Quasi Co-location Type-D relation between hierarchical beams in a Grid of Beams setup.

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Preface

In this report, the results of my research project are presented in fulfillment of the Masters of Science degree in Telecommunication Engineering at Politecnico di Torino. The research project has been carried out at Ericsson Luleå Research Centre premises.

First of all, I would like to thank my supervisor at Ericsson, Anders Landström who I look up to, for the support, guidance, feedback and the valuable insights throughout this journey. Also, I would like to thank Sven-Olof Jonsson for the guidance and for offering me this challenging yet incredible and rewarding opportunity. I want to thank Arne, Mats, Magnus, Medhat, Kjell, Sara, Marika and Peter, who assisted me and had their doors always opened for me. I want also to thank Ingela for her support and motivation. I have learned a lot from everyone at Ericsson, and I'm forever grateful and thankful for this opportunity.

From the university, I would like to thank my academic supervisor Prof. Roberto Garello for his support, throughout the thesis and the academic courses.

Further I want to thank my parents for their endless support, for being my backbone, for believing in me and for being always there for me. I credit them for who I am today.

Finally I want to thank my girlfriend Viktoria for her endless motivation and for being always next to me throughout this journey.

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Abstract

In NR, Beam forming based directional links, require fine alignment of the transmitter and receiver beams, achieved through a set of operations known as beam management. One mode of operation is beam management with indication, where a concept known as Quasi-co-location (QCL) is used to provide an instruction to the UE which it can use to adjust receiver settings.

Different QCL types and relations were defined by 3GPP. This work sheds light on QCL-Type-D relation specifically, which governs spatial relations between different antenna ports/beams. An investigation of the accuracy of the QCL-Type-D relation between Parent(Wide) and children(Narrow) beams in *LOS* and *NLOS* scenarios is presented, using field measurements from a 3GPP Release 15-compliant Ericsson 5G test-bed.

The analysis showed higher accuracy in the reception of the children beams (strongest child beam) and their(its) parent beam in *LOS* scenarios compared to *NLOS* scenarios when using spatial QCL indication. Moreover, the QCL-Type-D accuracy between the parent/children beams is shown to improve as the children tend to look similar to their parent beam. Finally, an estimate of the power losses endured in the reception of the strongest child beam due to a wrong QCL indication was provided.

Contents

1 Terminology

Abbreviation	**Explanation**
BM	Beam-Management
CSI	Channel State Information
CSI-RS	Channel State Information Reference Signal
DCI	Downlink Control Information
DL	DownLink
GoB	Grid of Beams
NLOS	Non Line of Sight
NR	New Radio
NB	Narrow Beam
LOS	Line of Sight
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
RACH	Random Access Channel
RS	Reference Signal
RSRP	Reference Signal Received Power
Rx	Receiver
SS	Synchronization Signal
SSB	Synchronization Signal Block
TP	Transmission Point (Base station)
Tx	Transmitter
UE	User Equipment
WB	Wide Beam

2 Introduction

To support 5G use cases, the decision to move towards higher frequency bands was taken. This implied higher power losses, especially in the mmWave bands due to the nature of such higher frequency electromagnetic waves, where most 5G signals, unlike most LTE ones, are not capable of traveling long distances (over a few hundred meters), and cannot easily penetrate solid objects, like cars, trees and walls, decreasing the cell's coverage, especially in Urban environments.

Beam forming was suggested to counter these challenges, using multi-antenna arrays and signal processing techniques to direct the signals' power in a certain direction in space,reducing interference and guaranteeing high SNR, especially for edge users[7]. The benefits of beam forming can also be utilized at lower frequencies. Beam forming require an accurate alignment of transmitted and received beams to guarantee the required end to end performance. For that, beam management(BM) operations were introduced in 5G NR. One of the introduced BM operations that serve the alignment process is beam indication using QCL-Type-D relation, where the TP (Transmission Point) provides an indication which the UE can use to adjust its Rx beam.

This work investigates how valid the QCL-Type-D relations are between hierarchical beams in a Grid of Beams (GoB) setup, mainly focusing on the narrow children beams and their QCL-Type-D validity with respect to their wider parent beams. The analysis is performed on Sub-6 field measurements from a 3GPP Release 15-compliant Ericsson 5G test-bed.

3 Grid of Beams (GoB) with Beamformer Receiver

A Grid of Beams, as the name implies, relies on predefined beams with different fixed directivity in space to run beam-management operations. The beams are formed using antenna combinations and antenna weights, which gives them their gain shape and their orientation in space. Wide beams are considered as parent beams for a set of children Narrow beams, where the latter lie under the gain umbrella of their corresponding parent beam (see Fig. 1). Generally speaking, in a GoB setup an antenna port can be simply defined as a beam carrying a reference signal and having a fixed orientation in space .

It should be noted that Fig.1 is an example used only for clarification, and is not related to the actual GoB used in the test-bed. In this work, different sets

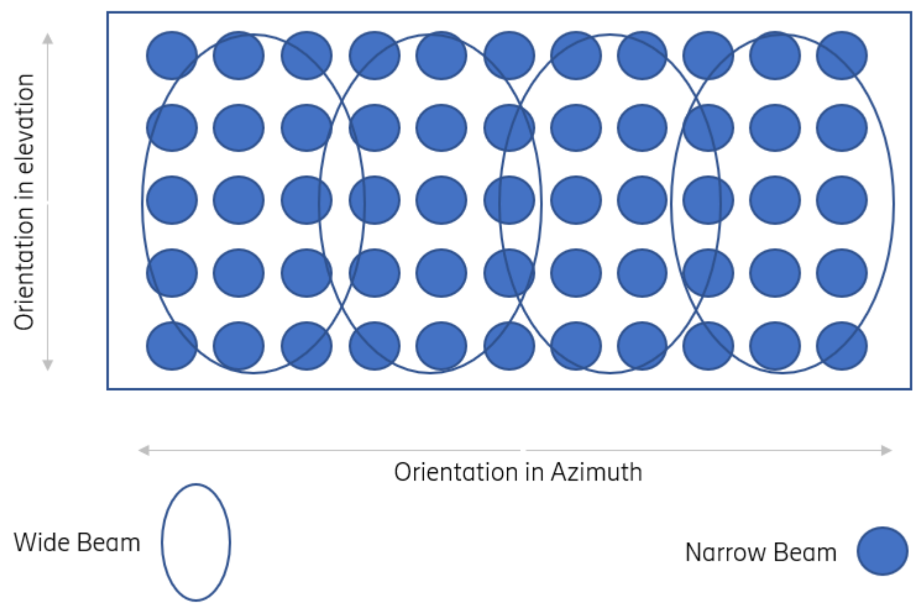


Figure 1: Grid of Beams Example

of Synchronization Signal(SS) beams are used to represent both the Narrow and the Wide beams. Each set of SS beams have a different shape(Gain shape) with respect to the other sets(This will be further illustrated in Section 6.2). Thus, a parent/child beam relation can be established between the different SS beams extracted from different sets..

