Total link migration
For each receiver:
    migrate receiver, transmitter and duplexed link to
    the uppermost channel within the subband and band half.

#Step two; Run optimisation algorithm:

Run(interference_calculation.py)
    #Output: interference levels for each receiving antenna
    #within the area compared to all interferers
    #in an interference matrix.

Run(clustering_classification.py)
    #Output: Classifies clusters based on common victim
    #receivers and harmful interferers.
    #Finds N amount of clusters.
    # One cluster = All interfering transmitters sharing a
       victim receiver, and all victim receivers sharing an
       interferer.
    #Size defined by amount of victims.

amount of clusters = N

while amount of clusters > 0:
    Find biggest cluster

    For the biggest cluster:
        if amount of victims > amount of interferers:
            migrate all interfering transmitters, their
               receivers
            and the duplexed link to the subsequent
            lower frequency channel
        if amount of interferers > amount of victims:
```

```
            migrate all victim receivers, their transmitters
            and the duplexed link to the subsequent
            lower frequency channel.

    Run(interference_calculation.py)
        #Output: interference levels for each receiving
           antenna
        #within the area compared to all interferers
        #in an interference matrix.

    Run(clustering_classification.py)
        #Output: Classifies clusters based on common
        #victim receivers and harmful interferers.
        #Size defined by amount of victims.
    amount of clusters = N

#Step three: Concentration of spectrum
Run(concentration.py)
    #Output: Checks if any duplexed link pair
    #may be migrated to a higher frequency channel pair
    #without causing interference.
```

The optimisation algorithm is run as described in Listing 3.1. Motivated by the spectrum-replanning discussions in ITU-R and North America, as described in the introduction, the algorithm aims to concentrate spectrum usage as high in the band as possible. It therefore starts by replanning all links to the uppermost available channels within the considered subplan. The main algorithm relies on several supporting functions, among which the interference calculation tool is particularly important due to its complexity.

Listing 3.2: Overview of the interference calculation tool

```
#Input: Data frame containing all links
# in area and the surrounding area.
#Output: Interference levels for each
#receiver within the area, or affected by the optimisation.

For each receiver in data frame:
    Find all transmitters within radius d
    For each transmitter:
        if the intended transmitter:
            skip

        Check if interference is possible
        by license numbers, carrier frequency and bandwidth.
            if interference:
                store antenna parameters for Rx, Tx.

                calculate link distance
                calculate path loss
                calculate amount of overlapping channels:
                    scale transmit power accordingly
                    for interference calculation
                calculate emitting angle from Tx to Rx.
                calculate incidice angle for Rx, from Tx.
                if RX polarisation = Tx polarisation:
                    use co-polar antenna pattern
                    find gain using angle
                else:
                    use appropriate cross-polar antenna
                       pattern
                    find gain using angle

                if pol1 == linear and pol2 == circular:
                    set polarisation loss = 3 dB

