clearly be diminished in the nLoS case. Thus, the purpose of this investigation was to compare the dominance of LoS components across all pathways. Figures 2.27, 2.28, and 2.29 depicts SS fading at 5 *metres*, 7 *metres*, and 9 *metres* deployment distance respectively. Table 2.7 summarises the results obtained from Rician fitting for all deployment distances.

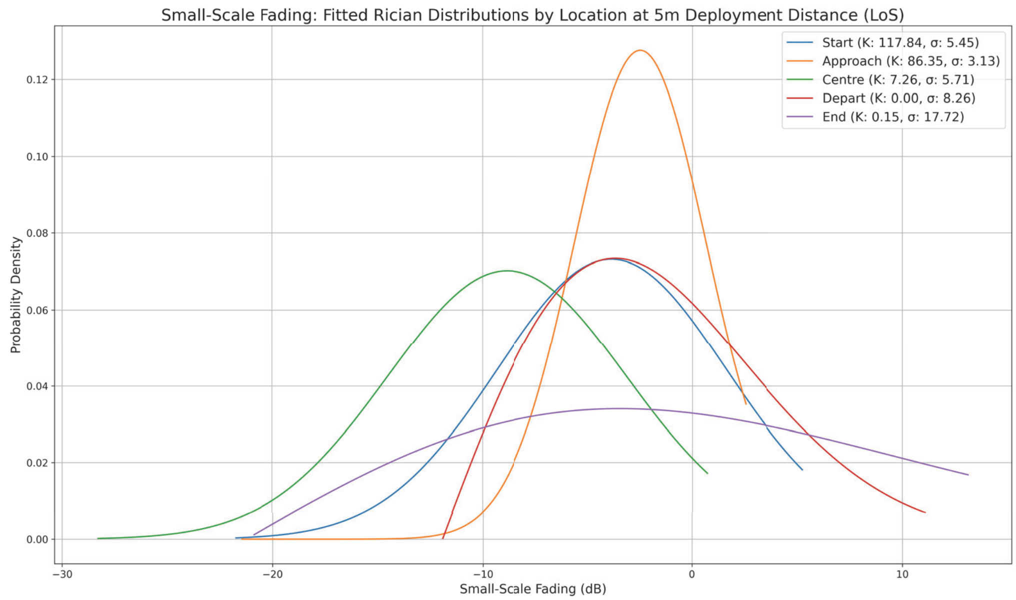


FIGURE 2.27: Rician Distribution Fitting to RSSI at Each Key-points on 5 m Pathway (LoS)

Deployment Distance	Location	Mean RSSI (dBm)	Fitted RSSI (dBm)	Shape Param (K)	Scale Param (σ)
3 metres	start	-63.26	-45.75	37.18	5.47
	approach	-47.54	-53.28	0.20	13.93
	centre	-44.71	-57.68	0.14	17.14
	depart	-57.09	-60.80	0.00	6.12
	end	-68.13	-63.22	0.00	5.04
5 metres	start	-63.26	-45.75	117.84	5.45
	approach	-47.54	-53.28	86.35	3.13
	centre	-44.71	-57.68	7.26	5.71
	depart	-57.09	-60.80	0.00	8.26
	end	-68.13	-63.22	0.15	17.72
7 metres	start	-66.99	-49.39	0.00	5.17
	approach	-56.46	-56.91	0.00	3.65
	centre	-54.64	-61.31	0.00	16.77
	depart	-57.55	-64.44	0.05	17.24
	end	-63.27	-66.86	0.21	15.87
9 metres	start	-66.64	-46.42	100.05	7.38
	approach	-50.38	-53.94	0.50	14.10
	centre	-55.01	-58.35	0.00	5.04
	depart	-48.32	-61.47	122.74	4.08
	end	-63.72	-63.89	102.79	6.33