3.1 Initial Beam Establishment

Upon entering the cell, the UE waits for the Synchronization Signal Block (SSB) which is sent periodically by the TP on a set of N different wide beams in an SS burst. N depends on the system implementation. Once the UE has identified the best SSB beam. It then transmits a PRACH on a random access occassion(RO). The preamble and the RO chosen refer to the best SSB beam.
The UE can then rely on the initial Rx beam direction for the reception and transmission of subsequent DL and UL streams respectively. This can be relevant especially in TDD schemes due to channel reciprocity.
After deciding on the initial beam pair on both sides, the UE and the TP exchange Msg2, Msg3, and Msg4. The TP and UE have established coarse beams for Tx and Rx, respectively, and in Msg4, the UE has received the Channel State Information Reference Signal (CSI-RS) configuration for the cell.

3.2 GoB DL Beam Refinement and Adjustment

As illustrated in Figure 2, in the next step, the TP schedules a set of CSI-RS-BM (CSI-RS for Beam-management) on a selected set of narrow beams and transmits them. The UE measures on all of them and returns a measurement report based on the Reference Signal Received Power (RSRP) , using the PUCCH (Physical Uplink Control Channel) or PUSCH (Physical Uplink Shared Channel).
The report is processed by the TP, which then adjusts its Tx beam accordingly.[5]

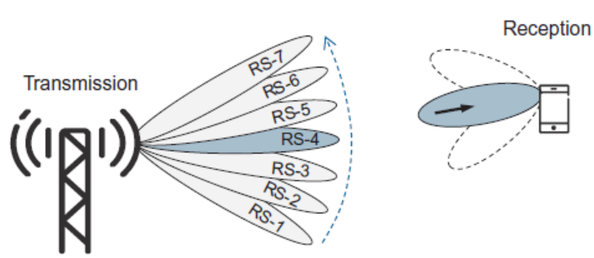


Figure 2: Refinement of Tx beams. Image courtesy of Erik Dahlman

3.3 Further steps

The TP now knows the best beam direction for the UE in which link adaptation can be carried out. The decision of the number of layers, modulation and the TP side precoding matrix is taken by the TP based on the UE's measurements and feedback on a transmitted set of CSI-RS in the downlink. Those reference signals are transmitted in the direction of the previous best received CSI-RS-BM towards the UE. The UE then reports back a set of report quantities (CQI, RI, ..etc) requested by the TP for the establishment of a multi-layer DL transmission if possible.

4 Quasi Co-location

On the UE side, the UE's receiver beam can be adjusted to guarantee a good beam pair selection, by following a beam sweeping operation where the TP repeatedly transmits a CSI-RS in direction of the previously best chosen beam during the initial beam establishment step, while the UE sweeps its receiver beam to find the best beam pair or by relying on a QCL indication by the TP. QCL is defined by the following statement:

"Two antenna ports are said to be quasi co-located if the properties of the channel over which a symbol on one antenna port is conveyed can be inferred from the channel over which a symbol on the other antenna port is conveyed."[6]

3GPP defined four possible QCL types, each of them holds a subset of channel parameters. The QCL types are defined as following[1] :

- QCL-Type-A: Doppler shift, Doppler spread, Average delay, Delay spread
- QCL-Type-B: Doppler shift, Doppler spread
- QCL-Type-C: Doppler shift, Average delay
- QCL-Type-D: Spatial Rx parameter

Generally speaking, stating that two antenna ports are QCL, indicates that these two, relative to a certain UE, witness similar large-scale channel properties according to the QCL type/relation indicated.
For example, saying that two antenna ports are spatially quasi co-located (QCL-Type-D) with respect to a certain UE with beamforming capabilities, indicates that, if the UE knows that a certain receiver beam direction is good to receive

one of the signals, it can assume that the same beam direction is suitable also for the reception of the other signal being the scheduled port.[5]

QCL framework was introduced initially to support the Coordinated Multi-Point transmission (CoMP) in Release 11, defining relations between reference signals transmitted from the same TP operating in a CoMP environment.
Back then, QCL relations constituted of the first three types mentioned above only. After introducing beam forming and multi-antenna transmissions at both the TP and the UE sides, and due to the dependence of the transmission and the reception on the angle of arrival and departure, spatial QCL relation (Type - D) was introduced in NR Release-15. These QCL relations may be useful for the receiver to know which assumptions it can make on the channel corresponding to different transmission. For example, it's useful for the receiver to know which large scale properties it can use when estimating the channel, in order to decode a transmitted signal. QCL-Type-D can be used to provide spatial relations (Considered as large scale channel property) between different reference signals, and thus help the UE select an analog Rx beam for their reception.[8] 3GPP defined the allowed possible QCL relations between different antenna ports. This is illustrated in Figure 3.

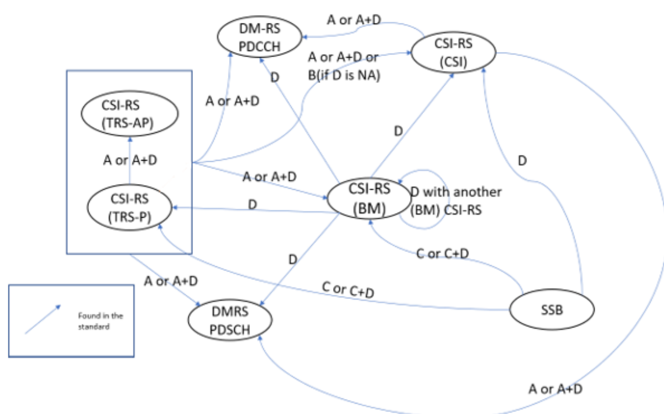


Figure 3: QCL relations defined by 3GPP.[1]

5 Beam Indication using QCL relations

Initially, the TP indicates for the UE the activation of a set of Transmission Configuration Indicator (TCI) states referring to Downlink RS antenna ports. The states refer to CSI-RS and/or SSB, and a corresponding QCL relation type from the four defined types for each RS[6]. Each TCI state can contain a maximum of two DL-RS with two non-intersecting QCL relations (see Fig. 4).

```
-- ASN1START
-- TAG-TCI-STATE-START

TCI-State ::=                       SEQUENCE {
    tci-StateId                         TCI-StateId,
    qcl-Type1                           QCL-Info,
    qcl-Type2                           QCL-Info
OPTIONAL,   -- Need R
    ...
}

QCL-Info ::=                        SEQUENCE {
    cell                                ServCellIndex
OPTIONAL,   -- Need R
    bwp-Id                              BWP-Id
OPTIONAL, -- Cond CSI-RS-Indicated
    referenceSignal                     CHOICE {
        csi-rs                              NZP-CSI-RS-ResourceId,
        ssb                                 SSB-Index
    },
    qcl-Type                            ENUMERATED {typeA, typeB, typeC, typeD},
    ...
}

-- TAG-TCI-STATE-STOP
-- ASN1STOP
```

Figure 4: Transmission Configuration Indication (TCI) state.[3]

Now, the UE knows which RS resources it is supposed to measure on and monitor and which channel parameters it should update, all depending on the QCL relation corresponding to the RS in the activated TCI states. As mentioned before, for QCL Type-D relations, the UE tries to find a suitable Rx direction for these RS. When the TP decides to schedule resources for a certain UE on a beam which is spatially quasi-colocated with a previously transmitted beam; which is in turn monitored by the UE throughout its activated TCI states, an indication referring to this TCI state included inside the Downlink Control Information (DCI) is scheduled for this UE. If the difference between the reception of the PDSCH and the received PDCCH scheduling it is more than a threshold of N symbols, the UE follows the QCL relation indicated and aims its Rx beam accordingly. If there's no indication, then the UE assumes that the TCI state or the QCL assumption for the PDSCH is identical to the TCI state or QCL assumption applied for the PDCCH reception[6]. The threshold N is based on reported UE capability [2], which is related to the time needed by the Rx to direct its beam in the suitable direction to receive the scheduled port. During the UE's session, it's the TP's duty to update the activated TCI states occasionally, which the UE monitors and updates its Rx settings correspondingly.