                calculate interference threshold for
                receiver bandwidth

                calculate interference level

                if interference level > interference
                   threshold:
                    save as a direct interferer
                else:
                    add interference level to
                    aggregated interference column
```

The interference calculation tool is summarised in Listing 3.2. Several lines in the pseudocode represent longer underlying functions. For example, the initial interference check determines whether a physical channel overlap exists between a transmitter and receiver. The offset-angle calculations also include several geographical factors, as described in the theory chapter. In total, the tool finds or calculates the variables needed for Equation 2.1 and stores the resulting interference contribution in the receiver's aggregated interference level.

3.3 Result visualisation and summary

When the algorithm had run for each case, the results had to be plotted and calculated in order to be presentable. The plots will be visible in the next chapter, but the calculation of the measurable improvements is worth highlighting.

In the next chapter, two results will be presented: the share of deployed spectrum in the band and the maximum interval of unused spectrum. For the first metric, share of deployed spectrum calculates the sum of the bandwidths of unique and non-overlapping channels which are used in the spectrum. The second metric, the maximum interval of unused spectrum, is calculated by finding the biggest interval of undeployed spectrum and finding the interval's magnitude.

The metrics only take the total optimisation area into account when finding these two metrics.

4
Results

This chapter displays the acquired results after running the optimisation algorithm for the three cities. The histograms of the results will show the number of links per frequency channel. The frequency channels are centred over their respective carrier frequency f_c, and the bandwidth of the channel is symbolised by the width of the histogram block. For different channel widths, this means that some channels may overlap in the plot. However, the interference algorithm has ensured that the links are either placed geographically in a way which prevents harmful interference and/or may, in combination with other properties, like different polarisations, be possible to operate on overlapping frequencies.

As described in section 3.3, there are two key results: the share of uniquely deployed spectrum in the band and the maximum interval of continuous undeployed spectrum. The former is referred to as the utilisation share, the latter as the maximum contiguous free spectrum.

