Improving the Robustness of Over-the-Air Synchronization for 5G Networks in a Multipath Environment

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Abstract

Synchronization between base stations is a fundamental part of any operating telecommunication system. With 5G and future generations of mobile networks, the data speeds are getting higher, which creates the need for fast and accurate synchronization. In wireless systems, the transmitted signals are affected by the environment. Both moving and stationary objects can cause a transmitted signal to be scattered or reflected, causing the receiver to receive multiple instances of one signal. If a synchronization signal is transmitted from one base station and received in multiple instances by another, it is hard for the receiving base station to know which of the received instances that should be used for calculating the synchronization error between the base stations.

In this thesis, multiple different algorithms for selecting a synchronization signal pair between two base stations to be used for calculating time alignment error have been tested. The results have been evaluated based on their accuracy of selecting a correct matching signal pair. It is shown that the proposed algorithms in this thesis all perform significantly better than the method currently in use. Further, the advantages and disadvantages of each of the new algorithms are discussed, and finally new concepts for future studies are suggested.

Keywords

Peak selection algorithms, Peak matching, Time alignment error, Over-the-air synchronization, Multipath environment
ii | Abstract
Sammanfattning


I detta examensarbete testas ett flertal olika algoritmer för att välja vilket synkroniseringssignalpar som ska användas vid beräkning av tidsfelet mellan två basstationer. Resultatet utvärderas baserat på hur hög precision algoritmen har i att välja ett korrekt matchat synkroniseringssignalpar. Resultatet visar att de algoritmer som presenteras i denna uppsats presterar märkbart bättre än den algoritm som används i systemen just nu. Vidare diskuteras fördelar och nackdelar med de olika algoritmerna och förslag på vidareutveckling av algoritmerna läggs fram.

Nyckelord

Toppvalsalgoritmer, Toppmatchning, Tidsfel, Luftburen synkronisation, Flervägsmiljö
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Anders Erninger
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<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Program</td>
</tr>
<tr>
<td>BS</td>
<td>base station</td>
</tr>
<tr>
<td>CIR</td>
<td>channel impulse response</td>
</tr>
<tr>
<td>CN</td>
<td>core network</td>
</tr>
<tr>
<td>DL</td>
<td>downlink</td>
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<tr>
<td>FDD</td>
<td>Frequency Division Duplexing</td>
</tr>
<tr>
<td>LOS</td>
<td>line-of-sight</td>
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<tr>
<td>MIMO</td>
<td>Multiple Input - Multiple Output</td>
</tr>
<tr>
<td>NLOS</td>
<td>non-line-of-sight</td>
</tr>
<tr>
<td>NR</td>
<td>New Radio</td>
</tr>
<tr>
<td>OFDM</td>
<td>orthogonal frequency-division multiplexing</td>
</tr>
<tr>
<td>PRB</td>
<td>physical resource block</td>
</tr>
<tr>
<td>RAN</td>
<td>radio access network</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplexing</td>
</tr>
<tr>
<td>TOA</td>
<td>time of arrival</td>
</tr>
<tr>
<td>TOF</td>
<td>time of flight</td>
</tr>
<tr>
<td>UE</td>
<td>user equipment</td>
</tr>
<tr>
<td>UL</td>
<td>uplink</td>
</tr>
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</table>
List of acronyms and abbreviations
Chapter 1

Introduction

The newest generation of telecommunications systems, 5G, offers many new features compared to the older generation. Higher communication speed and lower latency create the opportunity for a whole new usage of the networks, especially when considering connected devices. 5G networks allow for a larger scale of connectivity and allow for fast communication between them.

An important factor of any network is synchronization. With 5G, this becomes even more important. A faster network requires a more precise synchronization. If the network is out of sync, the whole communication fails. Over-the-air synchronization has been a topic of research to improve the robustness of the systems and reduce costs. A GPS can be used to synchronize base stations to have a common time reference. But the costs of installing a GPS can be significant. For indoor environments, GPS might not even be a viable solution [1]. This emphasizes the need for robust over-the-air synchronization.

A common method used for synchronizations includes two-way ranging. Two-way ranging is a method that sends a synchronization signal between two transceivers and measures the time alignment error based on the time of flight. However, this method requires a symmetrical propagation path and that the signals travel the same path regardless of which transceiver is transmitting or receiving. This is a very idealistic scenario, and the reality is often very different. The environment in which the signal propagates can cause the signal to be reflected or scattered, resulting in that multiple instances of the transmitted synchronization signal are received by the receiver at different time instances. This is called a multipath environment. It is then hard to determine which of the received signals to use when calculating the time alignment error. Previous methods for selecting a received synchronization signal have focused
on using the received signal with the highest energy. But this method is also vulnerable to multipath environments since there is no guarantee that the signal with the highest energy in two directions has traveled the same path. The main focus of this thesis is to improve the signal selection algorithm to better handle multipath environments.

1.1 Thesis Scope

The scope of this thesis is to improve the over-the-air synchronization between 5G base stations by increasing the robustness to multipath environments. The main focus will be on improving the peak selection algorithm, that is, the algorithm that decides which instance of the received synchronization signal to use for the time alignment error calculations.

1.2 Sustainability, Ethical and Societal Impact

The result of this thesis has an impact on several nontechnical areas. Over-the-air synchronization allows a network to have a higher level of independence from external factors and networks. Using over-the-air synchronization, the networks could function on their own without the need for outside references, such as GPS signals. This is important if external factors shut down for unknown reasons and would allow the society to still have functioning networks.

Further, as previously mentioned, there is an economic aspect to using over-the-air synchronization. Having the network synchronizing within itself reduces the need for communication with external networks, and as such, the equipment needed for those purposes can be removed. This does not only save money, but a reduced need for equipment also reduces the need for manufacturing, which has environmental benefits.

Looking at the thesis from an ethical perspective, it is hard to see that the work of this thesis imposes any ethical issues. The work of the thesis has been carried out independently and has not had any direct impact on external parties. Furthermore, the results of the thesis do not raise any specific ethical issue on its own. However, the possibility that the results of this thesis can be used in an unethical way in the future cannot be ruled out.
1.3 Structure of the thesis

Chapter 2 describes all background needed to understand the communication systems of a 5G network. It explains the basics of a 5G network, the different duplexing schemes and synchronization methods and procedures. Chapter 2 also provides a section describing related work on the topic of synchronization.

Chapter 3 presents the methodology used during the thesis. It presents how the data was gathered, what algorithms have been tested and on what grounds the results will be evaluated.

In Chapter 4, all results are presented and a discussion and evaluation of the results are presented in Chapter 5.

Finally, in Chapter 6 suggestions for potential future work and conclusions are provided.
Chapter 2
Background

2.1 5G New Radio

5G New Radio (NR) is the fifth generation mobile telephone network and the latest commercially released network standard for mobile communication. The 3rd Generation Partnership Program (3GPP) standardizes all aspects of commercial 5G networks, ranging from system architecture to protocols. The system architecture describes all communication at the different parts of the network. Starting from the user equipment (UE) that communicates with the radio access network (RAN). The RAN then sends the information forward to the core network (CN) which is responsible for forwarding the communication to external networks, such as the internet [2]. The communication chain is illustrated in Figure 2.1. The core network is what connects all different radio access networks. In contrast to the RAN, which handles all radio communication, the CN is connected and communicates by wires. The different radio networks in the core network also connect to the core network by wires. The core network is what allows for communication to reach recipients outside the RAN that the transmitter is currently connected to, be that another RAN in the same core network or another external network.