In the following example, each CORESET can be configured with a transmission configuration indication (TCI) state, that is, providing information of the antenna ports with which the PDCCH DMRS antenna ports are quasi co-located. If a CORESET is considered spatially co-located with a certain CSI-RS, the device can determine which Rx beam is appropriate when attempting to receive the PDCCH in this CORESET, as illustrated in Figure 5. Two CORESETs have been configured in the device, one CORESET with spatial QCL between DM-RS and CSI-RS #1, and one CORESET with spatial QCL between DM-RS and CSI-RS #2. Based on CSI-RS measurements, the device has determined the best reception beam for each of the two CSI-RS:es (After a CSI-RS transmission occ asion). When monitoring CORESET #1 for possible PDCCH transmissions, the device knows the appropriate reception beam (similarly for CORESET #2). In this way, the device can handle multiple reception beams on different symbol's time.[4]

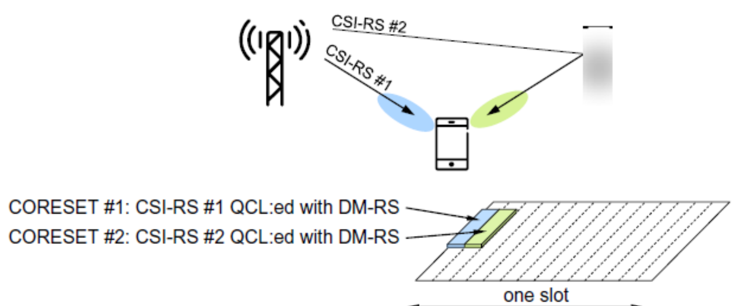


Figure 5: Image Courtesy of Erik Dahlman[4]. Quasi Co-location Type-D indication between PDCCH and CSI-RS.

6 Experiment Background

The experiment took place in an urban environnent in Kista, Stockholm.

6.1 Terrain and UE description

The terrain and the path taken by the UE is formed by LOS and N-LOS locations with respect to the BS, the terrain and the test-bed route are shown in Figures 6 and 7 :

Figure 6: Experiment Terrain

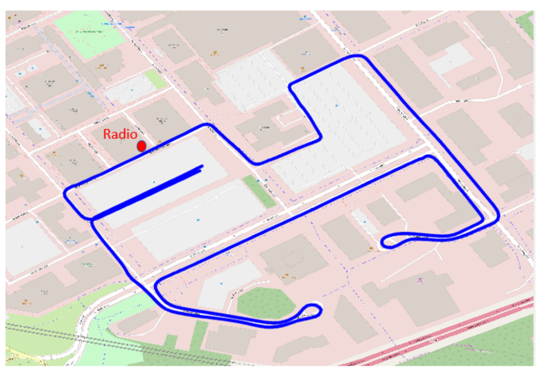


Figure 7: UE Trajectory

The UE test-bed was formed by four cross-polarized antennas, orthogonally directed in Azimuth each with a 90° wide gain sector. The UE emulates a multi-panel or beam forming receiver which can receive and distinguish signals from different directions. The gain of the antenna elements is presented in Figure 8.

It should be noted that the characteristics of the *strongest* signal received on a certain antenna panel are logged. Thus, the logged entities refer only to the

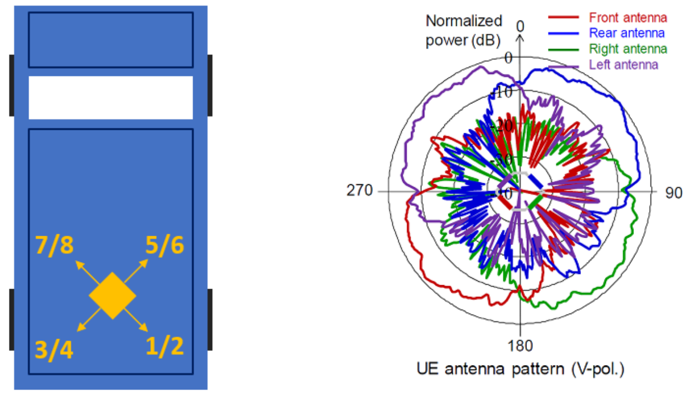
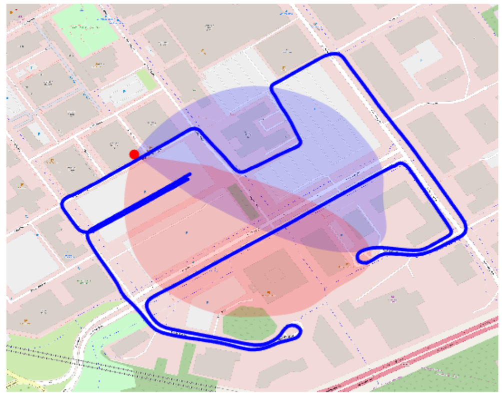


Figure 8: UE Antenna Gain and Directivity

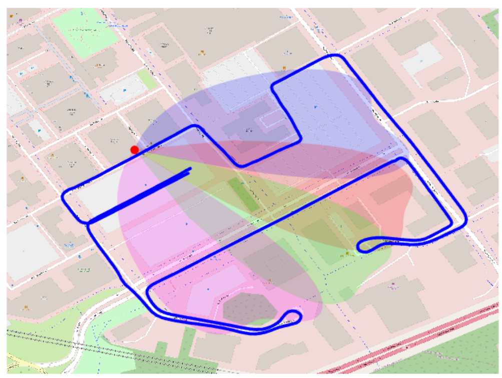
strongest signal which is received on an antenna panel having its directivity in one of the four directions.

6.2 Used beams and the Logs

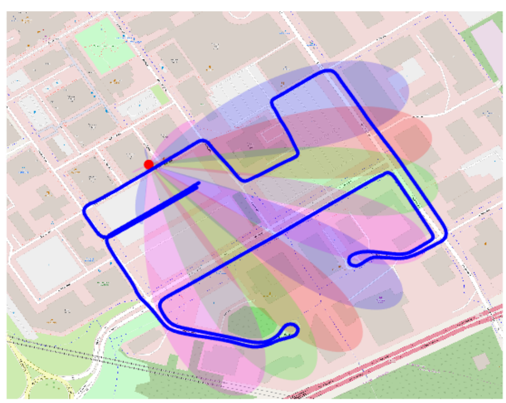
The TP has various SSB beam setups, each setup consisting of different number of transmitted SSB wide beams, with different beam shapes.
In this work, three sets of SSB beams were used. Each set constituted of a number of SSB beams having different shapes compared to the other SSB beams included in the other sets. The different sets of SSB beams with their gain distribution across the terrain are illustrated in Figure 9. The sets of Two and Four SSB beams used were transmitted in the same experiment during the same UE route, while the set of Eight beams were transmitted in a different experiment. The Eight SSB beams represent the Narrow beams in this work. The car drove the route again to collect the logs in each new experiment, implying different channel conditions between the measurements logs(On the one hand, the experiment containing the four and the two SSB's, on another hand the experiment containing the Eight SSB beams) due to dynamic traffic and slightly different exact UE path. The cell operates at 3.5 Ghz. The periodicity of transmission of the SSB beams was 20 ms, meanwhile the test-bed logging periodicity was 60ms, thus two transmission instances were lost between each two consecutive logged measurements.