4.1 Spectrum of original network in Toronto

The link/channel distribution of the original network in Toronto is displayed in Figure 4.1. The network consists of six links in SP1, six links in SP2 and 66 links in UB.

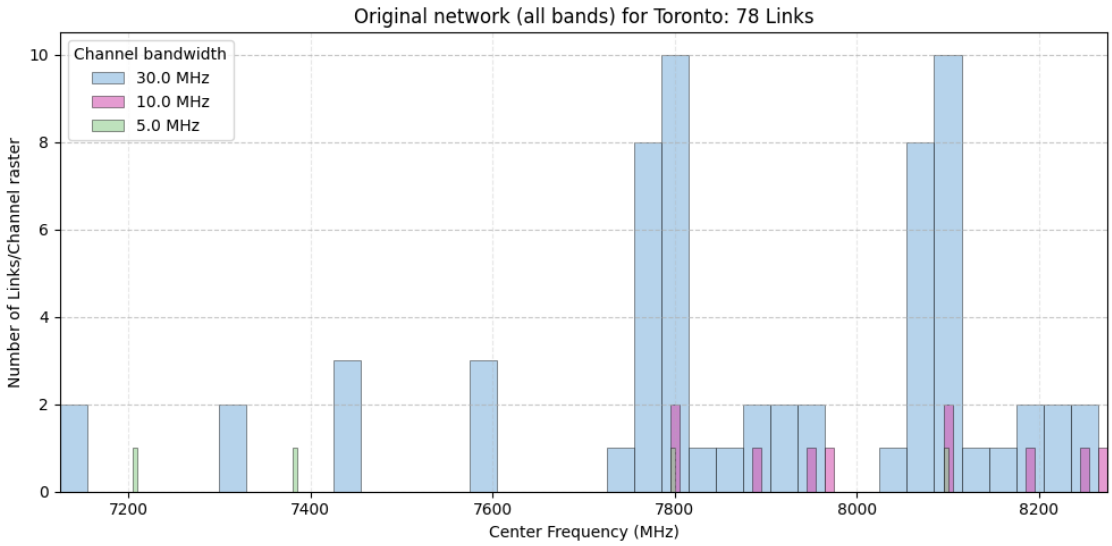

Figure 4.1: Histogram of the number of backhaul links per frequency channel in Toronto.

The results show a fully duplex-symmetric network with some unallocated spectrum gaps. The maximum contiguous free spectrum is 121.3 MHz. The utilisation share is 53.4%.

4.2 Optimisation of spectrum utilisation for Toronto

After the optimisation algorithm had run the data set for Toronto, the network could be concentrated to the upper band channels without causing interference. This decreased the utilisation share to 17.7%, and the maximum contiguous free spectrum increased to 600 MHz as subplan 1 and 2 are made redundant. There is also 150 MHz of unused spectrum within UB for each band half. A histogram showcasing this is seen in Figure 4.2.

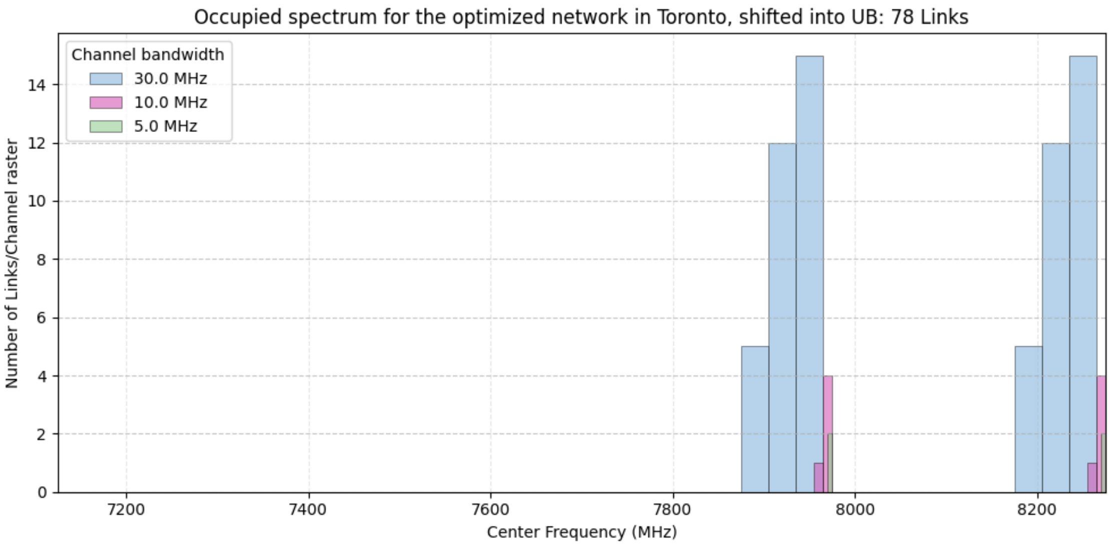

Figure 4.2: Histogram of the number of backhaul links per frequency channel in the optimised network, Toronto.

4.3 Spectrum of original network in Montreal

The link per channel distribution of the original network in Montreal is displayed below. The network consists of 68 links in SP1, 56 links in SP2 and 87 links in UB.

The original network, as seen in the Figure 4.3 is not fully symmetric within subplan 1 and 2. The upper band is, however symmetric. In total, the utilisation of the spectrum is 88%, and the maximum contiguous free spectrum is 30 MHz.

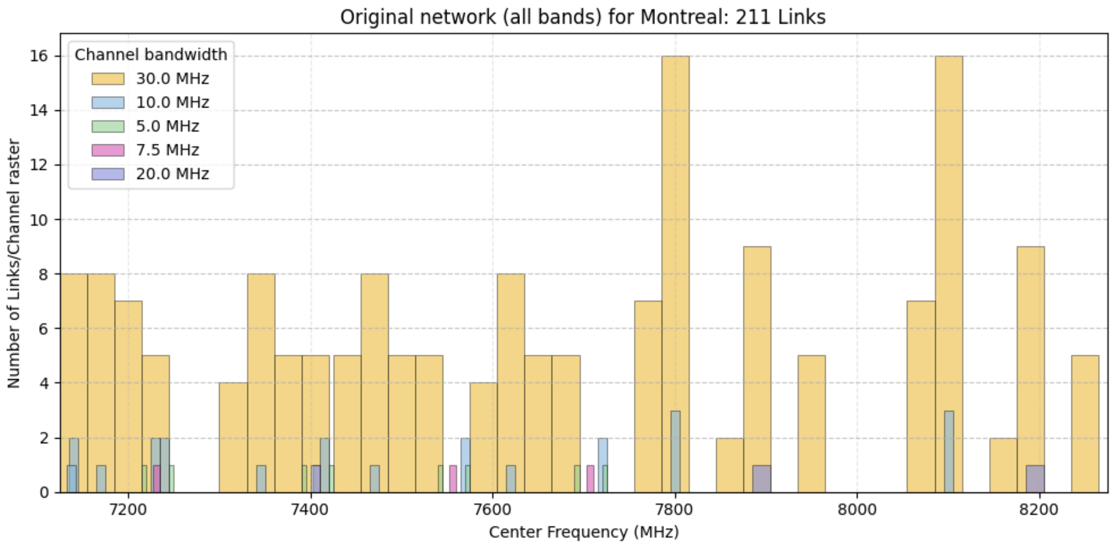

Figure 4.3: Histogram of the number of backhaul links per frequency channel in Montreal.

4.4 Optimisation of spectrum utilisation for Montreal

When optimising the network in Montreal, the slight asymmetry from the original network remains as the links are concentrated in the upper subplan, UB, as seen in Figure 4.4. The utilisation share is reduced to 37.8%, and, as for Toronto, the maximum contiguous free spectrum becomes 600 MHz since subplan 1 and subplan 2 can be made redundant. Despite this reduction, no free spectrum remains within UB, as all 30 MHz channels are required to avoid harmful aggregated interference.

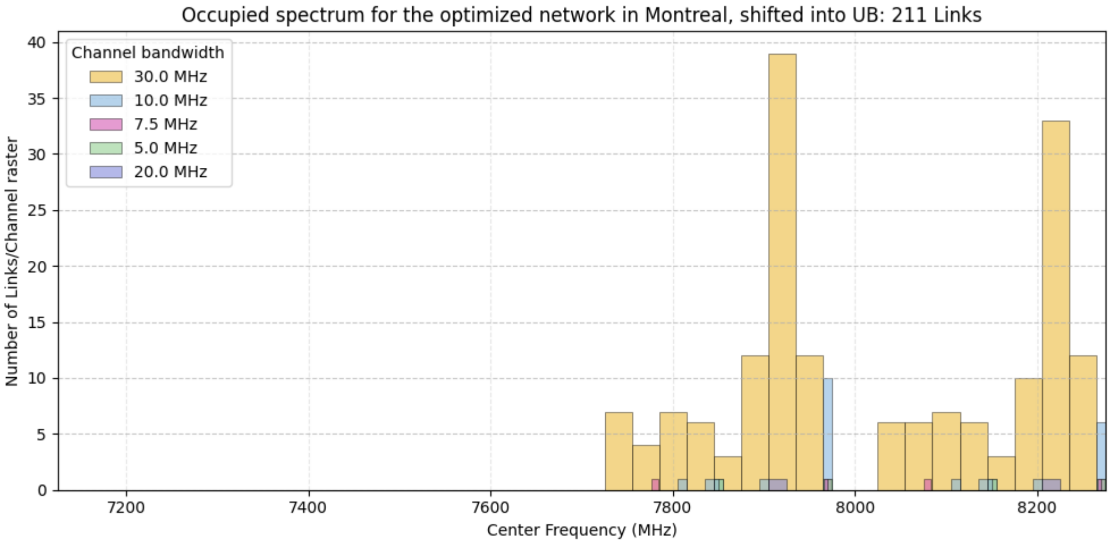

Figure 4.4: Histogram of the number of backhaul links per frequency channel in the optimised network, Montreal.

4.5 Spectrum of original network in Vancouver

Figure 4.5 shows the distribution of the Vancouver network when using the larger land area as described in Table 3.1.