Figure 2.1: 5G System architecture
2.1.1 Radio Access Network

The Radio Access Network is the local radio network that communicates directly with the user equipment. The RAN is composed of a network of nodes. The nodes are commonly referred to as gNB, where "g" stands for "5G" and "NB" stands for "Node B", which is inherited from previous generations of mobile networks and refers to the radio transmitters [2]. The nodes contain base stations with radio transmitters that handle the wireless communication. The RAN is divided into different cells. Each cell has one base station that is responsible for covering all communication with UE within that cell [3]. The cells are designed in the shape of a hexagon, but in reality, the edges of the cell coverage cannot be restricted that hard. Each cell is further divided into three sectors, as illustrated by Figure 2.3. The RAN then has multiple hexagon-shaped cells bordering each other, see Figure 2.2.

![Figure 2.2: 5G Radio Access Network.](image)

![Figure 2.3: Sectors of a 5G gNB cell.](image)

If two UEs in different cells want to communicate with each other, the communication first goes to the base station in the cell, which then communicates with the base station in the cell of the other UE. The base station in the cell of the receiving UE then forwards the communication to the receiving UE, as illustrated in Figure 2.4.
Different RANs are connected to each other through the core network. In contrast to the wireless communication in the RAN, the CNs are connected by wires. The CN is what allows communication outside the RAN where a UE is located and is responsible for forwarding the communication between the different RANs in the CN. The CN also serves as the gateway for communication with the rest of the world, which can be any external network.

2.1.2 **Time Division Duplexing**

In wireless communication systems, there are two fundamental duplexing schemes, Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD). A duplexing communication scheme is what allows for a two-way communication between two units, be that between two base stations or between different UEs. FDD communicates with uplink (UL) and downlink (DL) by using different frequency spectrums for UL and DL. The advantage of this is that it allows for simultaneous UL and DL communication. The disadvantage is that it requires a broader frequency spectrum usage, since there is a need for two isolated frequency spectrums for both UL and DL. In contrast, TDD makes use of the time domain for its communication, where the communications take place in a sequential UL and DL scheme. The UL and DL slots are transmitted in sequences separated by time. TDD schemes can also benefit from using frequency diversity. However, if the bandwidth is limited, the advantage of using TDD is that it can operate on a smaller frequency band. Using TDD with a smaller bandwidth does come at the cost of additional time delays. This is illustrated in Figure 2.5. A sequential duplexing scheme also brings a huge dependence on time precision and synchronization. If the synchronization is off, the UL/DL subframe sequence will be out of order \[^4\]. To aid this, guard periods can be implemented to give room for smaller errors, but this also comes at the cost of additional time delays. A simple TDD scheme is illustrated in Figure 2.6.
2.1.3 Frame Structure

Radio transmissions within a 5G network are organized in a frame structure, where the main categories are radio frames, subframes and slots. They follow a hierarchical structure starting with the radio frame, which can be divided into subframes, which in its own turn are divided into slots [5]. A radio frame in 5G is 10 ms and consists of 10 subframes of 1 ms each. The amount of slots for each subframe is dependent on what numerology is used [6]. The number of slots per subframe in relation to what numerology is used can be described by:

\[ s = 2^n, \]  

(2.1)

where \( s \) is the number of slots and \( n \) is the numerology. A more detailed overview of the attributes for different numerologies is shown in Table 2.1. Lastly, each slot contains 14 orthogonal frequency-division multiplexing (OFDM) symbols [7]. As can be seen, there is a tradeoff between the number of slots, and in extension the slot duration, and the subcarrier spacing. This is due to the orthogonality.
2.1.4 Physical Resource Block

The physical layer in 5G NR can be represented by a time-frequency resource grid. The smallest element in the time-frequency resource grid consists of one symbol and one subcarrier. The subcarriers are often grouped in numbers of 12 called a physical resource block (PRB). Transmissions in 5G are done in PRBs. Table 2.1 shows the subcarrier spacing for different numerologies. Given a numerology 1, the subcarrier spacing is 30 kHz, which gives one PRB a bandwidth of 360 kHz [5]. An illustration of the time-frequency grid is shown in Figure 2.7.

Figure 2.7: Time-frequency grid, one step on the time axis is one symbol and one step on the frequency axis is one subcarrier. The grey area marks one physical resource block.
2.1.5 Synchronization in 5G

As previously mentioned, the two main duplexing schemes FDD and TDD both have their advantages and disadvantages, where FDD requires a larger bandwidth usage. When trying to enable more communication, saving frequency spectrum is important. This is why TDD is widely used, as it requires less bandwidth at the cost of an increased delay. For systems running TDD, the functionality of the network relies heavily on a precise time synchronization. If the synchronization is misaligned, the UL and DL transmissions can be corrupted by each other [8]. In 5G, the slot duration is down to the size of microseconds, which makes the requirements of the synchronization to be very accurate. The maximum offset allowed in 5G communication networks is standardized to $\pm 1.5\mu s$ [9] [10].

2.2 Two-way Ranging for Time Offset Calculations

In general, the distance between two transceivers can be calculated according to:

$$d = T_{\text{prop}} \cdot c,$$

where $T_{\text{prop}}$ is the propagation time or as commonly referred to as the time of flight (TOF), $c$ is the speed of light, and $d$ is the distance. Given two base stations (BSs) communicating, BS$_1$ and BS$_2$, the propagation time $T_{\text{prop}}$ is given by:

$$T_{\text{prop}} = T_2 - T_1,$$

where $T_1$ is the time BS$_1$ sent the signal, and $T_2$ is the signal’s time of arrival (TOA) at BS$_2$ [11]. An illustration of the propagation time can be seen in Figure 2.8.

![Figure 2.8: A simple illustration of the $T_{\text{prop}}$.](image-url)
However, the propagation time $T_{\text{prop}}$ in Figure 2.8 is only true for an ideal scenario where the two base stations are perfectly synchronized. In reality, the occasions when the signal is sent from BS$_1$ and then received at BS$_2$ are measured in reference to their own internal clocks. If the clocks at BS$_1$ and BS$_2$ are out of sync, there will be a time alignment error between the base stations and the actual propagation time will be given by:

$$\tilde{T}_{\text{prop}} = T_2 - T_1 - \Delta t = T_{\text{prop}} - \Delta t,$$

where $\Delta t$ is the time offset between the base stations. To calculate the time offset and the real propagation time $T_{\text{prop}}$, two-way ranging is used. In two-way ranging, the propagation time is measured in two directions, first one time from BS$_1$ to BS$_2$, then a second time in the opposite direction. The procedure is illustrated in Figure 2.9. The two-way ranging gives the following estimates at BS$_1$ and BS$_2$:

$$\tilde{T}_{\text{prop}}^{(1)} = T_4 - T_3 + \Delta t = T_{\text{prop}} + \Delta t,$$

$$\tilde{T}_{\text{prop}}^{(2)} = T_2 - T_1 - \Delta t = T_{\text{prop}} - \Delta t,$$

which gives the following equation for $T_{\text{prop}}$ and $\Delta t$ [12][11]:

$$\Delta t = \frac{\tilde{T}_{\text{prop}}^{(1)} - \tilde{T}_{\text{prop}}^{(2)}}{2},$$

$$T_{\text{prop}} = \frac{\tilde{T}_{\text{prop}}^{(1)} + \tilde{T}_{\text{prop}}^{(2)}}{2}.$$  

For these equations to hold true, path symmetry is required. In other words, the signal must have traveled the same path in both directions. Another requirement for this to work is that the timestamps are transmitted with the signal each time, so that the other base station is aware of what time the received signal was transmitted.