(a) 2 SSB



(b) 4 SSB



(c) 8 SSB

Figure 9: Beam setups

7 Methodology

The main focus of this work is understanding the validity and accuracy of the Type-D indication, providing a spatial Rx relation at the UE side between the wide parent beams and the narrower children beams. In other words, the spatial QCL relation between the wide and narrow SSB beams (The Eight Narrow SSB beams actually have a close gain shape to the CSI-RS/CSI-RS-BM beams) is of special interest, especially in the GoB case for establishing a reliable data beam.

For clarification: in this work, a valid QCL-Type-D indication between two beams, means that the two the two signals transmitted on those beams were best received (in terms of RSRP) by the same antenna panel at the UE side.

7.1 SSB WB beams as a suitable guide for the NB

The SSB beams are not user-specific and thus can be utilized by all UE's, they have a static shape, directivity and their own periodic transmission occasion. For the QCL-Type-D property to be best utilized, the UE will try to update which Rx beam that should be used for each activated TCI state.

The SSB beams, due to their repetitive fashion and static shape, would be suitable and likely the most efficient beams (Non UE-specific) for the UE to carry measurements on and find the optimal receive direction of them. Moreover, the SSB beams will cover the cell, and will in fact be an umbrella for other narrower beams. Thus, it is of interest to know if the SSB can successfully act as a guide for the UE to adjust its own Rx beam and better receive the other narrower beams, by having a valid QCL-Type-D indication between them.

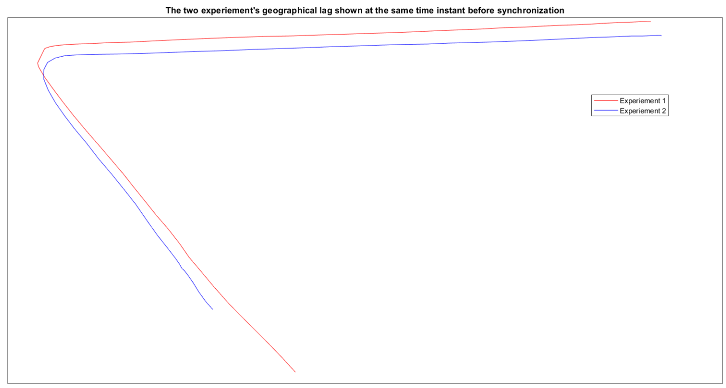
Beam sweeping is followed during what is called an 'SSB Burst' to transmit all the SSB beams one at a time, every 20ms. The UE will listen on and log the RSRP of the different transmitted SSB beams. Due to the test-bed setup, the logs indicate only the highest SSB RSRP obtained on an antenna in the most favorable direction to receive this signal at the UE side, and not on all antennas in all the four directions as mentioned before. In that way, the best receive direction among the four possible directions for all SSB beams is obtained at each logging instance; which corresponds to the best antenna panel Rx beam on the UE side.

7.2 Synchronizing the Logs

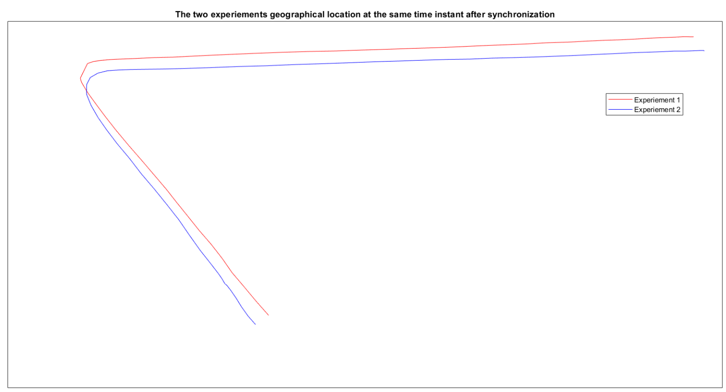
As mentioned before, the different two experiments (i.e measurement routes) using the different sets ($\{Four, Two\}$ beams,$\{Eight\}$ beams) of SSB beams were run separately. Thus, the UE geographic location logged using GPS had to be synchronized in time so that further comparisons between the entities of interest logged at the same UE geographical location in both experiments can run correctly, resulting in a comparable channel (disregarding the dynamic road traffic) witnessed by the UE in both experiments. The synchronization was done by considering a search window of variable size, which compensates for the geographical location mismatch between each experiment, by looking at the geographical location of the UE in one experiment at each logged instance, and finding it's corresponding closest logged sample in the second experiment, and then aligning them with each others. Figure 10 represents the location of the UE after 30s from the start in the two different experiments. We can see that before synchronization, the geographical UE location at the same time stamp differs. Doing comparisons of different entities of interest without synchronizing the UE location in the different experiments, would be like comparing apples and oranges, as the UE location is not the same, and thus the UE surrounding environment which our entity of interest(QCL-Type-D indication) strictly relies on is different. Therefore, synchronization of the different experiments with respect to the geographical location of the UE is a must. The UE location shown is represented in Cartesian coordinates, being extracted from the GPS logs in the two experiments before and after being synchronized.

7.3 Strongest Child beam

After synchronizing the logs, a study of the QCL-Type-D indication validity between the strongest child beam and it's corresponding parent beam that covers it was considered. Different beam sets were used, each set contains beams having different shapes compared to the other sets, and thus, different combinations of parent and children beams were possible. That would help understand the relation between the different hierarchical beams representing the parent/children beams and the QCL-Type-D indication validity. The best child beam in terms of RSRP was found at each logging instance, then the best antenna panel receiving it in the best direction was then compared with the best antenna panel receiving the strongest signal of its parent beam at the



(a) After 30s from the start of each experiment, the asynchronous locations of the UE, being represented in Cartesian coordinates are shown

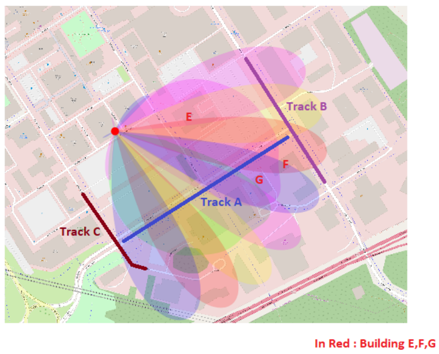


(b) After 30s from the start of each experiment, the synchronized locations of the UE, being represented in Cartesian coordinates are shown