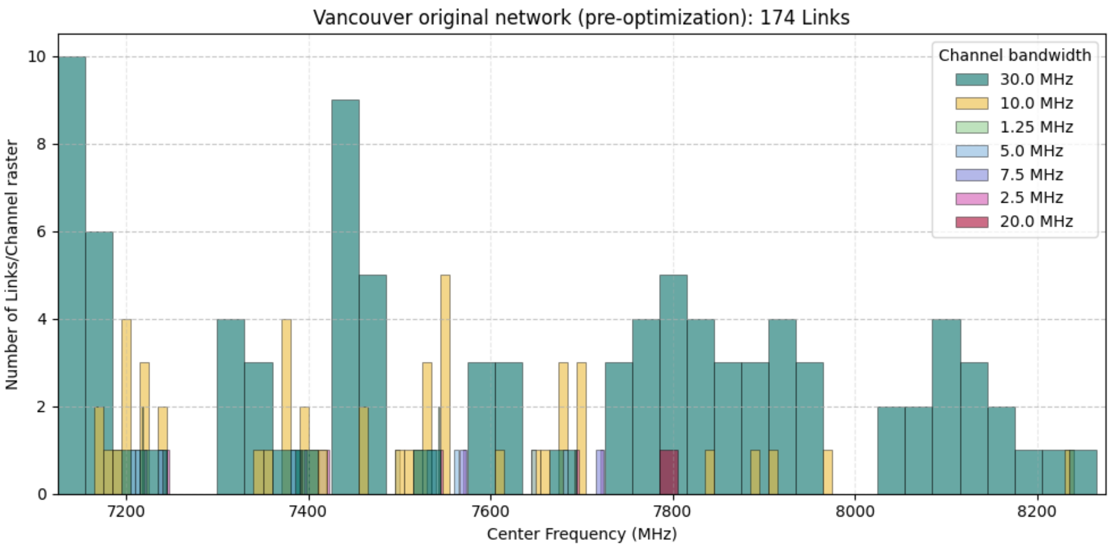

Figure 4.5: Histogram of the number of backhaul links per frequency channel in Vancouver.

This network is asymmetric within each subplan, and the optimisation did not converge to an optimised network due to the geographical distribution of the links. The corresponding map as seen in Figure 4.6 shows the full analysed area together with all backhaul links. Radio towers are marked with red markers, while the optimisation area is indicated by the red rectangle. Active physical hops are shown as black lines. The receiver count refers to the number of physical receiving antennas within the optimisation area, excluding duplexed antennas outside of the optimisation area, although the links are accounted included in the optimisation.

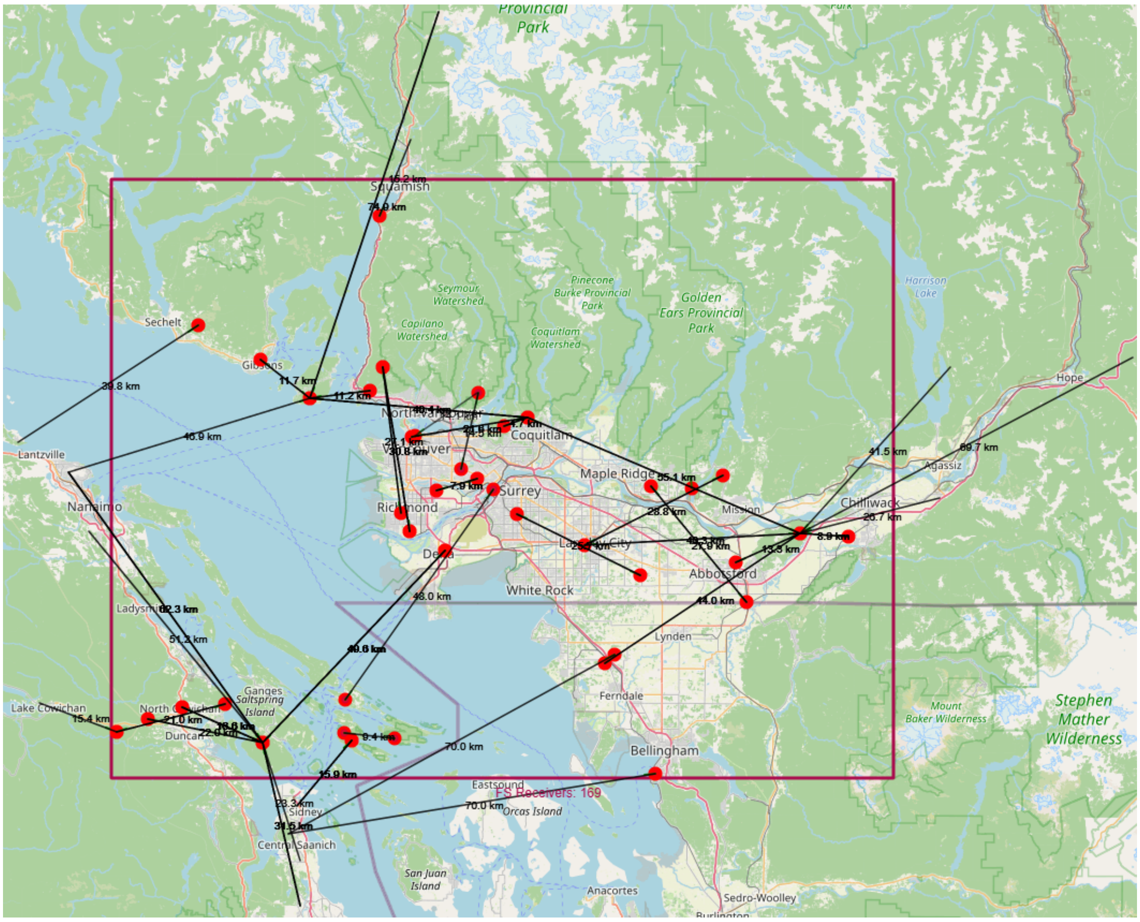

Figure 4.6: Map showcasing all physical FS hops within the selected area for Vancouver.

In Figure 4.6, there are many links providing data to islands close to Vancouver. These links are what prevent an optimisation, as they supply large capacity demands and consume most frequency channels in all subplans at each radio tower.

For further analysis, a smaller area was chosen for the urban part of mainland Vancouver, as in case two in Table 3.1. As described in the area selection chapter in the methodology, the links within this smaller area will consider the nearby, high-capacity links when optimised. The map of this area can be seen in Figure 4.7.

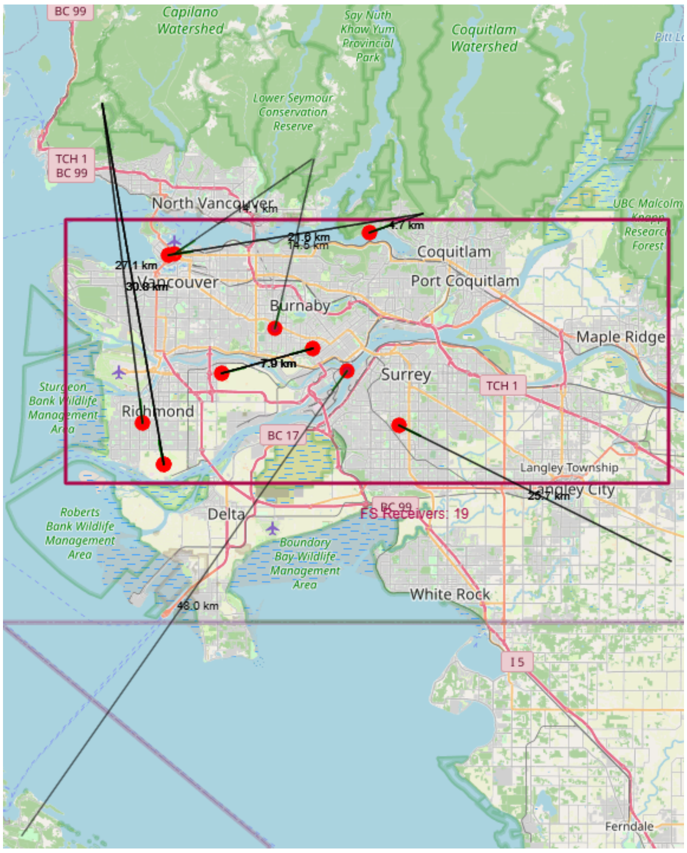

Figure 4.7: Map showcasing all physical FS hops within the smaller, selected area for Vancouver.

For this smaller area, the distribution of the original, smaller network is, as seen in Figure 4.8, still slightly asymmetric within the subplans. Subplan 1 has in total 14 links, subplan 2 has 10 links and the upper band UB has 10 links too. The utilisation share was 44.8%, and the maximum contiguous free spectrum was 130 MHz.

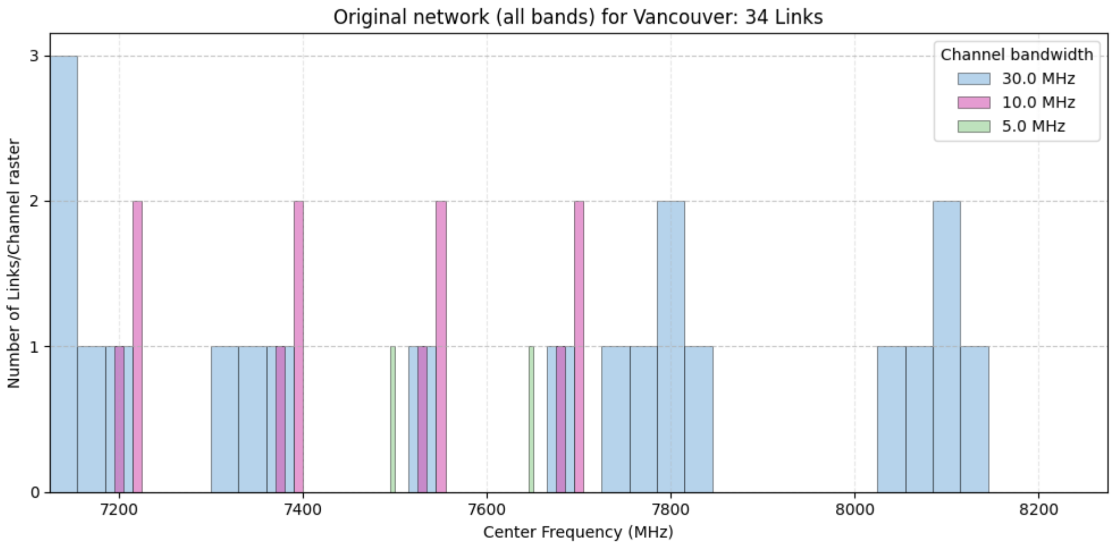

Figure 4.8: Histogram of the number of backhaul links per frequency channel in the original network, Vancouver, urban city.

4.6 Optimisation of spectrum utilisation for Vancouver

The smaller area for Vancouver could converge to an optimised solution even when the nearby high-capacity links were within the $d = 200$ km inclusion radius. The results are that the smaller network can be concentrated to the upper band UB, as seen in Figure 4.9, which increases the maximum continuous free spectrum to 600 MHz and decreases the utilisation share to 38%.

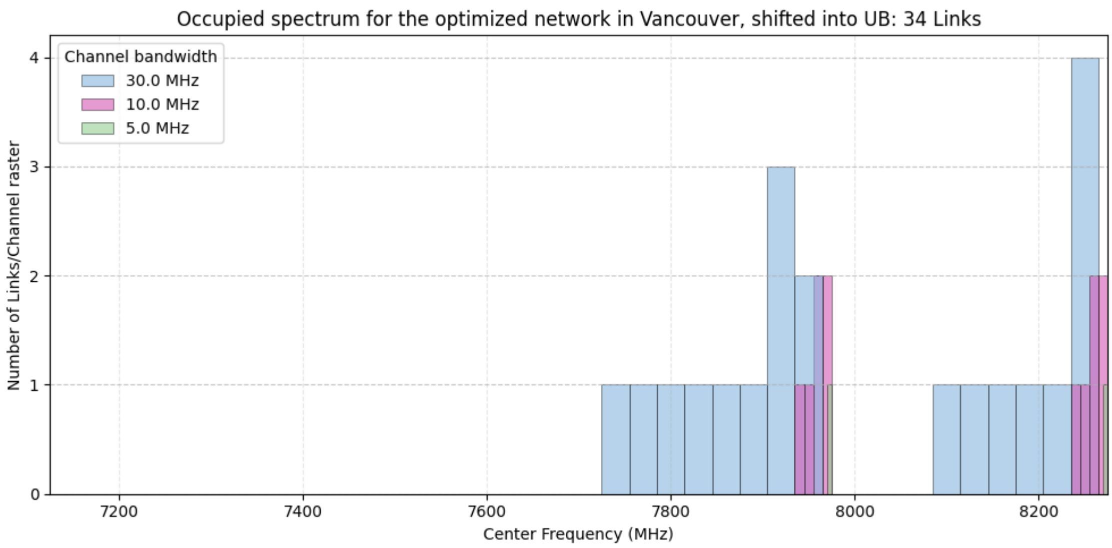