### 2.3 Cross-Correlation for Time Alignment Error Calculations

As mentioned above, a downside with the previously described method of measuring the time offset is that timestamps always have to be transmitted. To solve this issue, it is possible to use cross-correlation instead. This by setting up a synchronization scheme between two nodes where both the
synchronization signal and the time of transmission are known beforehand by both the transmitter and the receiver. In the context of two-way ranging, it means that the timestamps T1 and T3 are already known by both nodes. Furthermore, the synchronization signals that are being transmitted, \( s^{(1)} \) and \( s^{(2)} \), are known as well. When the received signal \( y \) is received after being transmitted over the communication channel, it is cross-correlated with the internally generated synchronization signal, which is a replica of the already known transmitted synchronization signal [13] [14] [15]:

\[
\begin{align*}
    r^{(1)}(\tau) &= (y^{(1)} * s^{(1)})(\tau), \\
    r^{(2)}(\tau) &= (y^{(2)} * s^{(2)})(\tau).
\end{align*}
\]  

(2.9) \quad (2.10)

\( r(\tau) \) is the cross-correlation between the synchronization signal \( s \) and the received signal \( y \). The estimated propagation time \( \tilde{T}_{prop} \) can then be estimated as the lag between the cross-correlated signals:

\[
\begin{align*}
    \tilde{T}^{(1)}_{prop} &= \arg \max_{\tau} r^{(1)}(\tau), \\
    \tilde{T}^{(2)}_{prop} &= \arg \max_{\tau} r^{(2)}(\tau).
\end{align*}
\]  

(2.11) \quad (2.12)

The final propagation time \( T_{prop} \) and time offset \( \Delta t \) can then be calculated in the same way as the normal two-way ranging according to Equation (2.8) and (2.7). This assumes that only one signal is received by the receiver. If multiple instances of the synchronization signal are detected by the receiver, problems
can occur with which signal to select as $\tilde{T}_{\text{prop}}$.

### 2.4 Multipath Channels

It is easy to assume that a transmitted signal always travels along a direct propagation path to a receiver. This is true given that the transmitter and the receiver are in direct line-of-sight (LOS). If the transmitter and receiver are in a position of non-line-of-sight (NLOS), there are still possibilities for a signal to be detected by the receiver. The transmitted signal can be reflected or scattered in the environment, thus still being able to reach the receiver. Regardless of whether the transmitter and receiver are in LOS or NLOS, the environment will affect the transmitted signal. A transmitted signal can be reflected and scattered in multiple objects, causing the receiver to detect multiple instances of the transmitted signal at different time delays based on what propagation path the signals have traversed. Figure 2.10 illustrates a multipath environment, where the transmitted signal is reflected in two objects before arriving at the receiver.

![Multipath Channel Diagram](image)

Figure 2.10: Illustration of multipath propagation.

A simple multipath channel can be modeled as:

\[
h(t) = \sum_{l=0}^{L-1} h_l \delta(t - \tau_l),
\]  

(2.13)
where $L$ is the number of multipath components, $h_l$ is the path gain and $\delta$ is the Dirac-delta function with $\tau_l$ being the delay of each of the received signals [16]. The received signal from a multipath channel can then be formulated as:

$$y(t) = x(t) * h(t) + w(t), \quad (2.14)$$

where $y(t)$ is the received signal, $x(t) * h(t)$ is the convolution between the transmitted signal $x(t)$ and the channel impulse response $h(t)$, and $w(t)$ is noise.

### 2.5 Multiple Input - Multiple Output

Modern base stations seldom only have one antenna, instead, they have multiple antennas in different design shapes and use a Multiple Input - Multiple Output (MIMO) system. The different antennas can be used for a variety of things, such as communicating with different receivers at the same time. A MIMO system with $M$ antennas at the transmitter and $N$ antennas at the receiver can be described by:

$$y(t) = H(t) * x(t) + w(t), \quad (2.15)$$

where $x(t)$ is transmitted signals from the $M$-array transmitting antennas,

$$x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{bmatrix}, \quad (2.16)$$

$y(t)$ is the received signals at the receiving $N$ antenna array,

$$y(t) = \begin{bmatrix} y_1(t) \\ y_2(t) \\ \vdots \\ y_N(t) \end{bmatrix}, \quad (2.17)$$

$H(t)$ is the $M \times N$ matrix with the corresponding channel impulse responses and $w(t)$ is the noise term [17].
2.6 Beamforming

The usage of multiple antennas stretches further than simultaneous communication. One technique that exploits the usage of multiple antennas is beamforming. Beamforming allows the radio energy from multiple antennas to be directed toward a desired direction or receiver. At the same time, the receiver could be set to receive signals from a specific direction [18]. Different beamforming patterns have different use cases. A narrow beam can be used to focus the energy towards a specific receiver, but, requires higher precision. A wider beam allows the receiver to be more in a general target area, but, has its disadvantage in lower hearability.

2.7 Related Work

Synchronization in 5G NR is a frequent topic of research and is important to many areas of a wireless network. It is an absolute necessity for having a functioning network, but it is also widely needed for having accurate localization. Over-the-air synchronization for ultra-reliable and low-latency communications (URLLC) and the requirements for it have been studied in [1]. The need for absolute time synchronization is discussed, and a combination of enhancement in the timing advance and of the system information block 16 is identified as an enabler for OTA synchronization in URLLC. A radio interface based synchronization (RIBS) scheme based on UL/DL timestamp transmission exchange can be designed, which would allow calculations of propagation delay in UE to BS time offset.

A look into over-the-air synchronization given multipath scenarios is provided in [16]. They show that a single wideband channel state information reference signal both covers a large distance between the base station and user equipment and also implies that a lower Reference Time Info (RTI) can be used compared to a Synchronization Signal Block (SSB). It is also described how to choose the RTI based on the DL reference signal, channel characteristics, distance between the base stations and the clock drift rate of the UE.

Using TOA ranging and over-the-air synchronization for indoor industrial Internet of Things (IoT) networks, and studying the synchronization error for both LOS and NLOS has been done by [19]. They found that using mmWave 5G networks instead of Ultra Wideband (UWB) networks performs significantly better in terms of synchronization accuracy and brings the over-the-air timing synchronization down to nanoseconds.
A closer look into two-way ranging for clock error compensation has been studied in [20]. Changes to a ranging method called, Double-Beacon Two-Way Ranging (DB-TWR) were presented. The changes consisting of two additional time captures and an updated time of flight calculation formula resulted in significant improvements related to errors caused by clock offset.