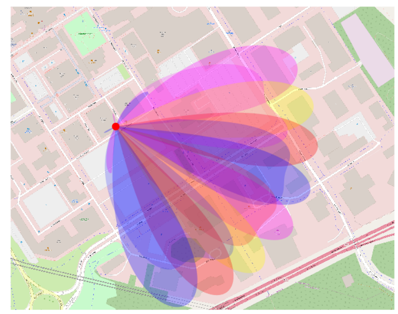
Figure 10: Experiments before and after Sync

UE side. This approach would present the QCL-Type-D indication validity between the strongest child beam and its parent beam. The three beam setups with the different possible combinations among them are shown in Figure 11
In the first setup, Eight Narrow beams emulating the children beam shapes with Two wide beams emulating the parent beams were analyzed. Each wide beam is a parent of Four children narrow beams(see Fig. 14), carrying its Four children under its umbrella.
In the second setup shown in Figure 11b, the same Eight children narrow beams were considered, but with Four narrower parent beams. Different hierarchical patterns can be established in this case, as some children beams exist between

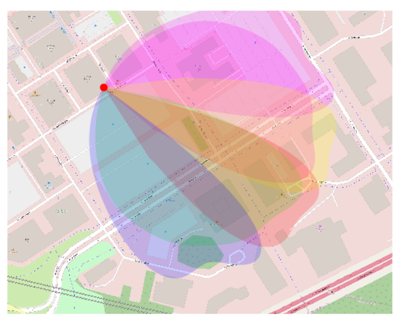
two parent beams. The choice of which child belongs to which parent can be decided based on which parent beam is strongest in the strongest direction of the child beam. In the last setup, the parent beams of the second setup (*Four* beams) were considered as children beams for the set of Two beams (The parent beams in the first setup). Each parent beam covered two children beams. Figure 11c illustrates the parent/children beam shapes of this setup.



(a) Two parent wide beams with their corresponding Eight children beams



(b) Four parent wide beams with their corresponding Eight children beams



(c) Two parent wide beams with their corresponding Four children beams

Figure 11: Different parent-children beam setups

7.4 Power loss estimate

Using the first setup described in Section 7.3, an estimate of the average *total* power loss of the strongest child beam in the case of an unvalid QCL-Type-D indication is presented in this work.

7.4.1 Total average power loss estimate

The estimates were found by searching for the closest sample to the current sample having the same receive direction of the same NB as the parent beam at the mismatching point. The search window size is equal to twelve samples. An illustration is found in Figure 12. Zero power loss points (See later in Fig.19,

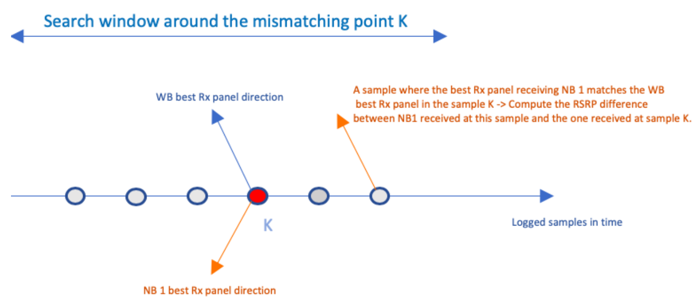


Figure 12: Illustration showing the method to compute the average power loss due to a followed un-valid QCL-Type-D indication

Section 8.3) indicates a valid QCL-Type-D indication and no loss, or may indicate an unvalid QCL-Type-D indication without a power loss estimate located within the search window around that point. Out of all the logged samples, 61% witnessed a valid QCL-Type-D indication, and 24% of the samples witnessed a non valid QCL-Type-D indication with a power loss estimate, meanwhile no valid estimate was found for the other samples (15%).

7.4.2 Fast Fading power loss estimate

The expected RSRP difference within the same Rx/Tx beam pair for the window size used was estimated as well. The procedure starts with the search for each non-matching-point[1], and considering a window of 12 samples centered at this non-matching point. We will call this window a 'Non Matching Window (NMW)' and its center point 'K' for simplicity. Inside this NMW, a search

[1] A non matching point refer to an unvalid QCL indication between the strongest NB(Narrow Beam) and its parent beam at this point

for the matching-points[2] was initiated, where another window of the same size as the NMW was considered centered around each found matching-point. We call these windows 'Matching Window (MW)' and their center 'P' for simplicity. Inside each of the MW, we run another search for all the matching-points which correspond to the same strongest Tx NB found at the non-matching point 'P'(being the center point of the MW) and having the same best receiving direction as the parent beam received at point 'P' as well. For these points found, we calculate their RSRP difference with respect to the matching NB[3] received at the point 'P' , and then we average the difference in power calculated in this MW. This is performed inside each MW constructed using the points with the criterion found above inside the NMW, and this in turn is done over all the map considering all the MW taking part of a NMW. In the end, the average and the median is considered for all the averages computed by using the MW. Here we assume that the at each point that the power loss due to fast fading is on average similar in both cases where matching(valid QCL indication) and non-matching(unvalid-QCL indication) occurs.

[2]A matching point refer to a valid QCL indication at this point between the strongest NB and its parent beam

[3]A matching beam, refers to a valid QCL-Type-D indication between this beam and its parent beam

8 Results

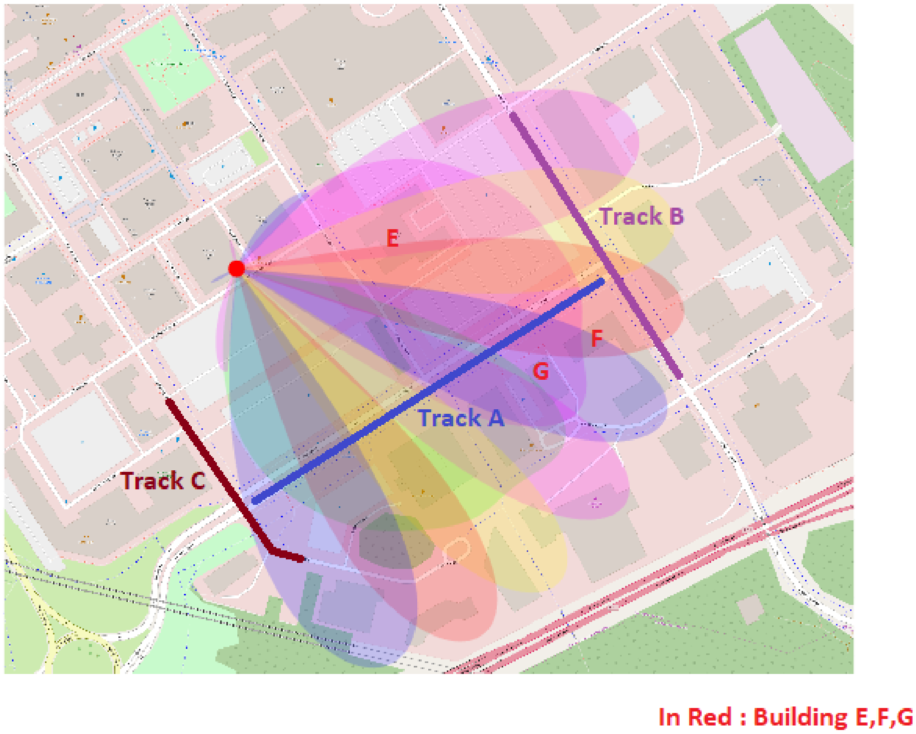
8.1 Strongest Child and its Parent beam QCL-Type-D indication validity

The method followed to compute the QCL-Type-D indication validity between the strongest child beam and its corresponding parent beam was discussed in Section 7.3. Figure 13b illustrates the validity measured on a LOS(Track A) - NLOS(Track B) track (see Fig.13a) .