Figure 4.9: Histogram of the number of backhaul links per frequency channel in the optimised network, Vancouver, urban city.

5

Discussion, Conclusions, and Future Work

This chapter concludes the thesis by discussing the results, drawing final conclusions and highlighting future work in the field.

5.1 Discussion

The results show a promising trend. The fixed service links may be concentrated in the upper parts of the 7–8 GHz spectrum band in the urban case studies in Canada. For Toronto, Montreal and urban mainland Vancouver, the lower parts of the band are redundant from an interference optimisation perspective and release up to 600 MHz of valuable spectrum in the optimised area, without changing the surrounding area's deployments. For mainland cities like Toronto and Montreal, the FS link density is the highest around the urban areas, so one may hypothesise that rural parts of the network may also be optimisable.

In Vancouver, however, the special geography and network topology prevent total optimisation of the 7–8 GHz band. As Vancouver includes high-capacity long-haul links between the mainland and the islands, which use multiple frequency channels in every subplan, an optimisation would not be fully feasible. As shown, 600 MHz continuous spectrum may be found within the mainland's urban area, but cannot be generalised. If subplan 1 and 2 are to be fully redundant, these high-capacity links may require the use of new multiplexing techniques like backhaul multiple-input multiple-output (MIMO), building more geographically dispersed radio tower sites such that isolation comes from geography or migrating the links to other frequency bands altogether. For all of these solutions, however, comes a cost for upgrades.

Furthermore, the results show that the fixed service links' spectrum utilisation may be optimised for today's network, but what about the fixed service demand in the future? As mentioned in the introduction, fixed services are facing capacity growth, however, from the results in Figures 4.2, 4.4, 4.9, the optimisation algorithm has concentrated the links on as high-frequency channels as possible and shows the opportunity of capacity growth in the unbalanced distribution. As mentioned in the introduction, when the FS network increases its capacity, the owners will likely buy another license for more bandwidth on the same physical hop, and then transmit with more active channels. For most of these links, there's an opportunity to license a supporting link on any of the lower channels which the results show are uncommon to use. For the case of Toronto, the results also contain three unused 30 MHz channels after optimisation, which is a great opportunity for capacity increase.

