Beam Switching in mmWave Cellular Networks: A Measurement-based Study

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***Abstract*—It is well-established that mobility is a prominent challenge for beam-based communication. Despite the beam management functions specified by 3GPP to facilitate beam-based communication, its reliability under beam-level mobility remains questionable. Hence, this paper highlights the challenges impeding the reliability of beam-based communication under user mobility and poor propagation conditions. Specifically, this paper investigates beam-switching in mmWave networks and assesses the merits of beam-switching optimization through parametrization. Several parameters, including a Hysteresis margin and a Time-To-Trigger, are investigated with regards to enhancing beam switching. To carry-out the analysis, real beamformed mmWave data is used. The results report key beam switching performance measures and show a critical beam switching optimization trade-off.**

***Index Terms*—Millimeter Wave, Beamforming, Beam Management, Beam Switching, Configurable Parameters, LOS/NLOS**

I. Introduction

The exponential increase in mobile data traffic and the accelerating proliferation of mobile devices are placing current generation cellular networks under strain [1]. To keep up with the inevitable data surge and the increasing demand for mobile services and applications, exploiting the abundant spectrum available at the millimeter wave (mmWave) band has become more crucial than ever. Operating at extremely high frequencies (EHF), i.e., *30–300 GHz*, allows mmWave to offer unprecedented data rates and capacity to users, thereby enabling the ambitious targets of next generation cellular networks (NGCN).

However, mmWave has the disadvantage of limited signal range and poor propagation properties. Namely, mmWave is susceptible to significant pathloss, atmospheric and precipitation attenuation, blockages, scattering and diffraction [2]–[4]. To counter these constraints, massive multiple-input multiple-output (massive MIMO) and beamforming technology are used to focus transmitted energy in a specified direction, forming what is known as a mmWave beam. Not only do directional beams enable spatial selectivity for mmWave communication, but they also achieve a practical mmWave range [5]. While beam-based communication is vital to enable mmWave technology, it poses several new challenges on the network. A primary challenge is that beams have a smaller coverage footprint, forcing users in motion to switch beams more frequently, and generating excessive signaling overheads [5]–[7]. Moreover, highly-directional beams are more prone to abrupt channel variations due to user mobility and blockages [3], [7]. As a result, beamformed communication gives rise to problematic beam switching ping-pongs and short-stays [8].

The 3rd Generation Partnership Project (3GPP) has defined a set of beam management functions to support mobility in mmWave networks [9]. However, the actual algorithms guiding the said functions, specifically the beam switching function, have not been standardized and are deferred to network implementation [8]. Research has yet to systematically investigate beam switching complications, their associated costs and the effect of configurable parameters on the performance of beam switching algorithms and the user experience. Few studies have recognized the importance of beam switching optimization, for example, the study in [8] proposes filtering beam strength measurements prior to beam switching decisions, in order to improve beam switching performance. However, the study did not report the delays associated with filtering and validate the use of filtering for aperiodic beam strength measurements. In [3], a sensitivity study of beam switching under filtering and parametrization (i.e., using a power threshold parameter) is presented. The performance of beam switching is assessed using simulated data in terms of beam time-of-stay (ToS) and beam outage. The authors in [7] and [10] utilize stochastic geometry to model and analyze the beam switching function, to evaluate the beam misalignment issue.

However, a systematic investigation of the beam switching performance in a real-world setting is still lacking. To the best of our knowledge, this is the first study that analyzes beam switching using real beamforming data from a gNodeB (gNB), operating on mmWave. In addition, this work advances the understanding of beam switching performance in Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) regions. In addition, the paper investigates how configurable parameters, such as a hysteresis margin (H) and a time-to-trigger (TTT), affect beam switching performance. The main objectives of this research are:

- assessing the extent to which ping-pongs and short-stays

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deteriorate the performance of beam switching in LOS and NLOS regions.
- to fine-tune beam switching decisions according to configurable parameters (i.e H and TTT), and considering an important trade-off in performance.
- using the optimum combination of parameters and evaluating the performance of beam switching, in terms of beam switching rate, the rate of unnecessary beam switches, average ToS in a beam and the average distance between beam switches.

The rest of the paper is organized as follows: Section II provides an overview of beam management, and in particular, beam switching. This section also presents our measurement-based beam switching optimization approach. Section III describes the dataset used in the study, and Section IV presents the results. Conclusions and future work are presented in Section V.