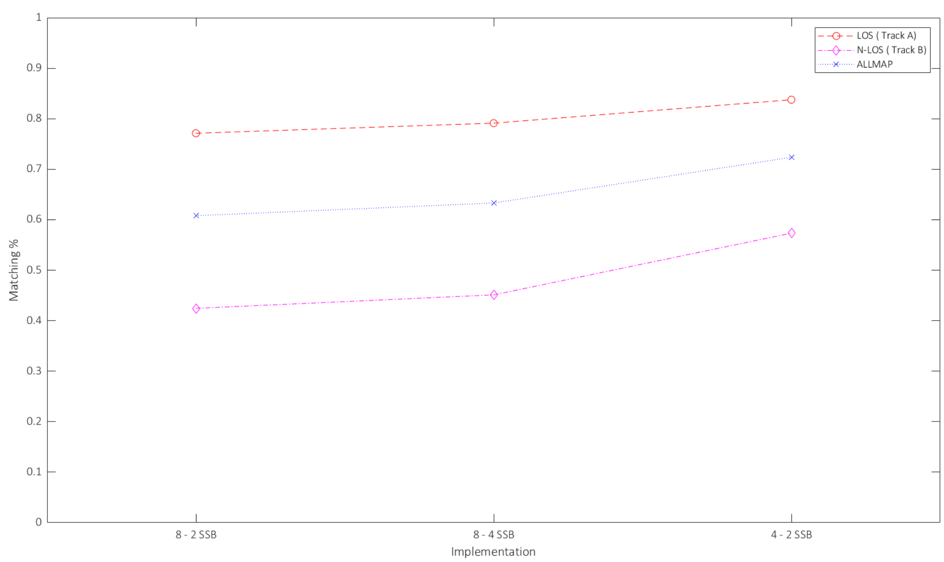
In Figure 13b, the QCL-Type-D indication validity is shown to increases as the shape and the size of the narrow beams become more comparable to the wide beam shape. The narrow beams starts to emulate their parent beams as their shape and width change and get more comparable to their parent shape. Thus, the signal of the narrow beams tends to be sent from the same spatial filter as that of their parent beam. This have an effect on the QCL-Type-D indication validity, where the strongest signals of both the parent and strongest child beam tend to take similar paths, and therefore, the best receiving direction/antenna panel at the UE side for both signals tends to be the same. Considering the validity on the different tracks, we note a good, around 80% validity percentile on track A(LOS). On the contrary, on track B, on the $NLOS$ track, the validity percentage degenerates.

8.2 QCL validity between *all* the children and their parent beam

The QCL-Type-D property is not necessarily dependent on the strongest child and its parent beam to be valid. In the following, we look at the CDF of the number children beams that are quasi co-located with their parent beam, when the latter is the strongest among all the other WB(Wide Beam/s).
This approach would show if a scheduled narrow (children) CSI-RS-BM beams can be received optimally by the UE to perform measurements on and report back certain quantities such as the RSRP of the different ports/beams. If the QCL-Type-D between *all* of the scheduled CSI-RS-BM beams and the parent



(a) *LOS* and *NLOS* tracks where the comparisons were considered



(b) Comparison between the different setups in terms of QCL validity on different tracks

Figure 13

beam in this case is shown to be valid, this means that optimal reception and reporting happen. Else, a power loss to the non quasi-co-located ports may occur(Due to the UE beam directivity towards the parent best receive direction), which may lead to a wrong decision on the best CSI-RS-BM beam due to a faulty/sub-optimal RSRP reporting, which in turn may effect the beam refinement phase. An illustration is represented in Figure 15.

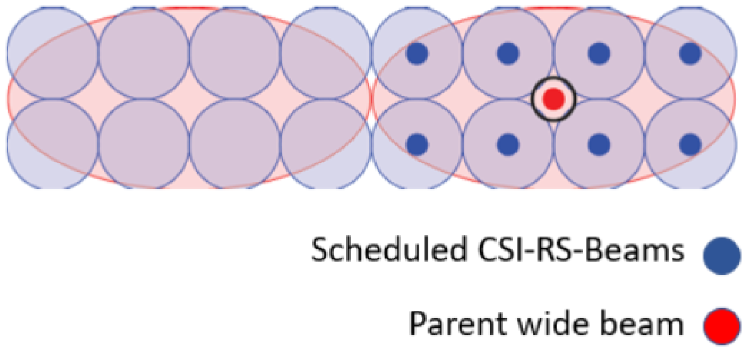


Figure 14: An example of the scheduled set of CSI-RS-BM ports within the corresponding parent SSB beam being the strongest

Figure. 16a shows how good and valid is the QCL property among the parent WB 1 (In all the different beam sets, counting of the beams always starts from the left most beam in the figure to right most beam in each set of beams, see Fig. 16b) and its four children Narrower beams on Track A, where more than 50% of the time, the children best receive direction match their parent beam best receive direction, and around 70% of the time, matching occurs for more than two beams. This means that in LOS scenarios, not only the strongest beam can be assumed quasi co-located with its parent beam, but also with a good probability, we can establish a correct and valid QCL-Type-D indication between at least three children beams with their parent beam. In the case of WB 2, the probability to find four matched narrower beams on Track A is less, due to the fact that the WB 2 sector is not as directed on track A as the WB 1 sector. Moreover, Beam eight doesn't cover or reach Track A properly, meanwhile beam seven covers it partially with an acceptable power gain. Therefore, the probability to obtain four matching children is lower as illustrated. On the other hand, around 20% of the time, none of the children beams matched their parents SSB beams. What may have influenced this considerable non-valid QCL-Type-D indication percentile of zero matching