The results are limited by the resolution of the source data, the modelling simplifications, the available computational capacity, and the assumptions required as a consequence of these limitations.

ATPC is one assumption with big influence and is strictly limited to the few links in the network causing interference within the original network. In the real network, ATPC may be further deployed than to the links included in these cases.

A smaller example is the flat power spectral mask assumption, which may slightly overestimate co-channel interference while excluding adjacent channel interference. Another is the exclusion of NLOS systems using diffraction, which causes the NLOS path to have a lower SNR than the LOS assumption made in this thesis.

Furthermore, assuming all links to have full LOS to the victim receiver is also a conservative assumption. In the real network, topology or clutter may further attenuate the interference levels from surrounding transmitters. As a consequence, the results are conservative, and if topology and clutter could be modelled into the algorithm, further optimisation might be possible.

One example of the dependence of the source data is the asymmetry found in Montreal and Vancouver's data sets. Although finding all FDD links, the network remains asymmetric around the subplan's midband in the original network. When studying the results more closely, asymmetry within one subplan can be either explained by single unidirectional links, legacy links, or a legacy channel allocation plan which the current databases do not disclose and only covers a few of the total links. For the results, this can mean a slight change, as there are only a few links creating this asymmetry (11/211 in Montreal, 1/34 in Vancouver). However, the overall conclusion that the spectrum utilisation can be optimised still holds.

5.2 Conclusions

In conclusion, the results show potential for upper band concentration for the urban areas in Canada, with results providing as much as 600 MHz continuous spectrum for future capacity growth of wireless networks. If the network were optimised, however, costs to upgrade hardware may follow as a consequence. The future capacity growth of the FS network may possibly be contained to the upper band, but this would require further studies which include demand projections.

There are currently high-capacity links that are not optimisable in the coastal area, and this would require hardware updates or site changes to possibly compress the spectrum usage for these hops.