TABLE 2.7: LS Fading

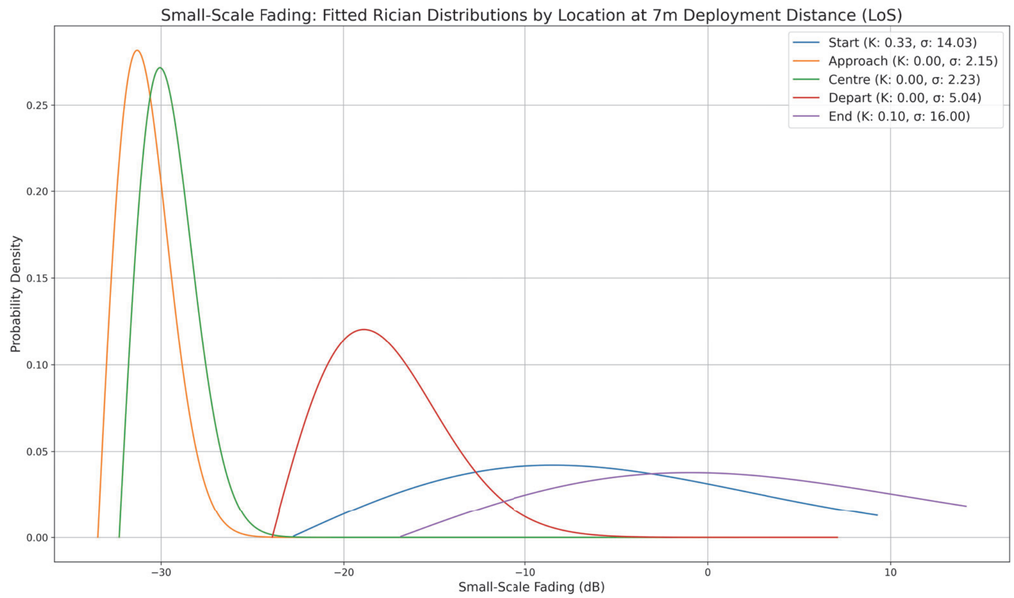


FIGURE 2.28: Rician Distribution Fitting to RSSI at Each Key-points on 7 *m* Pathway (LoS)

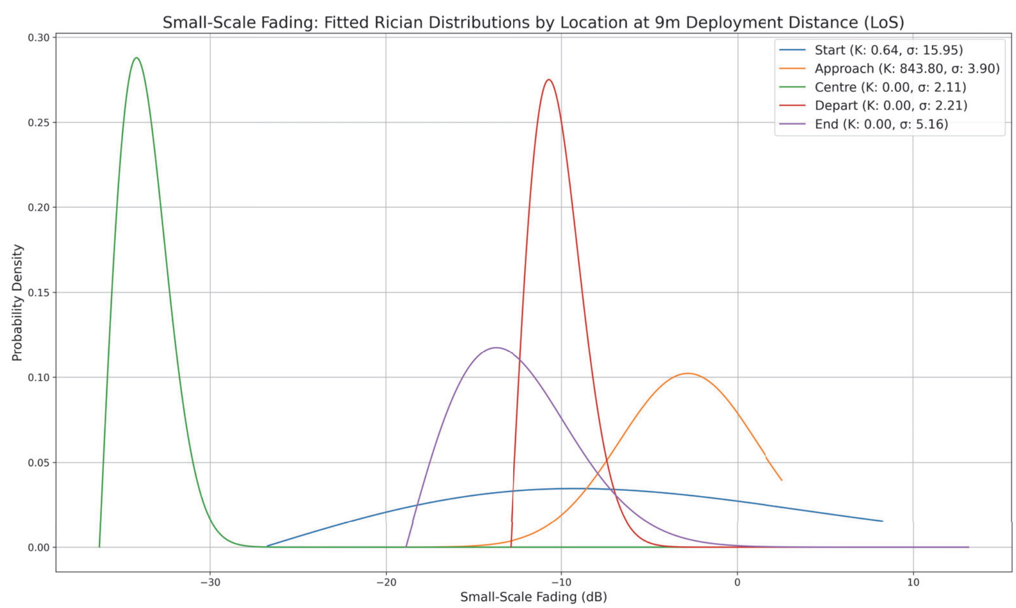
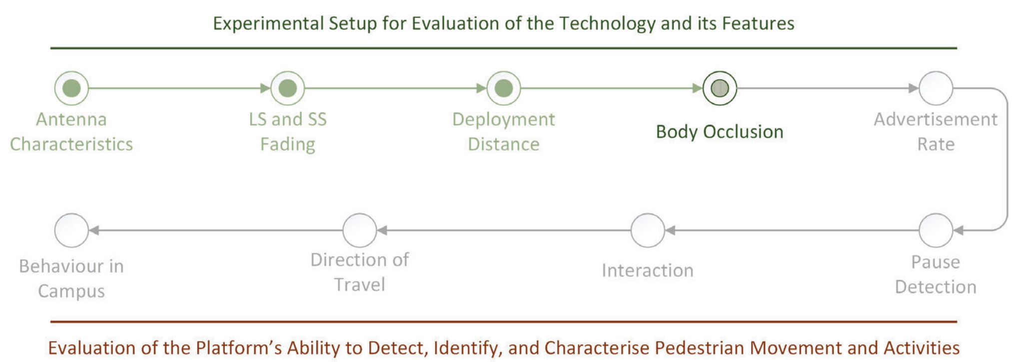