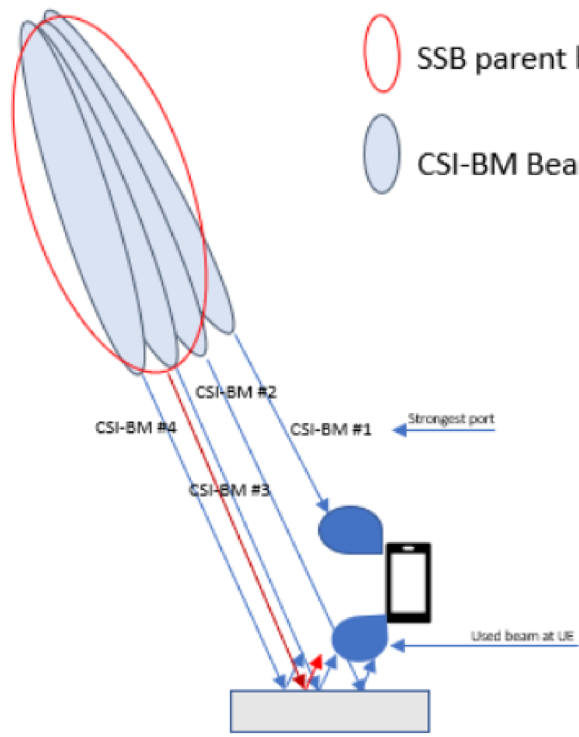
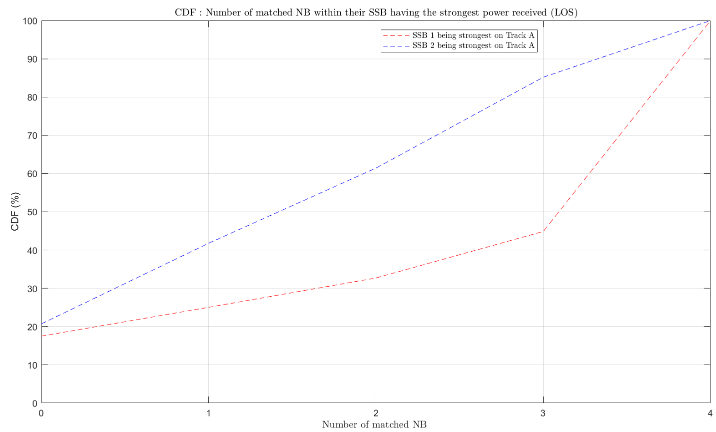


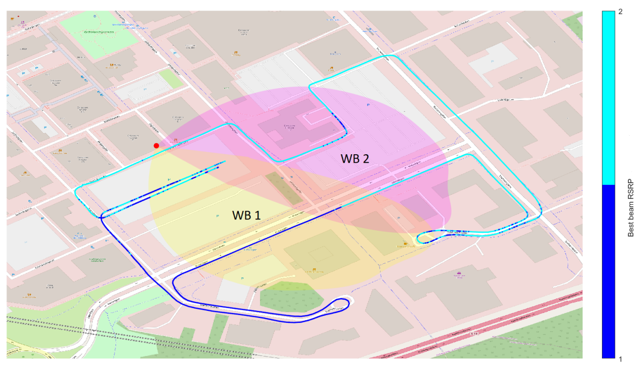
Figure 15: Wrong reporting in case of QCL-mismatch

children beams are the different experiments done separately for each set of the Eight and Two/Four beams, where the channel may have changed, and different moving objects may have blocked the signal at certain locations in each of the experiments.

Figure. 17 evaluates the CDF for the logs of Tracks B and C (see Fig. 13a). Since on Track B, the parent WB 2 is the only dominant WB, we only look at the CDF of the number of its corresponding children NB which have a valid QCL-Type-D indication with it. The same applies for WB 1 on Track C. The probability of having three and four matching children is too low in the case of WB 2 matching children narrow beams, on the other hand it has a good percentile when it comes to two beams only. This happens due to the blockage that occurs from building 'E' to beams seven and eight when the car routes behind it, and the blocking that occurs from building 'F' when the car moves behind it as well, blocking beams number five and six from reaching that road with the same best receive direction. Here it's important to note the considerable effect of the cell environment and the location of the UE with



(a) CDF of QCL-Type-D validity for different parent beams and their children beams



(b) WB 1 and WB2 dominant locations on map in terms of RSRP

Figure 16

respect to the beam gain sectors on the QCL validity. On the other hand, WB1 showed consistant performance similar to the direct LOS case on Track A. The difference here with respect to Track A, is that the Gain of the beams in the direction of Track C is minimal, still the matching percentile is good. The factor that assisted such a good performance is the reflection of the NB and WB 1 signals from the buildings residing beside Track A and reaching Track C, where the gain of those beams towards the buildings is maximal. On the other hand, one factor that may push our QCL validity percentile down are the side lobes of the NBs that can reach, say for example the UE while moving on Track C, having a better RSRP than the ones reflected by the buildings of Track A, and since our WB side lobes don't exist in that direction, the WB signal reflected from the buildings will most likely be considered as the strongest

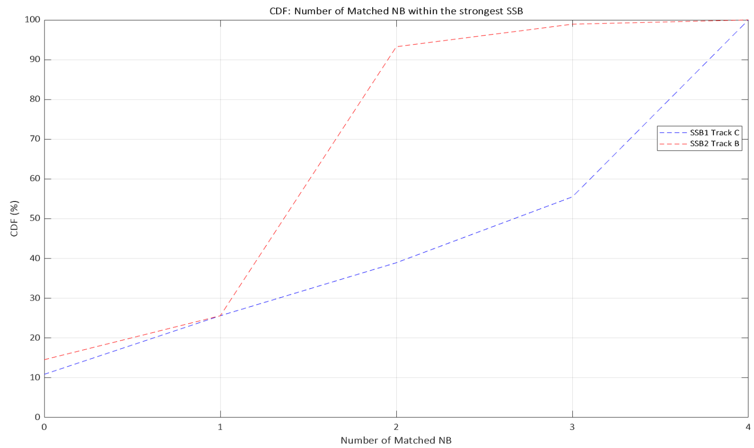


Figure 17: QCL-TD validity for different beam shapes and different scenarios

signal received, with the best receive direction being towards the buildings, The illustration of this phenomena will follow.

8.3 Power loss due to an invalid QCL indication

A non-matching QCL source indication may lead the UE to focus its receiving beam towards a non favorable direction to receive the Narrow beam, which may lead to power losses that may lead to an unreliable link establishement procedure. Figures 18, 19 show the estimated power loss all over the map. In this scenario, the QCL-Type-D indication was not valid between the strongest NB and his corresponding WB.
The estimated power loss spreads on different samples in the map in LOS and $NLOS$ cases. The average and the median power loss when a wrong indication is followed over the whole terrain is estimated to be around 3.9 dB and 3.2 dB respectively. In other words, more than half of the signal's power is lost in the non-matching measurement points where the best NB is not received optimally on the same antenna-panel as its QCL source. However, such a power loss estimate calculated may not be only referring to the excess path and reflections affecting the signal which is received by the UE when an un-valid QCL-Type-D indication is followed. The power loss may include losses due to fast-fading imposed by the channel. The procedure in Section 7.4 was then followed to estimate this kind of power loss. A mean and a median of 2.7 dB and 2.1 dB was estimated as a loss due to fast fading. The difference between the median and the average of the fast fading loss with respect to the all map

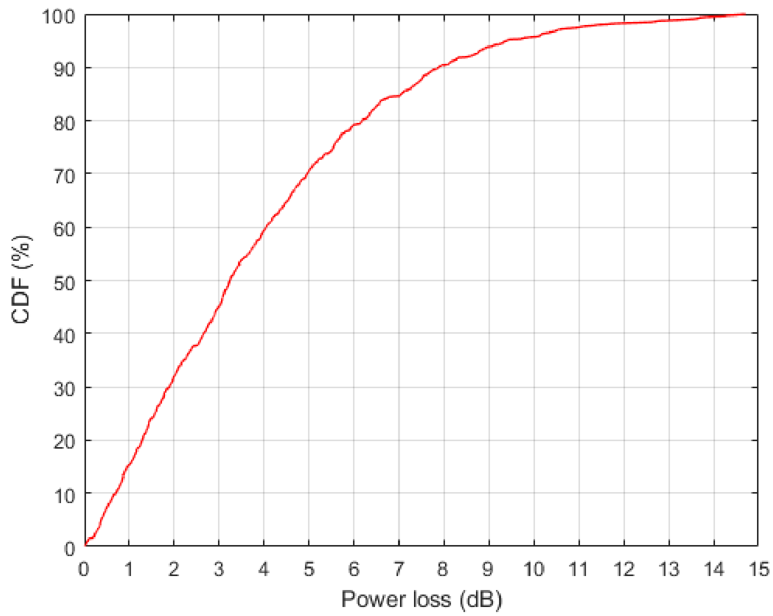


Figure 18: CDF of the power loss estimate in the case of an unvalid QCL-Type-D indication between Best NB and Parent WB

average power loss due to an un-valid QCL indication is 1.2 dB. This remaining estimated power loss thus represents the reflections and excess paths taken by the received signal when the un-valid QCL indication is followed by the UE.