In [21] the authors look at using correlation for synchronization of OFDM systems. They derived a maximum-likelihood estimator based on only sign bits and averaging over several OFDM frames. This study assumes an AWGN channel. Simulations showed that this significantly improved the synchronization performance.

Further, the authors of [22] study frame synchronization of OFDM systems using a correlation detector in the frequency domain at the receiver. Frame synchronization in OFDM systems in fading channels such as multi-path channels and the impact of frame misalignment are discussed in [23].
Background
Chapter 3

Method

3.1 Data

3.1.1 Data Collection

The data used in this thesis is collected from base stations active in a live environment. The base stations are set to monitor synchronization signals. In total, data has been collected between 12 different pairs of base stations. When collecting data, one base station is set as the master node and the other as the assisting node. The master node is responsible for transmitting the initial synchronization signal and the assisting node is responding. Any time a base station pair do a synchronization transmission, the signal is transmitted using only one polarization. The receiving base station is then set to receive signals in two different polarizations, the same polarization the synchronization is transmitted in and its orthogonal polarization. The captured data is then two separate data streams captured with different polarizations. These two data streams are then combined into one combined stream. So the available data is from the two different data streams and the combined data stream.

When the synchronization signal is transmitted, it first passes through an over-the-air channel with an unknown channel impulse response (CIR). However, the CIR is similar to a multipath channel described by Equation (2.14).

\[ \hat{s}(t) = s(t) * h(t) \]  

(3.1)

Here, \( s(t) \) is the initially transmitted synchronization signal and \( h(t) \) the multipath channel. The signal is also exposed to noise before being detected by the receiver:

\[ y(t) = \hat{s}(t) + w(t), \]  

(3.2)
where $y(t)$ is the signal received by the receiver and $w(t)$ is noise. When the signal $y(t)$ is received, it is first converted to the digital domain through an analog-to-digital converter with a sampling period of $T_s$,

$$y[n] = y(nT_s). \quad (3.3)$$

The signal is then passed through a matched filter $g[n]$ which is matched to samples of the originally transmitted synchronization signal $s[n]$,

$$y_{MF}[n] = y[n] * g[n]. \quad (3.4)$$

The matched filter is there to detect the instances of the original synchronization signal. The output from the matched filter $y_{MF}[n]$ is then used to calculate the propagation time and time alignment error. A peak in $y_{MF}[n]$ represents a detected synchronization signal. A simplified block scheme of the communication system used to collect data can be seen in Figure 3.1.

![Figure 3.1: A block scheme over the communication system.](image-url)

It is important to consider that the described system is a simplified view of the system. In reality, the CIR from the multipath channel is not constant and could change between different transmissions. Scatters from moving objects could impact the output of the modeled channel, creating different multipath environments. However, since the base stations are stationary, some propagation paths are constant over all transmissions due to stationary reflections or if the base stations are in LOS. An example of outputs from a pair of base stations can be seen in Fig 3.2. The output in the figures corresponds to $y_{MF}[n]$ in Equation (3.4).
3.1.2 The Processed Data

The final data set used in this thesis consists of sample pairs from the available raw data that all fulfill certain criteria which makes them suitable for analysis.
The criteria are as follows:

1. Has at least one peak above the predetermined threshold in both directions.

2. Has less than 15 peaks above the predetermined threshold in both directions.

3. Has no peak above 1000 mW.

These criteria have been selected from studying the measurements. In general, the measurements have less than 5 distinctive peaks above the chosen threshold and in the case where more peaks were more than 15 peaks were detected, it was the result of bad measurements. The same goes for measurements containing peaks above 1000 mW. An example of a bad measurement with both more than 15 peaks and peaks above 1000 mW can be seen in Figure 3.3. The lower bound threshold ensures that any peaks are the result of a detected signal and not the result of noise. The algorithms will be tested on two different threshold levels, 21 mW and 36 mW. These threshold levels are set beforehand by the system.

Figure 3.3: An example of a bad measurement with more than 15 peaks and peaks above 1000 mW.
3.2 Peak Selection Algorithms

When the synchronization signal has been processed through the system described in Section 3.1.1, there is a need to select which signal to use for any calculations such as propagation time or time alignment error. In this section, different methods for selecting what signal to use will be described. In this section, \( x^{(1)}[n] \) will be used to represent the output from the matched filter \( y_{MF}[n] \) when BS\(_1\) is the transmitting base station and BS\(_2\) is the receiving base station. When the roles are reversed, the output of the matched filter is represented by \( x^{(2)}[n] \). That is, \( x[n] = y_{MF}[n] \), where \( y_{MF}[n] \) is the output from the matched filter given by Equation (3.4).

In all peak selection algorithms described in this section, \( p^{(1)} \) and \( p^{(2)} \) will represent the selected peak in each transmission direction. The selected peak \( p \) will indicate at what sample \( n \) the peak was detected. The selected peaks \( p^{(1)} \) and \( p^{(2)} \) are what will be used for time alignment error calculations, that is, \( p^{(1)} \) and \( p^{(2)} \) represent the \( \tilde{T}_{prop} \) in Equation (2.11) and Equation (2.12). This further extends into calculating the time alignment error \( \Delta t \) in (2.7) and the propagation time \( T_{prop} \) in (2.8).

3.2.1 Max Peak Selection

A simple peak selection is to use the signal with the highest peak. The disadvantage of this method is that it requires symmetrical CIR between two base stations and that the received signals with the highest energy in both directions have the same propagation path. Which is not always the case. The algorithm can be described as follows,

\[
p^{(1)} = \arg \max_n x^{(1)}[n], \quad n \in \{0, \ldots, N\} \tag{3.6}
\]

\[
p^{(2)} = \arg \max_n x^{(2)}[n], \quad n \in \{0, \ldots, N\} \tag{3.7}
\]

where \( p^{(1)} \) and \( p^{(2)} \) are the selected peaks or signals in the respective transmission direction.
3.2.2 Cross-Correlation Selection

The outputs from the matched filter can be seen as an estimate of the CIR of the multi-path channel, given that the autocorrelation function of the synchronization signal is close to a Dirac-delta pulse. Since both base stations are stationary, there are propagation paths that are constant in each transmission due to reflections of other stationary objects. In addition to the constant propagation paths, there is also the chance to have other propagation paths due to scatter and reflection from moving objects.

Since the matched filter outputs could be seen as estimates of the CIRs, it is then possible to compare the CIRs in both transmission directions, to find common components. One way to measure the similarities between the matched filter outputs is to apply cross-correlation to the matched filter outputs. It is then possible to see at what lag the two matched filter outputs are most correlated. This can be used as the time alignment error or as a basis for what area the selected peak should be searched for.