The assumptions of the project have been limited by the modelling complexity, time scope of the project and limitations on international public data but have still provided a methodology which can successfully investigate if the spectrum utilisation in the 7–8 GHz band can be optimised.

5.3 Future Work

This thesis gives a baseline which shows that the current conversations of the 7–8 GHz band's future should also include studies on how to optimise the current incumbent's spectrum utilisation. This thesis uses a greedy optimisation for lower spectrum utilisation limited by interference. However, for future works, many different degrees of freedom could be further explored.

Two of these can be the inclusion MIMO systems and network replanning. Other degrees of freedom could be the optimisation of polarisation usage and XPIC in the network, as the distribution of polarisations is uneven in Canada, as seen in Appendix C.1, C.2, C.3, C.4.

Another degree of freedom to include could be changing the directionality of some of the frequency-division-duplexed links. An observation was made that on some radio towers which contain multiple antennas, there could be multiple receivers in the lower half of the subplan's band. It would therefore be interesting to see if an improvement could be made if some of these receivers were optimised to use the high half of the subplan's band instead to alleviate same-site interference. Such an investigation must, however, also take saturation levels, near-field effects, as well as interference modulation into account.

Furthermore, this optimisation problem could be tested by many different optimisation algorithms. As this thesis did not aim to solve the computer science question of which algorithm would perform the best, the greedy heuristic algorithm was chosen over the few tested algorithms using weighted randomisation of frequency allocations. It would, however, be interesting to further study whether the results in this report are a global optimum or if the results could be further optimised.

Finally, this thesis was heavily limited to the public data supplied by ISED. Although Canada is a relevant baseline as ISED already works with spectrum optimisation, it cannot serve as more than an example and baseline in further discussion without a bigger international dataset. For future work, the most pressing expansion would be to source more detailed data from other countries in different regions in the world and where the fixed service network may be even more densely deployed.

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A

Appendix A: Transmit powers

A.1 Transmit power of FS links in Canada

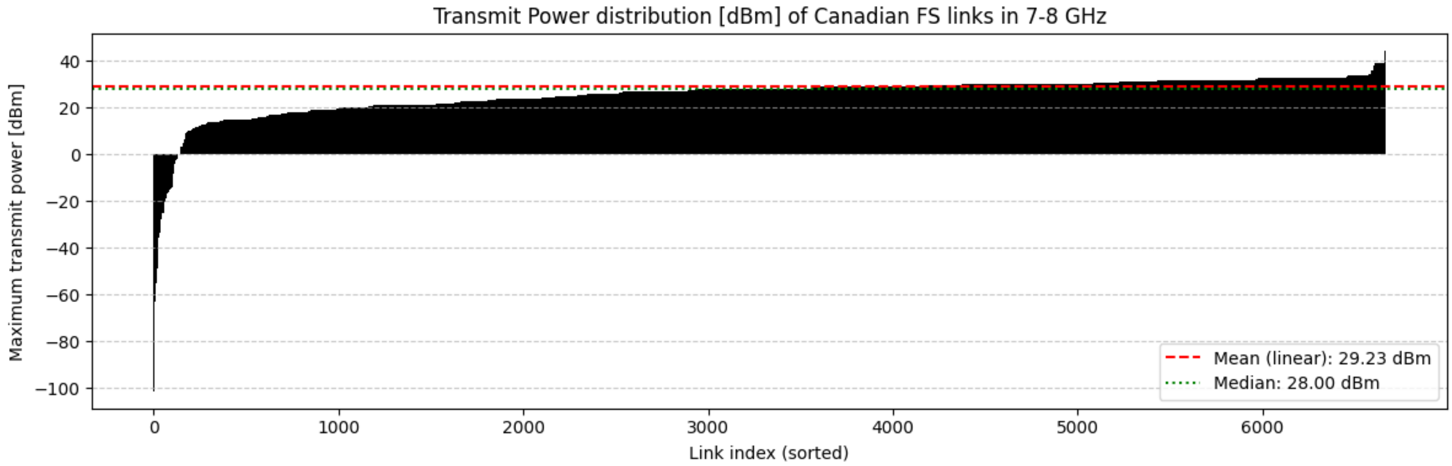