II. Beam Management For Beam-level Mobility

Two frequency ranges have been defined by 3GPP for 5G networks: Frequency Range 1 (FR1) and Frequency Range 2 (FR2) [11]. FR1 is comprised of frequency bands between 4.1 GHz to 7.125 GHz and is associated with legacy network communication, FR2 is comprised of frequency bands between 24.25 GHz and 52.6 GHz and is dedicated to small cells with high data rate communication (i.e., mmWave) [11]. In the presence of this heterogeneity, user mobility in NGCN is categorized into cell-level mobility and beam-level mobility [12], [13]. In cell-level mobility, the user equipment (UE) traverses between different gNBs. On the other hand, beam-level mobility describes the movement of a user within a single gNB operating beamformed mmWave communication (i.e., FR2) [12], [13]. This paper focuses on beam-level mobility. In contrast to cell-level mobility, beam-level mobility is performed using physical and Medium Access Control (MAC) control signals, as the control is managed locally by the serving gNB.

Beam management functions play a significant role in maintaining a seamless connection with the gNB, under beam-level mobility. As shown in Fig. 1, the main beam management functions are beam sweeping, beam tracking, beam switching, and beam failure detection and recovery. First, beam sweeping is used to seek the best beam for initial access. Second, beam tracking ensures that the UE is connected to the beam with the best signal during a connection session, based on measured downlink or uplink reference signals. This paper focuses on beam management using downlink reference signals. Third, beam switching is used to maintain seamless connectivity for mobile users, it takes place when the serving beam's reference signal received power (RSRP) falls below that of another beam. Thus, beams are switched for the user to remain connected to the best beam at all times. Lastly, beam failure detection and recovery are used to monitor and detect link failures, depending on predefined criteria.

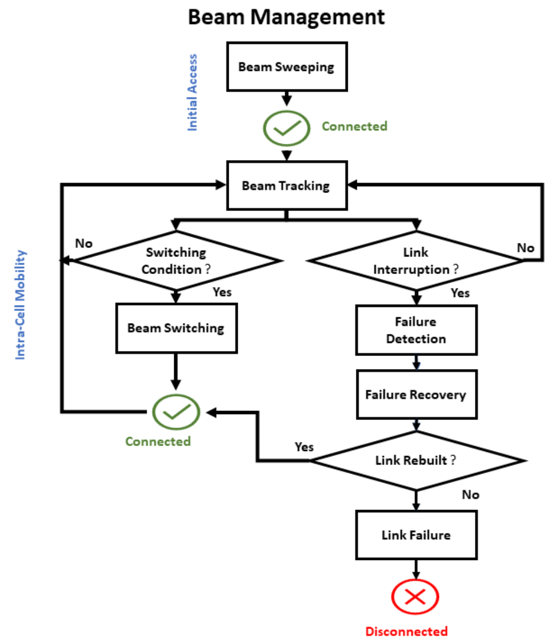

Fig. 1. Beam management functions (from [14] ©2022 IEEE)

A. Optimized Beam Switching

A beam switching procedure for a downlink network scenario is illustrated in Fig. 2. The UE performs recurrent measurements based on downlink reference signals and reports the measurements back to the gNB. The downlink reference signals are transmitted in bursts by the gNB to the UE in the form of periodic synchronization signals (SSB), where each SSB represents a single beam. Then, the UE reports the beams with the highest RSRP values to the gNB. According to the reported measurements, the gNB compares the RSRP for the serving beam with other reported beam measurements. If the beam switching conditions are met, the gNB sends a beam switching command to the UE, for the UE to perform the beam switching process. In a baseline beam switching, the following condition must be met:

$$P_{bx}(t) > P_{bs}(t) \tag{1}$$

where $P_{bx}(t)$ is the signal power for any beam other than the serving beam measured at time t, and $P_{bs}(t)$ is the signal power for the serving beam. If this condition is met for multiple beams, the UE shall switch to the beam with the highest RSRP [8].

Abrupt variations in beam strength measurements caused by dynamically changing network conditions and user movement, can impair beam switching decisions, causing unnecessary beam switches. Therefore, it is necessary to regulate the beam switching decisions, such that they are based on steady and not instantaneous changes in beam strength measurements. This paper proposes using controlling parameters similar to those used to improve handover decisions. We put forth introducing H and TTT conditions to reduce unnecessary beam switches. If the conditions below hold, beam switching is triggered.