First, the cross-correlation between the matched filter outputs is calculated according to Equation (A.2),

\[ r_{x(1)x(2)}[k] = \sum_{n=-\infty}^{\infty} x^{(1)}[n]x^{(2)}[n + k]. \] (3.8)

Secondly, the lag \( l \) that gives the highest correlation is obtained,

\[ l = \arg \max_{k} |r_{x(1)x(2)}[k]|. \] (3.9)

Then the peak with the highest energy in the first transmission direction is chosen:

\[ p^{(1)} = \arg \max_{n} x^{(1)}[n], \quad n \in \{0, \ldots, N\}, \] (3.10)

where \( p^{(1)} \) is the selected peak when BS\(_1\) is transmitting and BS\(_2\) is receiving. Lastly, \( p^{(1)} \) combined with the lag \( l \) is chosen as a basis on what interval to search for \( p^{(2)} \):

\[ p^{(2)} = \arg \max_{n} x^{(2)}[n], \quad n \in \{ (p^{(1)} - l) - 5, \ldots, (p^{(1)} - l) + 5 \}. \] (3.11)

The need for having to search for a peak in an interval around \( (p^{(1)} - l) \), instead of just using the lag value at \( x^{(2)}[p^{(1)} - l] \), is based on the fact that there is no guarantee that \( x^{(2)}[p^{(1)} - l] \) is an actual peak. The value 5 is chosen because
it is small enough to not interfere with samples that are parts of other peaks.

### 3.2.3 Multiplication Selection

Another method for finding common components is to simply multiply the two signals, if components align there will be distinctive energy peaks. Meanwhile, if a peak in one signal is not aligned with a peak in the second signal, the peak will be flattened in comparison to where peaks align.

The algorithm starts by multiplying the two matched filter outputs $x^{(1)}[n]$ and $x^{(2)}[n]$,

$$m[n] = x^{(1)}[n] \cdot x^{(2)}[n].$$  \hspace{1cm} (3.12)

Then the peak with the highest combined energy is selected:

$$m_{max} = \arg \max_n m[n], \quad n \in \{0, \ldots, N\},$$  \hspace{1cm} (3.13)

which is then used as the base for where to find the peaks in each matched filter output $x^{(1)}[n]$ and $x^{(2)}[n]$:

$$p^{(1)} = \arg \max_n x^{(1)}[n], \quad n \in \{m_{max} - 5, \ldots, m_{max} + 5\} \hspace{1cm} (3.14)$$

$$p^{(2)} = \arg \max_n x^{(2)}[n], \quad n \in \{m_{max} - 5, \ldots, m_{max} + 5\}. \hspace{1cm} (3.15)$$

The need to search for a peak in an interval around $m_{max}$ is because there is no guarantee that $x[m_{max}]$ is the actual peak, again the value 5 is chosen because it is small enough to not interfere with samples that are parts of other peaks. The big disadvantage of this method is that if no peaks align, and if the synchronization is off by a large enough margin, there is a risk that no common components will be detected, and the method will fail to select a matching peak pair.

### 3.2.4 Combining Multiplication and Cross-correlation Selection

One of the problems with the cross-correlation selection is that there is still a need to choose a peak that will be used as a starting point. Previously, in Section 3.2.2, the highest peak in $x^{(1)}[n]$ was used as the starting point. A way to come around this is by combining the two previously described selection algorithms, cross-correlation selection and multiplication selection. By first using the cross-correlation to see how much the two matched filter outputs are
shifted,

\[ r_{x(1),x(2)}[k] = \sum_{n=-\infty}^{\infty} x^{(1)}[n] x^{(2)}[n + k]. \]  

(3.16)

\[ l = \arg \max_k |r_{x(1),x(2)}[k]|. \]  

(3.17)

One of the two matched filter outputs is then shifted so that the two matched filter outputs are lined up,

\[ x^{(2)}_{\text{shifted}}[n] = x^{(2)}[n - l]. \]  

(3.18)

By then multiplying the first matched filter output and the shifted matched filter output, an indication of where the signals have common components can be found,

\[ m[n] = x^{(1)}[n] \cdot x^{(2)}_{\text{shifted}}[n]. \]  

(3.19)

The peak with the highest energy in the combined signal indicates what area to search for peaks to be selected as a match,

\[ m_{\text{max}} = \arg \max_n m[n], \quad n \in \{0, \ldots, N\}. \]  

(3.20)

Then the peaks in respective signal \( x^{(1)}[n] \) and \( x^{(2)}[n] \) can be found by using \( m_{\text{max}} \) as a base for what area to search for the peaks,

\[ p^{(1)} = \arg \max_n x^{(1)}[n], \quad n \in \{ (m_{\text{max}} - 5), \ldots, (m_{\text{max}} + 5) \} \]  

(3.21)

\[ p^{(2)} = \arg \max_n x^{(2)}[n], \quad n \in \{ (m_{\text{max}} + l - 5), \ldots, (m_{\text{max}} + l) + 5 \}. \]  

(3.22)

### 3.2.5 Relative Lag Matching

In both transmission directions, the CIR should be similar with a few common components. One way to match useable peaks from both directions is to look at the relative distance between peaks. Peaks with equal relative distance between them in both directions can be seen as parts of the same CIR. Figure 3.4 shows an example of common components between signals \( x^{(1)}[n] \) and \( x^{(2)}[n] \) based on the relative lag between peaks.
Figure 3.4: Example of relative lag between peaks. The distance between \( n_1 \) and \( n_3 \) is equal to the distance between \( n_2 \) and \( n_4 \).

Looking at the relative lag between the peaks, the time difference between the peaks in both signals should be equal. The lags between the signals then have the relation:

\[
 n_4 - n_2 = n_3 - n_1 \tag{3.23}
\]

Peaks that share the same relative distance to other peaks in both transmission directions can then be seen as common CIR peaks. The selection can then be based on the following algorithm. First, find all peaks that are above the threshold:

\[
 n_i^{(1)}, \quad i \in \{1, \ldots, I\}, \tag{3.24}
\]

\[
 n_j^{(2)}, \quad j \in \{1, \ldots, J\}, \tag{3.25}
\]

where \( n_i^{(1)} \) and \( n_j^{(2)} \) is a sample that has a peak. Secondly, the peak pair with the most common components is calculated according to:

\[
 f(i, j) = \sum_{l=1}^{I} \sum_{k=1}^{J} H(d - |(n_l^{(1)} - n_i^{(1)}) - (n_k^{(2)} - n_j^{(2)})|), \tag{3.26}
\]

where \( H(\ldots) \) is the Heaviside function defined in Equation (A.5), \( d \) can be seen as a sensitivity parameter that decides how big of an error that is allowed in the relative lag. The error of the relative lag can be formulated as:

\[
 \Delta n = |(n_l^{(1)} - n_i^{(1)}) - (n_k^{(2)} - n_j^{(2)})|, \tag{3.27}
\]
which expands into the argument for the Heaviside function to:

\[ f(i, j) = \sum_{l=1}^{I} \sum_{k=1}^{J} H(d - \Delta n), \]  

(3.28)

so that the Heaviside function is positive when

\[ d > \Delta n. \]  

(3.29)

The sensitivity parameter \( d \) is set to a small fixed value to allow as few wrongfully matched relative lag pairs to pass as possible. The selected peaks can then be the peaks \( i \) and \( j \) that maximize \( f(i, j) \), since it is the peak pair that has the largest number of common peaks with relative distance. In the case where there is only one peak detected in any of the directions, the algorithm defaults to using the peaks with the highest energy. That is, the algorithm will behave in the same manner as the max peak selection described in Section 3.2.1.