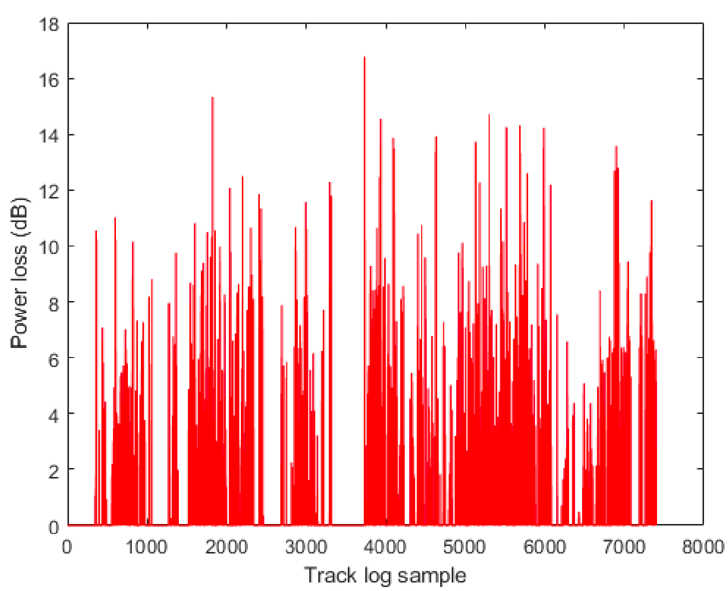


Figure 19: Power loss estimate as a function of time

9 Beams shape effect on QCL-Type-D indication validity

One possible theoretical reason for an un-valid QCL-Type-D indication between a parent and a child beam, are the parent/children beam gain shapes and the cell environment itself. The beams gain shape may affect this validity, especially if the QCL source (parent) and the child beam have a large gain difference in a certain direction. Looking at the beam shapes used in our setup, as illustrated in Figure 20; The wide beam gain is directed in this case towards the building. If the signal emerging from that direction reaches the UE antennas with a propagation and reflection power loss less than the difference between the *LOS* signal and the *NLOS* signal of this wide beam, then this Rx direction would be the most favorable to receive the wide beam signal. On the other hand, the direct LOS narrow beam signal will be favorable in its maximum gain direction(or due to diffraction shown). Un-valid QCL-Type-D indication may happen here mainly due to the non-uniform power gain distribution of the parent WB. Else, if this parent beam gain bias in *Azimuth* was adjusted, we may have better validity between those two beams (The parent WB and child NB).

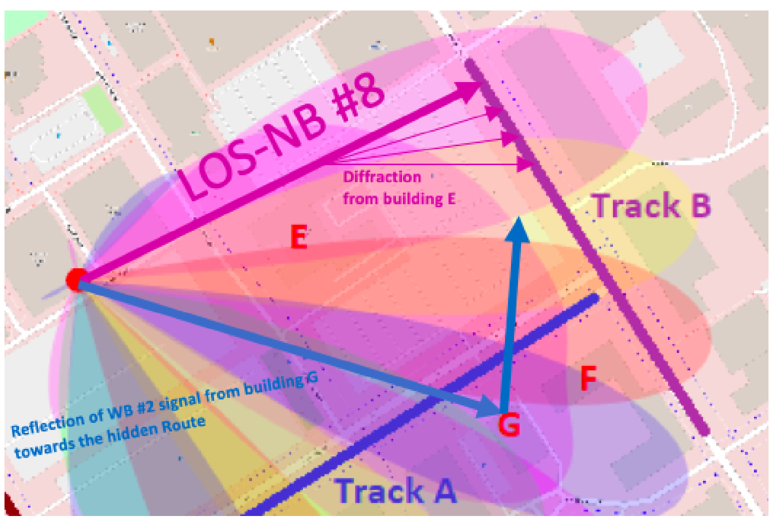


Figure 20: Different beam power shapes and the environmental effect on the favorable receive direction of the different beams

10 Conclusions

This study showed the possibility of having a beam-management scheme with indication, where the QCL-Type-D indication validity was demonstrated, especially in the LOS scenarios. QCL-Type-D indication validity of 4/4 and 3/4 of the children beams was demonstrated in more than 50% and 70% of the time in LOS scenario respectively. This shows that a QCL indication between these children beams and their parent beam may work good for example, for the reception of a scheduled set of CSI-RS-BM beams, and carry RSRP measurements on them fairly while all of those scheduled children beams match with their parent beam. Meanwhile, in the NLOS cases, this validity degenerates, which indicates that QCL-Type-D here may require special procedures to guarantee the best reception of the children beams. A relation was found between the beam shape and the QCL validity, where as similar are the children beam shapes to their parent beam, the better is the QCL validity between them, since they tend to have a similar spatial filter, which in turn increases this validty. This was demonstrated in Fig. 13b, where the QCL validity between the strongest beam and its parent beam increases in the LOS scenario from 78% to 88%, and from 44% till 58% in the NLOS scenario, as the beam shapes get closer between the children and their corresponding parent beams ((2-8) $\rightarrow$ (4-8) $\rightarrow$ (2-4)).

The power losses due to a wrong indication was estimated to be around 1.2 dB after considering the fast fading losses.

A hybrid SSB set of beams can address the *NLOS* validity degeneration, where a wide SSB can be used in *LOS* scenarios, and Narrower SSB beams can be used in the *NLOS* scenarios, thus having a closer shape to the children beams which they cover. The power losses due to having a wrong QCL indication demonstrated may be more critical in *NLOS* scenarios, where the link budget in this case is more fragile. It's noteworthy to mention that these results may only be valid in this specific cell, and may change when using a different cell, where the QCL-Type-D indication validity is dependent on the cell environment, which drives the signals' path.

11 Further Studies

In this study, in the case of the Narrow beams, only one set of beams was considered (one row arrangement in the GoB). For this, we don't know if the other beam row arrangements would have a similar QCL-Type-D indication validity as the one demonstrated in this work. Moreover, this work didn't consider a power delay profile, which would have better demonstrated the path's taken by the strongest signal and thus better demonstrated the environmental effect in terms of reflections on the QCL-Type-D indication validity.
Finally, the radio used to obtain the measurements operated at 3.5 GHz. It is of interest see if working in higher frequency bands would affect the QCL indication validity differently.

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