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$$\begin{aligned} P_{bx}(t) - P_{bs}(t) \geq H \\ \text{for TTT} \geq \tau \end{aligned} \tag{2}$$

Where, H is the maximum allowable drop in the serving beam strength compared to other beams, and τ is the time window in which the first condition should hold before triggering the switching action.

Moreover, the choice of the controlling parameters' values is just as important as the use of parametrization to enhance beam switching. The choice of the parameters for beam switching can either improve the performance by decreasing unnecessary beam switches or impede the performance by increasing beam outages. This is because parametrization reduces beam switching rate, by increasing the ToS per beam. Hence, excessive parametrization delays beam switching execution, which potentially compromises the link quality as the user travels beyond the coverage of its serving beam [3]. An optimal choice of parameters is that which balances the trade-off between unnecessary beam switches and the delay in beam switching, meaning that reducing unnecessary beam switching does not come at the cost of increasing beam outages. Considering all that has been discussed so far, it is evident that optimizing beam switching is achieved by balancing the trade-off between the rate of beam switches and the rate of beam outages.

B. Beam Switching Performance Evaluation

The evaluation metrics used to assess the performance of beam switching are the following:

- Beam switching rate: this metric measures the number of beam switching events throughout the user travel. In general, a greater beam switching rate indicates a less-satisfactory performance.
- Rate of unnecessary beam switches: this metric calculates the rate of unneeded beam switching events (e.g., ping-pongs and short-stays). This metric is important to quantify wasted resources due to inefficient beam switching.
- Outage rate: an outage occurs when the link quality drops to the point that communication is impossible [8]. A greater outage rate indicates beam switching failures due to late switching decisions.
- Beam ToS: this metric measures the time spent by a user within a specific beam coverage. While not always true, a short ToS indicates a high beam switching rate and possibly a high rate of unnecessary beam switches. In some cases, a short ToS suggests the user is moving with a high speed [3].
- Distance between beam switches: this is the distance traveled between two beam switches. This measure in addition to the ToS evaluation reflects the true beam switching performance, regardless of the user movement or the speed of movement.

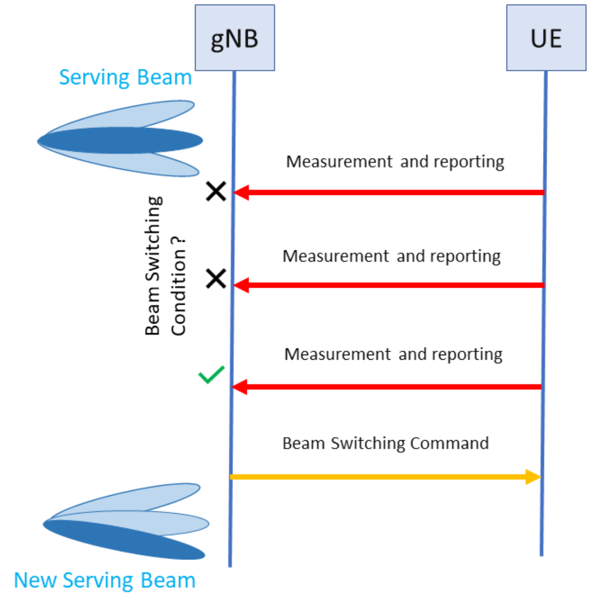

Fig. 2. A basic beam switching example

III. Data Acquisition and Analysis

A. Beamforming Dataset

The dataset used in this paper was obtained from an experimental gNB at Ericsson office in Lund, Sweden. This experimental gNB operates at mmWave and employs analog beamforming, with wide beams used for transmitting SSB and narrow beams used for data transmission. A series of data collection experiments were performed by Ericsson to measure the RSRP of the wide and narrow beams, as reported by a mobile user. The data was collected several times on different days while traveling the routes shown in Fig. 3. To ensure that the conducted experiment resembles a real-world scenario, the experiment location was chosen in a dense urban area, with LOS and NLOS regions, and the data was collected under different speeds: slow walking, fast walking and recreational bicycling. In order to enhance the randomness in the data, different movement directions, UE orientations and mounting positions were used during the experiments. In addition to the RSRP measurements, the dataset also reports the GPS location of the UE at each timestamp. In accordance with 3GPP standards, rather than reporting negative dBm RSRP values, an indication of RSRP measurement is used instead. Hence, the reported RSRP measurements are integers ranging from *16 to 113*; and the mapping between these integers and the corresponding RSRP range is given in [15, Table.10.1.6.1-1].