Figure A.1: Transmit power [dBm] of Fixed Service links [Id] in Canada, including passive reflectors.

A.2 Transmit power of FS links in Toronto

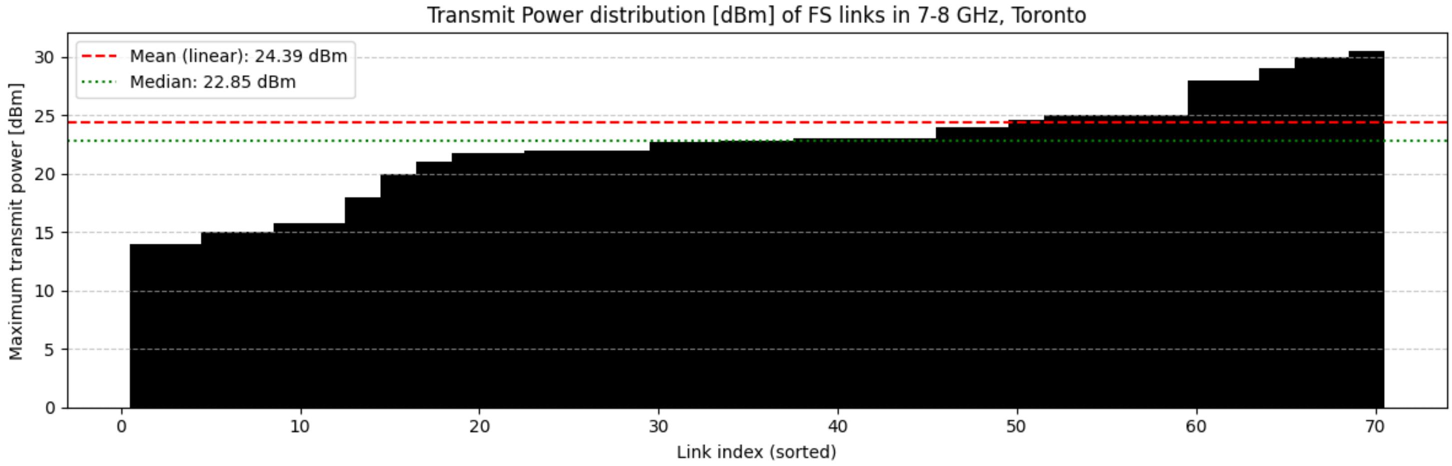

Figure A.2: Transmit power [dBm] of Fixed Service links [Id] in Toronto, no passive reflectors within the area.

A.3 Transmit power of FS links in Montreal

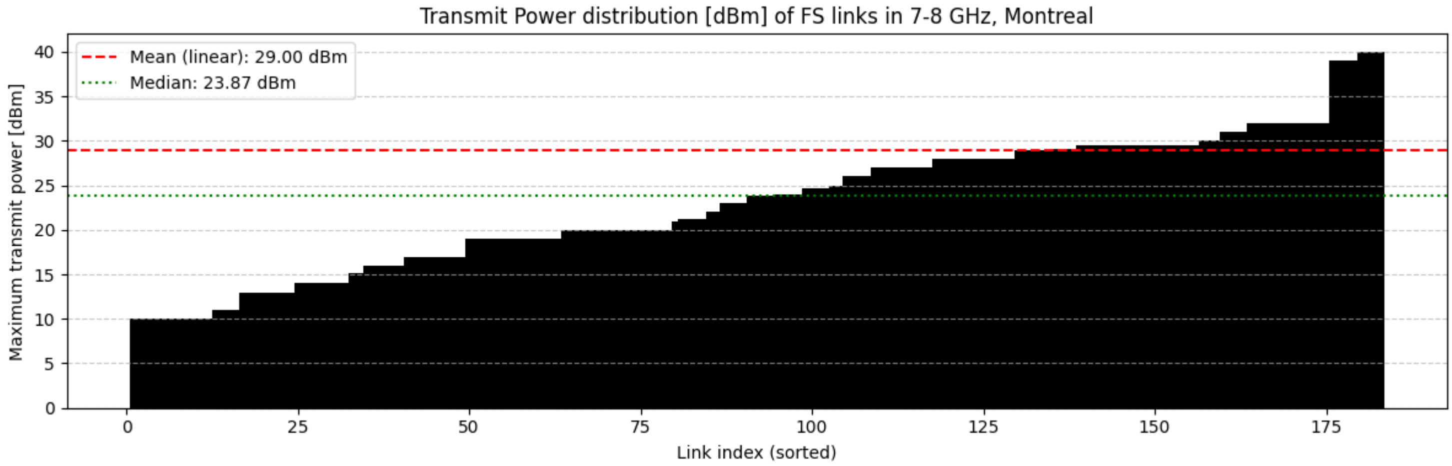

Figure A.3: Transmit power [dBm] of Fixed Service links [Id] in Montreal, no passive reflectors within the area.

A.4 Transmit power of FS links in Vancouver

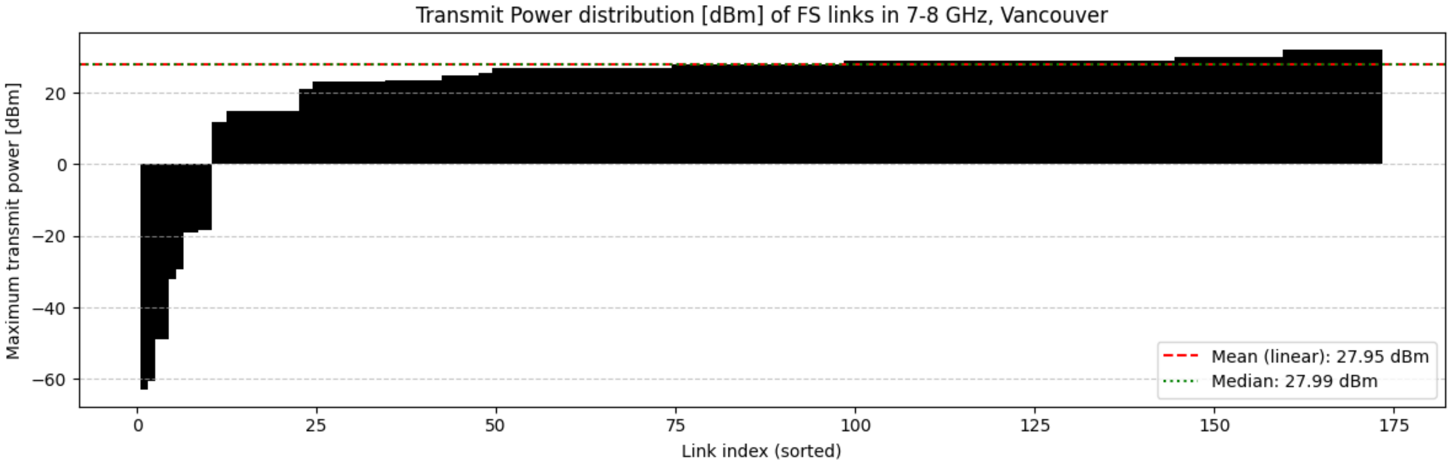

Figure A.4: Transmit power [dBm] of Fixed Service links [Id] in Vancouver, including passive reflectors within the area.

B

Appendix B: Link distances

B.1 Backhaul link distance in Canada

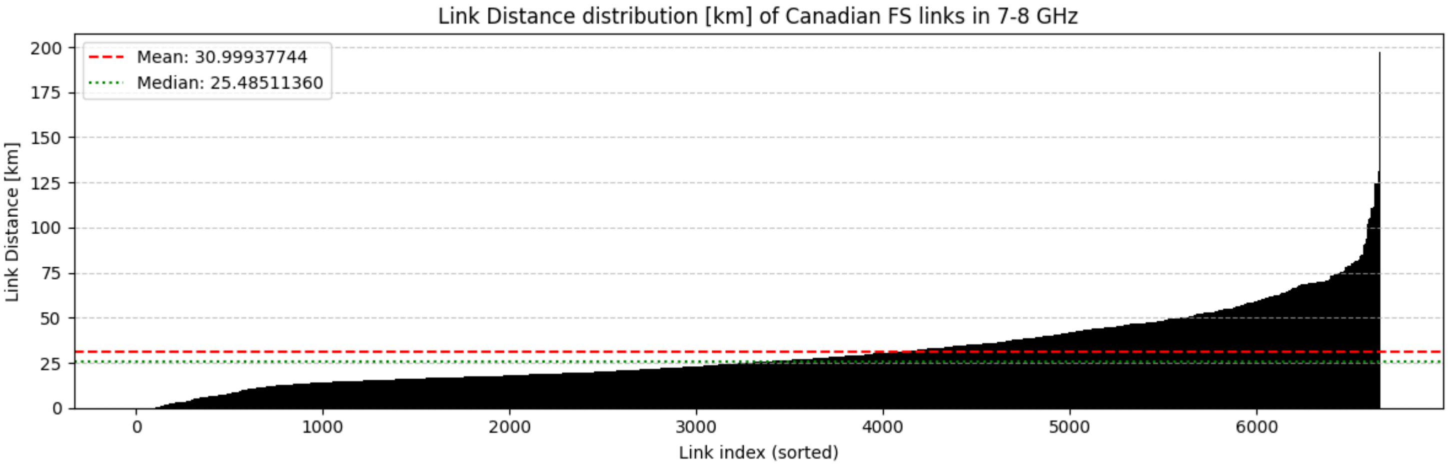

Figure B.1: Backhaul link distance [km] in Canada. Plotted against link ID number.

B.2 Backhaul link distance in Toronto

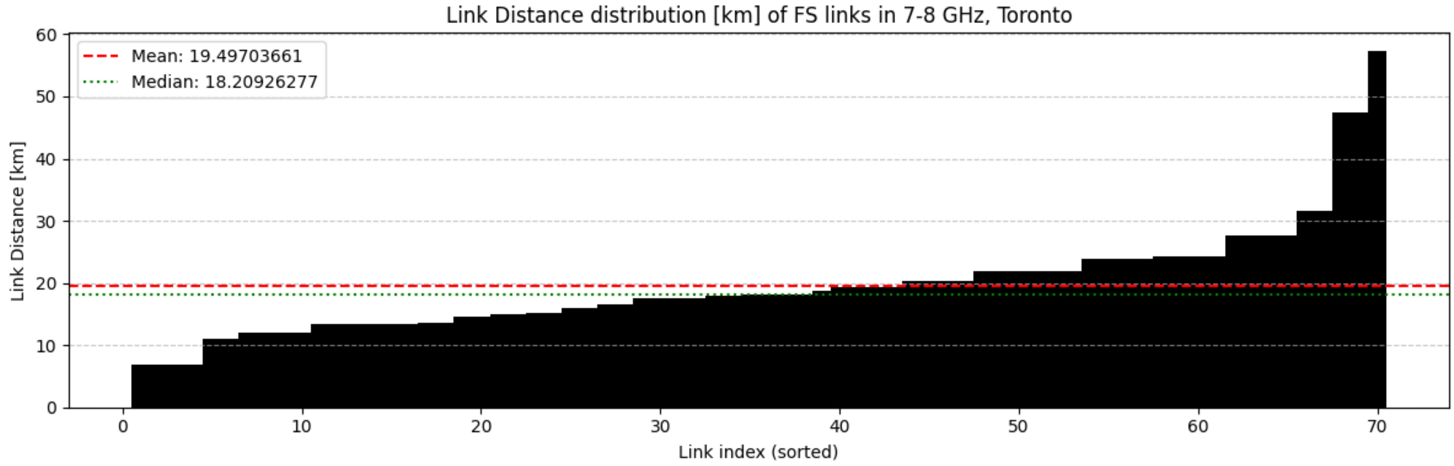

Figure B.2: Backhaul link distance [km] in Toronto. Plotted against link ID number.

B.3 Backhaul link distance in Montreal

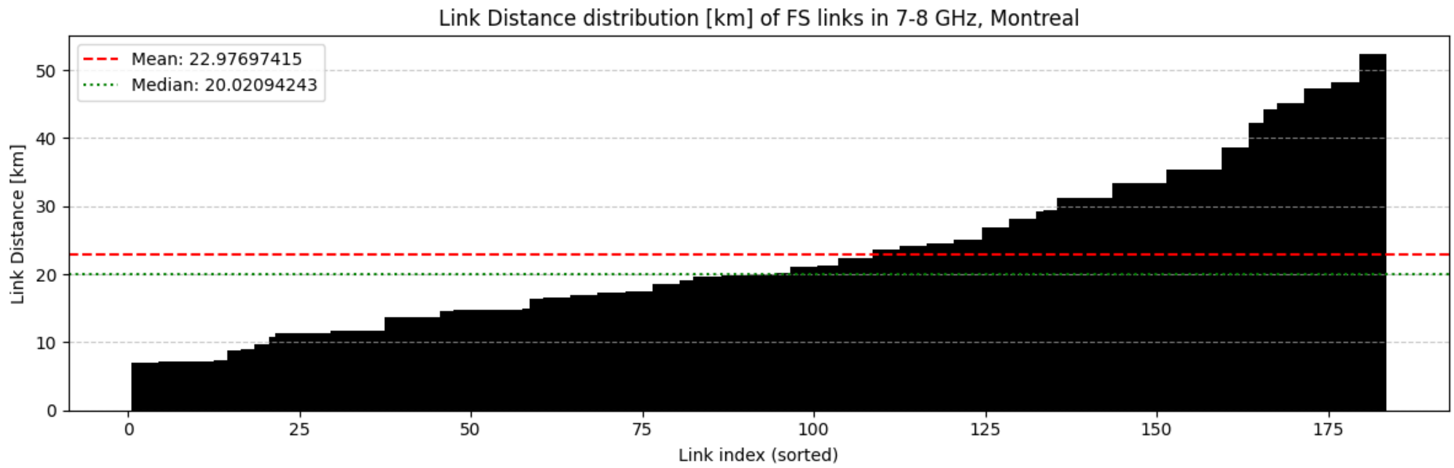

Figure B.3: Backhaul link distance [km] in Montreal. Plotted against link ID number.

B.4 Backhaul link distance in Vancouver

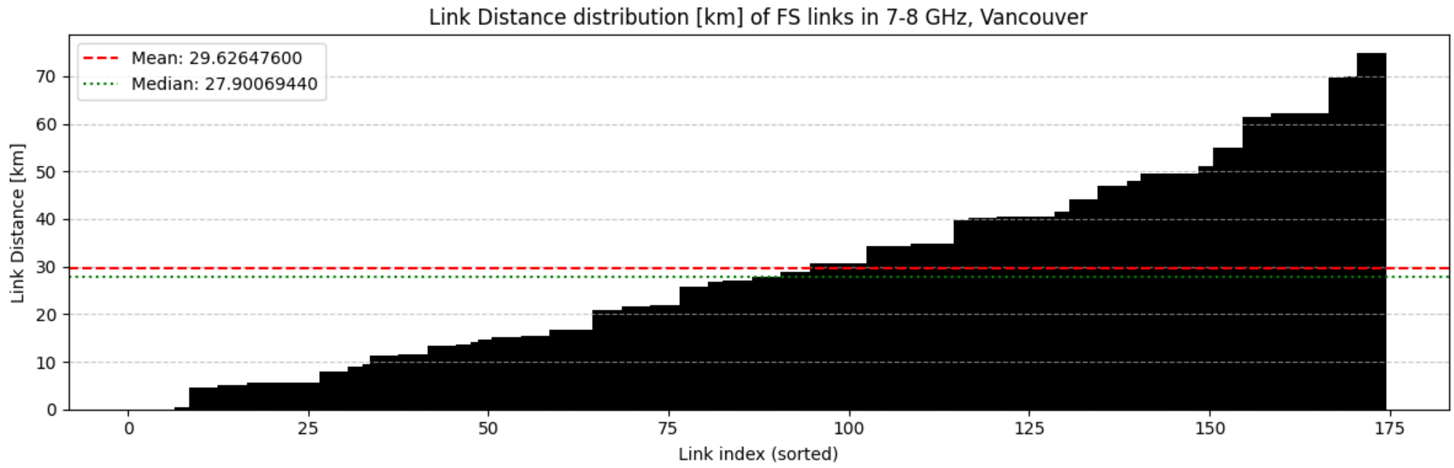

Figure B.4: Backhaul link distance [km] in Vancouver. Plotted against link ID number.

C

Appendix C: Distribution of polarisations

C.1 Distribution of different polarisations in Canada

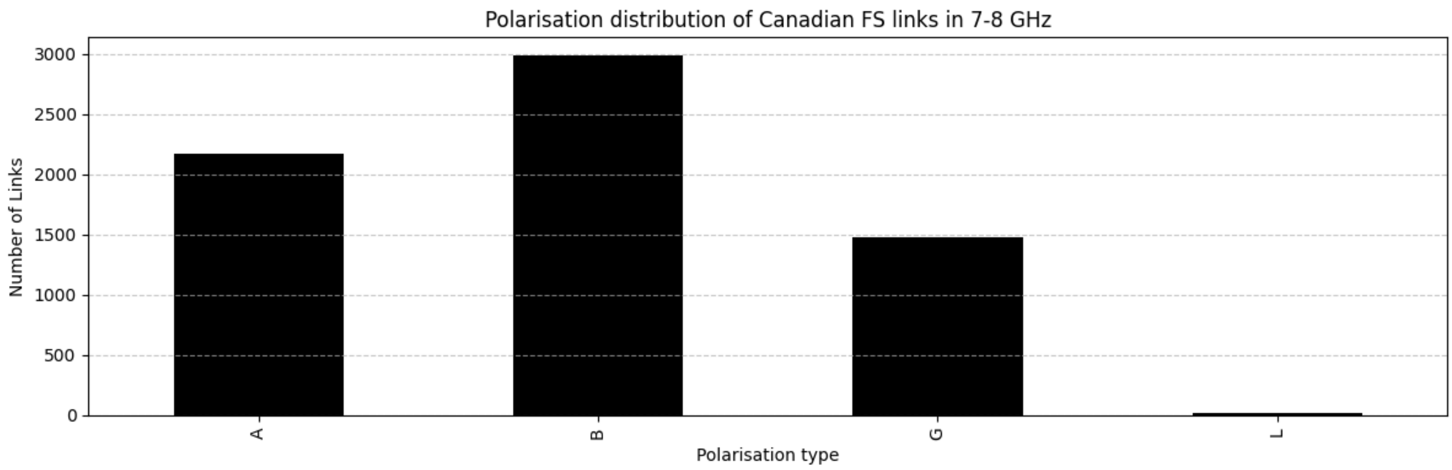

Figure C.1: Amount of links per polarisation in Canada. A = Horizontal polarisation, B = Vertical polarisation, G = Co-channel dual polarisation, L = Dual polarised.

C.2 Distribution of different polarisations in Toronto

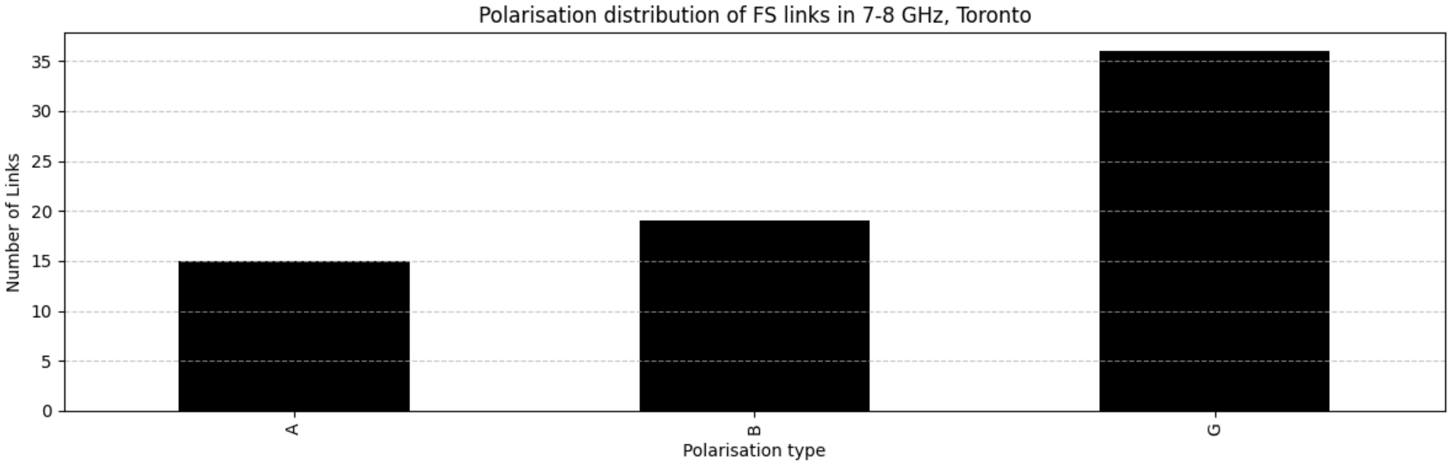

Figure C.2: Amount of links per polarisation in Toronto. A = Horizontal polarisation, B = Vertical polarisation, G = Co-channel dual polarisation.

C.3 Distribution of different polarisations in Montreal

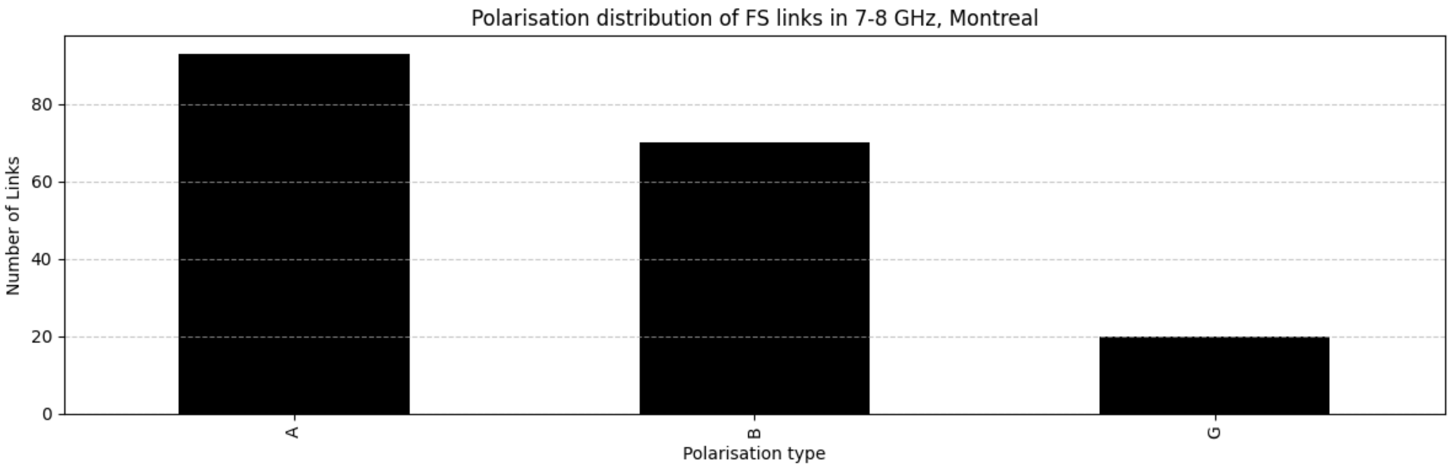

Figure C.3: Amount of links per polarisation in Montreal. A = Horizontal polarisation, B = Vertical polarisation, G = Co-channel dual polarisation.

C.4 Distribution of different polarisations in Vancouver

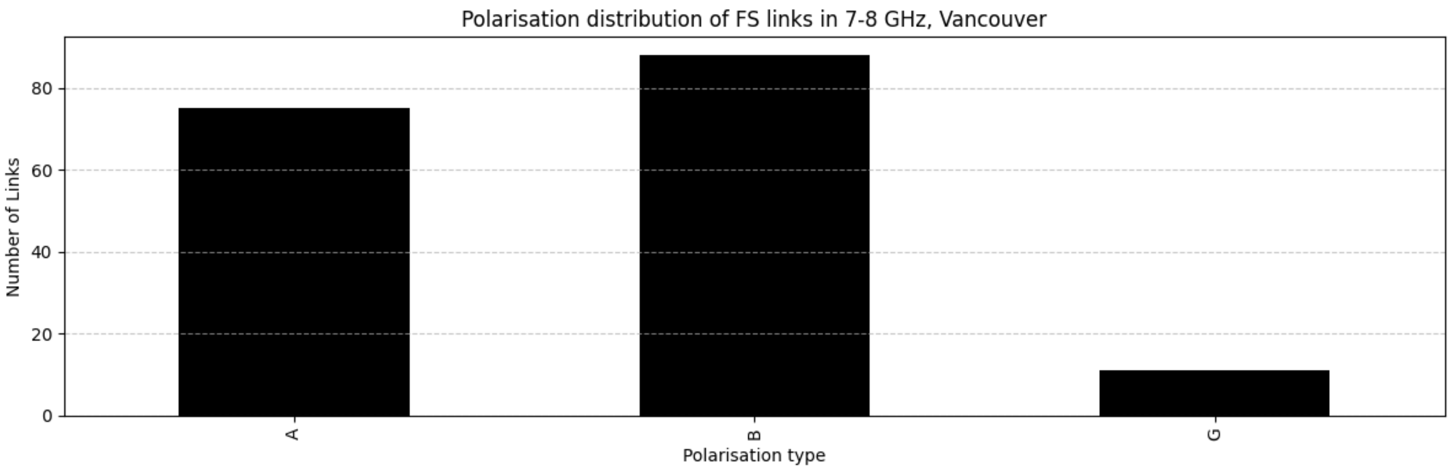

Figure C.4: Amount of links per polarisation in Vancouver. A = Horizontal polarisation, B = Vertical polarisation, G = Co-channel dual polarisation.

D

Appendix D: Distribution of fade margins

D.1 Distribution of fade margins in Canada

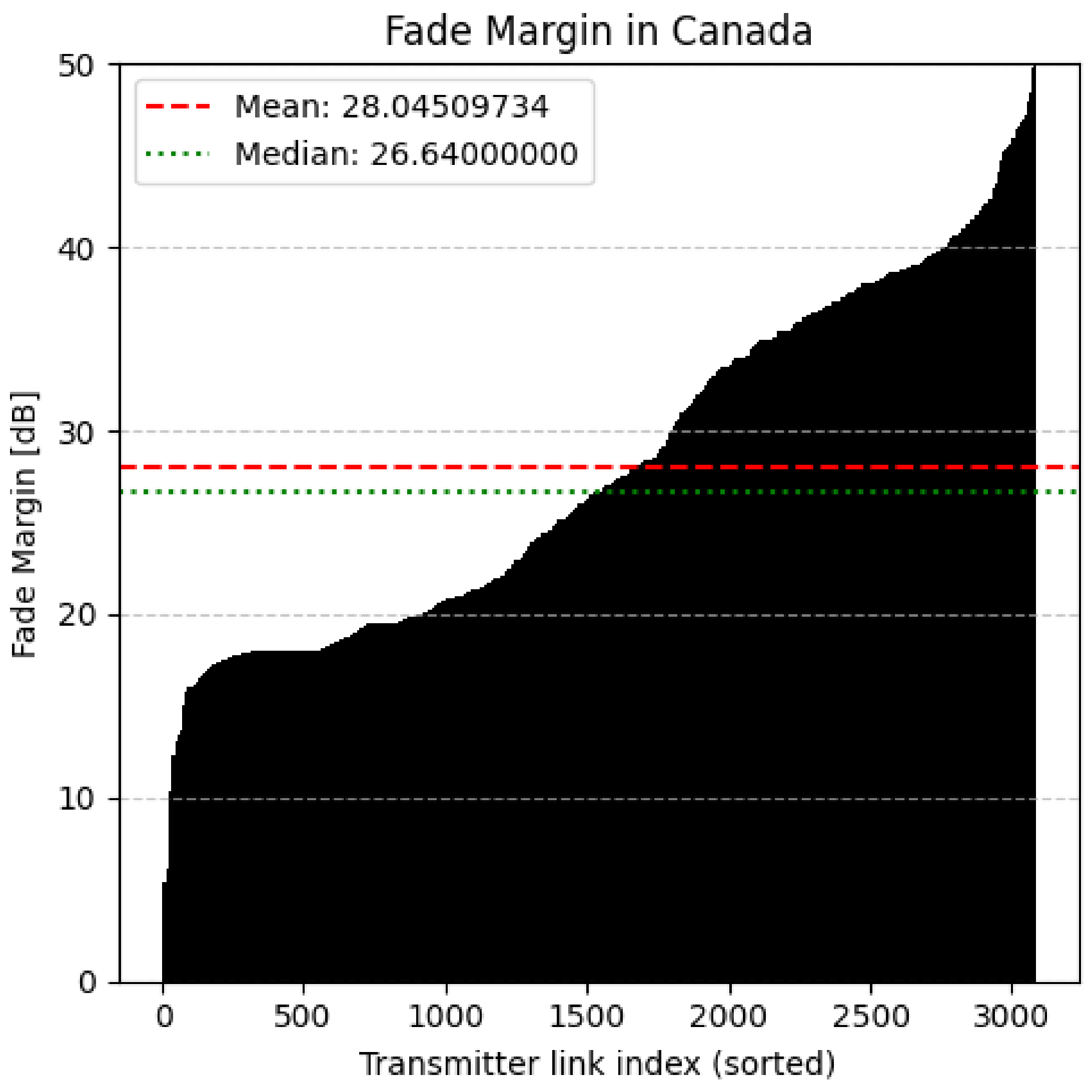

Figure D.1: Fade margin [dB] of every backhaul link [id] in Canada.

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