### 3.3 Testing and Evaluation

#### 3.3.1 Testing

The algorithms will be tested on the two separate data streams, and the combined data stream. Currently, the algorithm is only running on the combined beam data, which is why it is interesting to see the performance compared by using only a separate beam. Further, the algorithms will be tested using two different thresholds, 21 mW and 36 mW.

#### 3.3.2 Evaluation

The results of the algorithms will be evaluated based on the accuracy in which the algorithms select a valid signal pair. For each sample pair used for testing, a number of correct signal pairs is predetermined. If an algorithm selects a pair that matches the correct pairs, the selection is considered correct. The selection can be described by the following algorithm:
Algorithm 1

How to determine if a signal pair selected by an algorithm is valid

for each correct signal pair do
    if $|p_{c}^{(1)} - p_{A}^{(1)}| = 0$ and $|p_{c}^{(2)} - p_{A}^{(2)}| = 0$ then
        Selected signal pair is correct.
    end if
end for

Where $p_{c}$ is the correct peak in each direction and $p_{A}$ is the peak selected by the algorithm.
Method
Chapter 4

Results

The different peak selection algorithms were tested on synchronization signals that were transmitted using one polarization. The receiver then captured two data streams, one using the same polarization as the transmitted signal, in this chapter referred to as data stream 0. The second data stream was captured using an orthogonal polarization and is referred to as data stream 1. The two data streams are then combined into a combined data stream, referred to as the Combined data stream. The number of pairs to test on varies for each data stream based on the criteria stated in Section 3.1.2. Throughout this chapter, abbreviations will be used to refer to the different peak selection algorithms. The algorithms and the abbreviations are stated in Table 4.1.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Abbreviation</th>
<th>Described in Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max peak selection</td>
<td>Max</td>
<td>3.2.1</td>
</tr>
<tr>
<td>Multiplication selection</td>
<td>Mult</td>
<td>3.2.3</td>
</tr>
<tr>
<td>Relative lag matching</td>
<td>Relative</td>
<td>3.2.5</td>
</tr>
<tr>
<td>Cross-correlation selection</td>
<td>XCorr</td>
<td>3.2.2</td>
</tr>
<tr>
<td>Combining cross-correlation and multiplication</td>
<td>XMult</td>
<td>3.2.4</td>
</tr>
</tbody>
</table>

Table 4.1: Abbreviations used for the different peak selection algorithms.

For all tests, the sensitivity parameter $d$ in the relative lag matching algorithm, see Equation (3.26), is set to a small fixed value of 5, which gives that the relative distance can have a maximum error of 5 samples to be considered correct.
4.1 Minimum Peak Threshold of 36 mW

Table 4.2 shows the results for when the minimum peak threshold was set to 36 mW. The table also shows the absolute number of correctly selected peak pairs. The accuracy of each algorithm is shown in Table 4.3. It shows that all proposed algorithms perform significantly better than the max peak selection, with the multiplication selection having the highest overall accuracy. When the threshold was set to 36 mW, the number of valid test pairs is rather low for the separate data streams compared to the combined data stream.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>No. tests</th>
<th>Max</th>
<th>Mult</th>
<th>Relative</th>
<th>XCorr</th>
<th>XMult</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2074</td>
<td>1769</td>
<td>2035</td>
<td>2025</td>
<td>1966</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1259</td>
<td>881</td>
<td>973</td>
<td>924</td>
<td>925</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>3786</td>
<td>2265</td>
<td>3452</td>
<td>2713</td>
<td>3078</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Results of the different algorithms with the threshold set to 36 mW. The numbers of each algorithm correspond to the numbers of correctly selected peak pairs.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>No. tests</th>
<th>Max (%)</th>
<th>Mult (%)</th>
<th>Relative (%)</th>
<th>XCorr (%)</th>
<th>XMult (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2074</td>
<td>85.3</td>
<td>98.1</td>
<td>97.6</td>
<td>94.8</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1259</td>
<td>70.0</td>
<td>77.3</td>
<td>73.7</td>
<td>73.5</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>3786</td>
<td>60.0</td>
<td>91.2</td>
<td>78.8</td>
<td>81.3</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Results of the different algorithms in percentage with the threshold set to 36 mW.

4.2 Minimum Peak Threshold of 21 mW

The result of the algorithms when the threshold was lowered to 21 mW is shown in Figure 4.4 and Figure 4.5. The overall number of tests increased greatly when the threshold was lowered, especially for the separate data streams. The overall accuracy of the algorithms was lowered as a result of the threshold allowing for more slack and might in some cases allow unwanted peaks to pass. Again, the multiplication selection algorithm had the highest overall accuracy among all data streams.
### Results

<table>
<thead>
<tr>
<th>Data stream</th>
<th>No. tests</th>
<th>Max</th>
<th>Mult</th>
<th>Relative</th>
<th>XCorr</th>
<th>XMult</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3157</td>
<td>2572</td>
<td><strong>3043</strong></td>
<td>2969</td>
<td>2995</td>
<td>2918</td>
</tr>
<tr>
<td>1</td>
<td>2694</td>
<td>1349</td>
<td><strong>1915</strong></td>
<td>1738</td>
<td>1674</td>
<td>1711</td>
</tr>
<tr>
<td>Combined</td>
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<td>2522</td>
<td><strong>3871</strong></td>
<td>2798</td>
<td>3385</td>
<td>3462</td>
</tr>
</tbody>
</table>

Table 4.4: Results of the different algorithms with the threshold set to 21 mW. The numbers of each algorithm correspond to the numbers of correctly selected peak pairs.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>No. tests</th>
<th>Max (%)</th>
<th>Mult (%)</th>
<th>Relative (%)</th>
<th>XCorr (%)</th>
<th>XMult (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3157</td>
<td>81.5</td>
<td><strong>96.4</strong></td>
<td>94.0</td>
<td>94.9</td>
<td>92.4</td>
</tr>
<tr>
<td>1</td>
<td>2694</td>
<td>50.1</td>
<td><strong>71.1</strong></td>
<td>64.5</td>
<td>62.1</td>
<td>63.5</td>
</tr>
<tr>
<td>Combined</td>
<td>4415</td>
<td>57.1</td>
<td><strong>87.7</strong></td>
<td>63.4</td>
<td>76.7</td>
<td>78.4</td>
</tr>
</tbody>
</table>

Table 4.5: Results of the different algorithms in percentage with the threshold set to 21 mW.