B. LOS/NLOS Coverage

Following from the above, another objective of this paper is to investigate the impact of the LOS/NLOS coverage on the beam switching performance. In the presence of blockages and obstructions (e.g., buildings, trees, vehicles and pedestrians),

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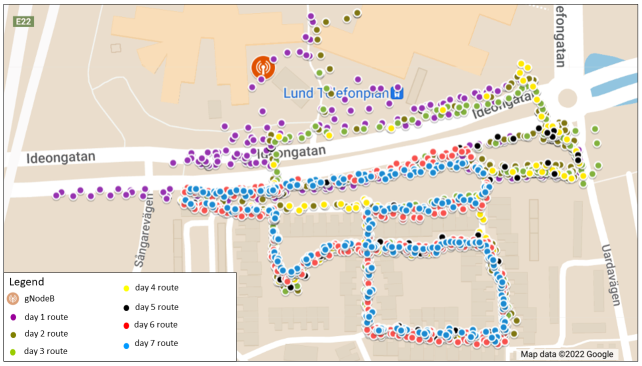

Fig. 3. Map showing the routes taken and gNB location (map data ©2022 Google)

the quality of the received beam signals depends on whether the propagation path is LOS or NLOS. This is further validated by inspecting the RSRP values in the experimental area, as reported by the dataset discussed in Section III-A. Fig. 4 illustrates an example of the spatial variation in the received power levels in the experimental area, in relation to the distance from the gNB. The figure shows that the received power levels are higher in the open space region closer to the gNB, as compared to the densely built region further away from the gNB. This finding, while preliminary, validates the simple LOS-ball model in approximating the LOS/NLOS regions [10]. Hence, the rest of the analysis assumes a LOS-ball model with a distance approximated using the measured RSRP values in the dataset.

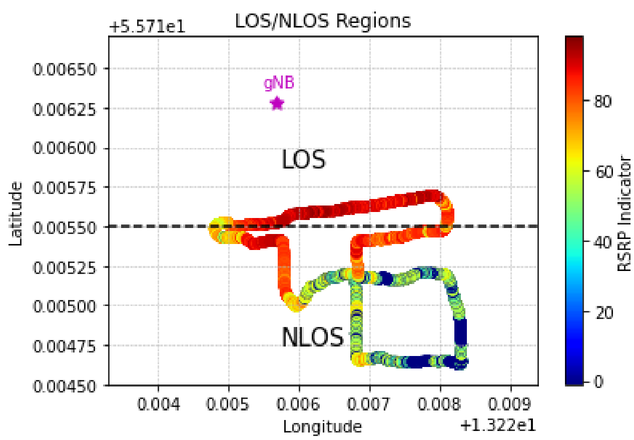

Fig. 4. The received power levels mapped over the experiment route

C. Unnecessary Beam Switches

A drawback of baseline beam switching is the increase in unnecessary beam switches, resulting in significant signaling overheads [7]. This section evaluates the number of unnecessary beam switches resulting from baseline beam switching. Unnecessary beam switches can be defined as early beam switching attempts that are deemed unneeded after execution, such as ping-pongs and short-stays. Ping-pong switching happens when the UE is switched from one beam to another, only to return to the original serving beam within a short time τ_u. In short-stays, the UE switches to a new serving beam for a short time τ_u before switching to a different beam [8]. Analysis using baseline beam switching reveals that 44% of the total number of beam switches are unnecessary in the LOS region compared to 52% in the NLOS region. Further details are shown in Fig. 5 where the number of ping-pongs and short-stays in the LOS and the NLOS regions are demonstrated. It can be seen from the figure that the number of unnecessary beam switches in NLOS region exceeds that in LOS region, which suggests a higher beam switching rate and, subsequently, a worse user experience. Moreover, the figure shows a slight increase in the number of ping-pongs and short-stays, as expected when the period to define unnecessary switching τ_u is increased to $160(ms)$ compared to $40(ms)$. This finding indicates that most unnecessary beam switches can be captured, even with a short τ_u period.