### 4.3 Large Time Offsets

To see how the algorithms handled larger synchronization offsets, the CIR was shifted by 50 samples in one of the transmission directions:

\[
y_{MF}^{(2)}[n] = y_{MF}^{(2)}[n - 50]. \tag{4.1}
\]

The accuracy of the different algorithms is shown in Table 4.6. It shows that the accuracy of all algorithms was kept the same, with the exception of the multiplication algorithm, which accuracy dropped to zero. An interesting observation is that for all the different data streams, the algorithm with the highest accuracy changed.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>No. tests</th>
<th>Max (%)</th>
<th>Mult (%)</th>
<th>Relative (%)</th>
<th>XCorr (%)</th>
<th>XMult (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2074</td>
<td>85.3</td>
<td>0</td>
<td><strong>98.0</strong></td>
<td>97.6</td>
<td>94.8</td>
</tr>
<tr>
<td>1</td>
<td>1259</td>
<td>70.0</td>
<td>0</td>
<td>73.4</td>
<td><strong>73.7</strong></td>
<td>73.5</td>
</tr>
<tr>
<td>Combined</td>
<td>3786</td>
<td>60.0</td>
<td>0</td>
<td>71.7</td>
<td>78.8</td>
<td><strong>81.3</strong></td>
</tr>
</tbody>
</table>

Table 4.6: Results of the different algorithms in percentage, with \(y_{MF}^{(2)}\) shifted 50 samples and the threshold set to 36 mW.
4.4 Channels Without Resolvable Multipath Components

There is no guarantee that the receiver will detect multiple instances of the transmitted synchronization signal. A very realistic scenario is that the receiver will only detect one peak above the threshold. It is then interesting to see how the algorithms perform in a situation where only one peak is detected in one of the transmissions and one or multiple peaks in the other. When only one peak was detected in one of the transmissions, the algorithms all perform similar. The best-performing algorithm was the multiplication selection for both data stream 0 and data stream 1, while the combination of the cross-correlation and multiplication selection had the highest accuracy on the combined data stream. The accuracy for transmissions where only one peak is detected is shown in Tables 4.7 and 4.8.

<table>
<thead>
<tr>
<th>Data Stream</th>
<th>No. tests</th>
<th>Max</th>
<th>Mult</th>
<th>Relative</th>
<th>XCorr</th>
<th>XMult</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>661</td>
<td>626</td>
<td><strong>642</strong></td>
<td>626</td>
<td>641</td>
<td>611</td>
</tr>
<tr>
<td>1</td>
<td>239</td>
<td>168</td>
<td><strong>199</strong></td>
<td>168</td>
<td>174</td>
<td>171</td>
</tr>
<tr>
<td>Combined</td>
<td>1123</td>
<td>976</td>
<td>1033</td>
<td>976</td>
<td>969</td>
<td><strong>1037</strong></td>
</tr>
</tbody>
</table>

Table 4.7: Results of the different algorithms when only one peak was detected in one of the transmissions. The threshold was set to 36 mW.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>No. tests</th>
<th>Max (%)</th>
<th>Mult (%)</th>
<th>Relative (%)</th>
<th>XCorr (%)</th>
<th>XMult (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>661</td>
<td>94.7</td>
<td><strong>97.1</strong></td>
<td>94.7</td>
<td>97.0</td>
<td>92.4</td>
</tr>
<tr>
<td>1</td>
<td>239</td>
<td>70.3</td>
<td><strong>83.3</strong></td>
<td>70.3</td>
<td>72.8</td>
<td>71.6</td>
</tr>
<tr>
<td>Combined</td>
<td>1123</td>
<td>86.9</td>
<td>92.0</td>
<td>86.9</td>
<td><strong>92.3</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.8: Results of the different algorithms in percentage, when only one peak was detected in one of the transmissions. The threshold was set to 36 mW.

4.5 Multipath Channels

When multiple peaks are detected by the receiver, it is the result of multipath propagation. The aim of the thesis was to improve the peak selection algorithm’s robustness in multipath environments. It is then important to see how the algorithms perform in the scenario where multiple peaks
are detected. Tables 4.9 and 4.10 shows the performance of the different algorithms when there are at least 2 peaks detected in both transmissions. It shows that for data stream 0, the relative lag matching algorithm was the best-performing algorithm, while for data stream 1 and the combined data stream, the multiplication selection algorithm had the highest accuracy.

<table>
<thead>
<tr>
<th>Data Stream</th>
<th>No. tests</th>
<th>Max</th>
<th>Mult</th>
<th>Relative</th>
<th>XCorr</th>
<th>XMult</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1413</td>
<td>1143</td>
<td>1393</td>
<td>1406</td>
<td>1384</td>
<td>1355</td>
</tr>
<tr>
<td>1</td>
<td>1020</td>
<td>713</td>
<td>774</td>
<td>756</td>
<td>754</td>
<td>754</td>
</tr>
<tr>
<td>Combined</td>
<td>2663</td>
<td>1289</td>
<td><strong>2419</strong></td>
<td>1737</td>
<td>2015</td>
<td>2041</td>
</tr>
</tbody>
</table>

Table 4.9: Results of the different algorithms when there were at least two peaks in both transmission directions. The threshold was set to 36 mW.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>No. tests</th>
<th>Max (%)</th>
<th>Mult (%)</th>
<th>Relative (%)</th>
<th>XCorr (%)</th>
<th>XMult (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1413</td>
<td>80.9</td>
<td>98.6</td>
<td><strong>99.5</strong></td>
<td>98.0</td>
<td>95.9</td>
</tr>
<tr>
<td>1</td>
<td>1020</td>
<td>69.9</td>
<td><strong>75.9</strong></td>
<td>74.1</td>
<td>73.9</td>
<td>73.9</td>
</tr>
<tr>
<td>Combined</td>
<td>2663</td>
<td>48.4</td>
<td><strong>90.8</strong></td>
<td>65.2</td>
<td>75.7</td>
<td>76.6</td>
</tr>
</tbody>
</table>

Table 4.10: Results of the different algorithms in percentage when there were at least two peaks in both transmission directions. The threshold was set to 36 mW.

From Table 4.10 it shows that all the proposed algorithms have significantly higher accuracy in multipath scenarios compared to the max peak selection.
Chapter 5

Discussion

5.1 Accuracy of Algorithms

Overall, the accuracy of all the proposed algorithms performed better than the max peak selection algorithm. On the raw data, the multiplication selection algorithm had the highest accuracy. But in a scenario where the data from one of the transmissions was shifted to illustrate what would happen if the base stations were more out of sync, the performance of the multiplication selection algorithm was dropped to zero. This shows that in this specific network, the algorithm was robust to the multipath environment, but would fail significantly if the synchronization was off by a large enough margin. The combination between cross-correlation and multiplication selection is shown to bring no improvement in terms of accuracy compared to the two algorithms on their own, which renders the algorithm redundant.

When there is only one peak detected in one of the transmission directions, the accuracy for all algorithms is kept rather high. The performance of max peak selection and relative lag matching is identical, which is expected since the algorithm is the same when there is only one peak in any of the directions. When the number of peaks increases due to multipath propagation, the overall performance of all algorithms drops quite heavily.

5.2 Threshold

In this thesis, a fixed value for the threshold was used that was applied to the data of all different base station pairs. However, using the same threshold for all pairs is quite harsh. Instead, it would be beneficial to have different thresholds for the different base station pair based on their conditions. Many
factors can affect what threshold should be used, such as the direction of the antennas or the distance between the base stations. So, looking into the needs of each different base station pair and setting a threshold based on their prerequisites is something that should be considered.

### 5.3 Computational Complexity

Throughout this thesis, the complexity of the algorithms has not been considered, the focus has instead been on accuracy. However, in real-time systems, computational complexity is vital, especially in time-sensitive networks such as telecommunication. This is where the max peak selection algorithm has its big advantage; its simplicity is a huge benefit in terms of computational complexity. Operations such as cross-correlation have a much higher computational complexity, which might make algorithms that use cross-correlation unusable or less favorable in real-time systems. Even though the algorithms that use cross-correlation, in this thesis the cross-correlation selection and the combination between cross-correlation and multiplication selection, have among the highest overall accuracy, their usage might be limited due to their complexity. A rough characterization of the algorithm’s complexities is shown in Table 5.1. To lower the computational cost of cross-correlation, one could limit the number of lags it is calculated for. For example, just calculate the lags corresponding to the maximum allowed synchronization error. Another way to try to lower the computational cost could be to set all the values except any peaks to zero. However, this would have to be tested to see how the accuracy is affected. The multiplication selection on its own performs well, and its complexity is as high as the previously mentioned algorithms. However, the robustness to synchronization offset is very low and therefore the usage as a time misalignment algorithm greatly diminishes. Looking at the relative lag matching, the number of computations needed varies depending on how many peaks are detected. At the moment, the algorithm uses all peaks above the threshold, but there is potential to modify the algorithm in order to reduce the amount of computation needed.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Max</th>
<th>Mult</th>
<th>Relative</th>
<th>XCorr</th>
<th>XMult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>$\mathcal{O}(N)$</td>
<td>$\mathcal{O}(N)$</td>
<td>$\mathcal{O}(l^2), \mathcal{O}(lJ), \mathcal{O}(N)$</td>
<td>$\mathcal{O}(N^2)$</td>
<td>$\mathcal{O}(N^2)$</td>
</tr>
</tbody>
</table>

Table 5.1: Characterization of the complexity of the different algorithms, based on the amount of samples $N$ or the number of peaks detected $l$ or $J$. 
5.4 Different Data Streams

The results for the different data streams are limited to this specific network and its topology. It is easy to assume that since data stream 0 has the best accuracy and therefore the algorithm should always run on data stream 0. However, while data stream 0 has the best results overall in this network, the results might differ between different networks. The wireless channel will change between networks and their base stations, and it is never obvious how the wireless channel will impact the transmitted signals. This is why the combined stream is widely used, and is the main data stream used in real systems. But, it might be interesting to look into the specific base station pairs to see if there is a dominant data stream that produces better results and thus apply synchronization algorithms to that data stream. However, this will be limited to the individual base station pairs, since general assumptions can be faulty. An example of data from the different data streams is shown in Figure 5.1. In Figure 5.1a there is one clean peak while Figure 5.1b shows quite messy data. In the combined data stream shown in Figure 5.1c, two peaks are clearly visible. One main peak, and a smaller side peak, clearly influenced by the data from data stream 2. An interesting observation is that in scenarios where there are multiple peaks detected, the algorithm performance on data stream 1 is significantly better than on data stream 2 and the combined data stream. The overall lower performance for the combined data stream might also be the result of the data stream combining method being suboptimal.

![Figure 5.1](image-url)

(a) Data from stream 1. (b) Data from stream 2. (c) Data from the combined stream.

Figure 5.1: The data from different data streams from a synchronization signal transmission.
Discussion
Chapter 6
Conclusions

6.1 Future work

Future studies in the peak selection algorithms could involve looking deeper into the Relative Lag Matching algorithm. The algorithm can be modified for potential improvements. At the moment, it uses all detected peaks in both transmission directions. If \( I \) peaks are detected in one direction and \( J \) peaks are detected in the other. The algorithm needs to test \( I \times J \) hypotheses before selecting a peak pair. This could be limited to only using a set number of peaks in each direction, such as the \( I \) highest peaks in each transmission. Thus, potentially reducing the number of hypotheses tested and sets the complexity of the algorithm so that the worst scenario is always known. Pushing this further, the algorithm could be limited to always select the maximum peak in one transmission direction and the \( I \) highest peaks in the other. This is under the assumption that it is unlikely that the highest peak in one direction is not a peak in the other direction. This gives the need to only test \((2I - 1)\) different hypotheses. Another part of the algorithm that could change is the sensitivity parameter \( d \). In this thesis, \( d \) has been used at a fixed level. One could look into having a scaling \( d \), where the allowed slack is increased as the number of detected peaks is increased. However, then the peak pair selection used at the moment, to maximize \( f(i, j) \), has to be reconsidered. Allowing a higher \( d \) would make the algorithm more error-prone, then, maximizing \( f(i, j) \) can result in a wrongful pair selection if \( d \) is too large.

Another aspect of future studies could involve looking into using artificial neural networks to help with calculating the time alignment error. One such artificial neural network could be a siamese neural network. A siamese neural network takes two separate inputs and runs them through two different neural
networks, and then compares the output from the networks [24]. The inputs to the siamese neural network in this case could be the output from the matched filters, $y_{MF}^{(1)}$ and $y_{MF}^{(2)}$.

Furthermore, it could be interesting to more in-depth study the different beam polarizations for the data streams. As it is now, the transmitter is sending in one polarization while the receiver is receiving in two different polarizations. One that is the same as the transmitting polarization and the second polarization is orthogonal to the first. The results show that the accuracy is much higher on the data stream that is received in the same polarization as the transmitted polarization, and that the combined data stream has a much lower accuracy. So it would be interesting to study the reciprocity of a channel between a pair of base stations for the different beam polarization. Another aspect is that the method used for combining the two data streams might not be optimal. Further studies into the steam combining method could be interesting to see if other methods would yield a higher performance on the combined data stream.

### 6.2 Conclusions

This thesis has presented multiple algorithms for peak selection. The proposed algorithms have been shown to perform better than the previously used algorithm. When looking at scenarios where multiple signals were detected, signals that were subject to multipath propagation, the performance is shown to be significantly better for the algorithms suggested in this thesis. However, the algorithms suggested in this thesis all come with a higher computational complexity. In real-time systems, time complexity and computational costs are highly relevant factors, where the need for a quicker and less resourceful algorithm might be preferred at the cost of lower accuracy.
References


Appendix A

Useful Definitions

A.1 Cross-correlation

Cross-correlation describes how two signals are correlated with each other. The cross-correlation for time continuous signals is defined by:

\[
 r_{xy}(\tau) = \int_{-\infty}^{\infty} \overline{x(t)} y(t + \tau) dt, \quad (A.1)
\]

where \( \overline{x(t)} \) is the complex conjugate of \( x(t) \) and \( r_{xy}(\tau) \) is the cross-correlation between signals \( x(t) \) and \( y(t) \) [25].

For time discrete signals, the cross-correlation is defined by:

\[
 r_{xy}[k] = \sum_{n=-\infty}^{\infty} \overline{x[n]} y[n + k], \quad (A.2)
\]

where \( \overline{x[n]} \) is the complex conjugate of \( x[n] \) [26].

A.2 Dirac-delta function

The Dirac-delta function is defined as [27]:

\[
 \delta(x) = \begin{cases} 
 0, & x \neq 0 \\
 \infty, & x = 0 
\end{cases}, \quad (A.3)
\]

with the characteristic:

\[
 \int_{-\infty}^{\infty} \delta(x) dx = 1. \quad (A.4)
\]
A.3 Heaviside function

The Heaviside step function is defined as:

\[ H(x) = \begin{cases} 
1, & x > 0 \\
0, & x \leq 0 
\end{cases} \]  

(A.5)