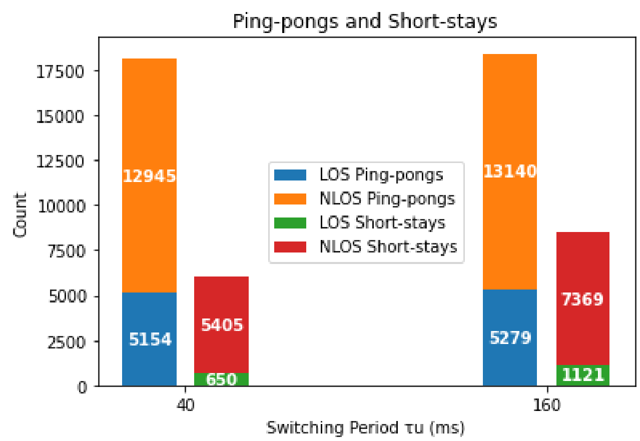

Fig. 5. Number of ping-pongs and short-stays using baseline beam switching

IV. Results and Performance Analysis

To investigate the degree to which the performance of beam switching is improved using parametrization, the rate of beam switching is calculated and plotted for different combinations of the proposed configurable parameters (i.e., H and TTT), as shown in Fig. 6 and Fig. 7. From Fig. 6, it can be seen that without any parametrization, the rate of beam switching is 14%, whereas by using a small TTT value of only $40(ms)$, the rate is reduced by one third to 9%. Furthermore, a drastic reduction in beam switching rate can be achieved using a small H margin H$=\ 1(dBm_{indicator})$. It is interesting to observe the predominance of the H margin over the TTT parameter in reducing the rate of beam switching, which is more clearly highlighted in Fig. 7. The figure shows a large drop in the rate of beam switching when using a small H margin, H$=\ 1(dBm_{indicator})$ (i.e., orange curve) compared to H$=0(dBm_{indicator})$ (i.e., blue curve), which accounts for 70% reduction in beam switching rate. Additionally, as the

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values of H and TTT increase, the rate of beam switching decreases, although the pace at which beam switching is reduced slows down as the parameters increase.

On the other hand, Fig. 6 and Fig. 7 also plot the rate of beam outages against the reduction in beam switching rate to confirm the trade-off in performance discussed in Section II-A. As discussed, parametrization can reduce the rate of beam switching; however, it increases the rate of beam outages. In the figures, the worst-case beam outage rates are presented. As H and TTT parameters increase, the beam outage rate increases, although the increase is steeper in Fig. 6, when the outage rate is plotted against the H parameter. This reconfirms the above observation, which suggests H margin's predominance in improving the beam switching performance. Based on the trade-off between beam switches and beam outages, an optimal combination of parameters is evaluated to minimize beam switching rate, while maintaining an acceptable beam outage rate. The optimal choice of parameters is found to be H$= 2(dBm_{indicator})$ and TTT$= 40(ms)$, as this combination achieves the perfect balance of beam switching rate and beam outage rate. The rest of the analysis uses this combination to assess the effect of parametrization on beam switching performance.

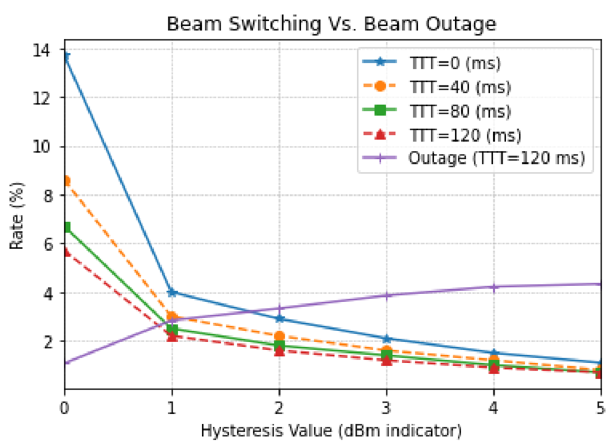

Fig. 6. The effect of the H parameter on the beam switching performance for different TTT values

Another important measure of the beam switching performance is the average ToS in a beam, besides the average distance between beam switches, which is complementary to the ToS measure. Fig. 8 shows the empirical Cumulative Distribution Function (CDF) of the ToS under different scenarios: baseline beam switching, optimized beam switching, LOS coverage and NLOS coverage. Whereas, Fig. 9 presents the CDF for the distance between beam switches. As shown in both figures, baseline beam switching (with H$= 0(dBm_{indicator})$ and TTT$= 0(ms)$) result in a small range for ToS and a limited distance between switches. The figures indicate that the ToS in a beam is certainly less than $50(s)$ and the distance between beam switches is less than $5(m)$, using baseline beam switching. This finding reveals beam switching is occurring, even when the user barely moves. The figures also report a slightly

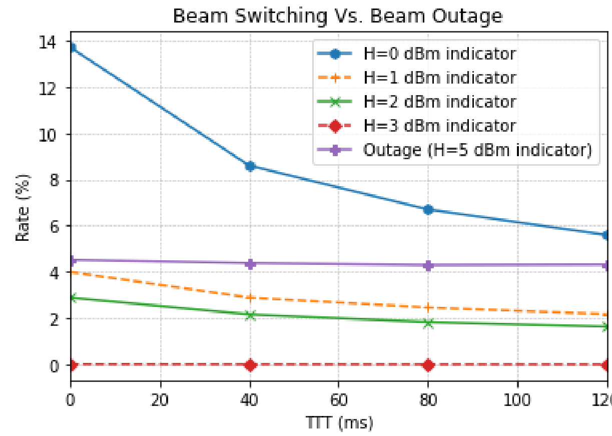

Fig. 7. The effect of the TTT parameter on the beam switching performance for different H values

worse performance of the baseline beam switching in NLOS regions, which verifies the results obtained in Section III-C. For optimized beam switching, the performance is improved; this is evident, as the ToS and distance between switches taking small values have a smaller cumulative probability. It is worth noting that the optimized performance is better in LOS regions than in NLOS regions, suggesting that the optimal choice of parameters should vary based on the propagation conditions.

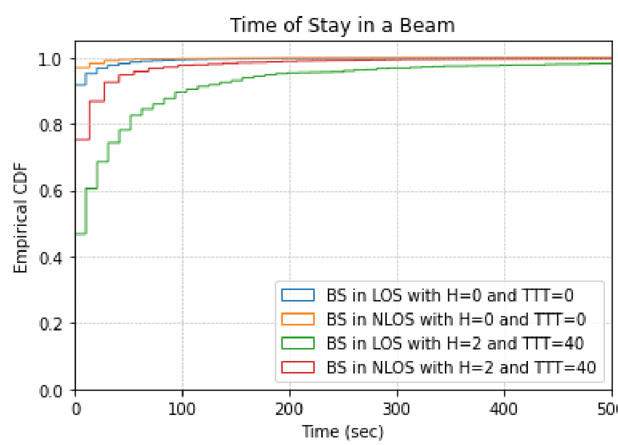

Fig. 8. Empirical CDF for ToS in a beam

V. Conclusion

This paper investigated beam switching for beam-level mobility. The objective was to identify and evaluate beam switching challenges that hinder reliability under user mobility and different propagation conditions. The paper applied configurable parameters (i.e., H and TTT parameters) to enhance beam switching performance, by eliminating ping-pongs and short-stays. An optimization trade-off was also highlighted. In order to find the optimal parameters which balance the trade-off in performance, real beam measurements were used.

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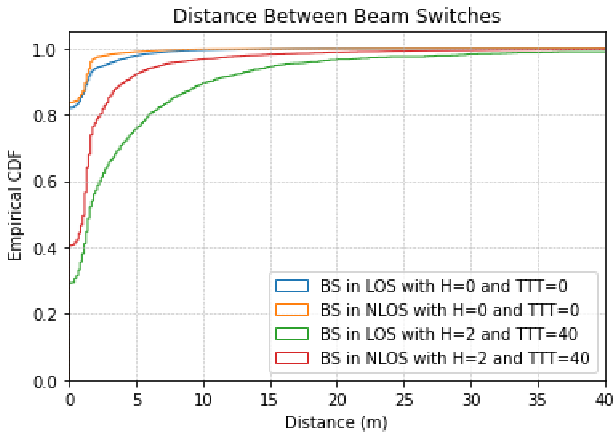

Fig. 9. Empirical CDF for distance between beam switches

Results reported different performance metrics to compare optimized beam switching to baseline beam switching. The findings in this paper will help develop more efficient beam switching algorithms. Future work is needed to provide insight on the effect of user speed on the beam switching performance. Further investigations are also necessary to understand the effects of choosing different optimization parameters for different regions (i.e., LOS and NLOS) and open the door for developing self-optimized beam switching. To develop a full-picture of beam switching performance, future work needs also to quantify the impact of optimized parameters on throughput and latency.

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