FIGURE 2.29: Rician Distribution Fitting to RSSI at Each Key-points on 9 *m* Pathway (LoS)

Section Summary

The outcome of this experiment highlights both 3 *metres* and 5 *metres* as optimal candidates for the deployment distance of the Observer for the selected hardware components for this PhD research. While this set of results could be intuitive as it indicates that the strength of BLE signals dissipates with distance, this experiment proved to be useful. Despite that intuition, it can be seen that the RSSI of the signal emanating from the distance of 9 *metres* are similar to the 5 *metres* and 3 *metres* deployment distances in some locations on the pathways. Surprisingly, the deployment distance of 9 *metres* has provided better results in comparison to the deployment distance of 7 *metres*.

2.1.4 Detecting Occlusion between the Broadcaster and the Observer



The results of the previous experiments show that the behaviour of the BLE based platform is comparable in an outdoor setting with the noiseless anechoic chamber. However, to assess the feasibility of the technology and the platform, an investigation to understand whether occlusion can be detected between the BLE Broadcaster and the Observer was conducted. As stated in the Section 1.3 Methodology chapter 1, three experimental setups were defined to test this case.

This experiment was devised to understand the effect of body occlusion on the RSSI of the BLE device carried by a pedestrian on a linear pathway. To do this, the Observer was deployed at a distance of 3 *metres* and RSSI was collected from a Broadcaster with an advertisement rate of 2Hz. The experiment was divided into the following three sub-experiments:

1. *Sub-experiment 1: RSS values are recorded from a stationary pedestrian at each waypoint from A to E*
2. *Sub-experiment 2: RSS values are recorded from a stationary pedestrian at each waypoint from P to S)*
3. *Sub-experiment 3: Continuous RSSI collection while pedestrian traverses the path*
   (a) Pedestrian walking from *start* to *end* with Broadcaster in LoS of the Observer (no occlusion).
   (b) Pedestrian walking from *end* to *start* with Broadcaster in LoS of the Observer (no occlusion).

(c) Pedestrian walking from *start* to *end* with Broadcaster in nLoS of the Observer (occlusion).

(d) Pedestrian walking from *end* to *start* with Broadcaster in nLoS of the Observer (occlusion).

The first two sub-experiments allowed the comparison of occlusion and non-occlusion cases when the movement of pedestrians is not affecting the patterns on the resulting RSSI as captured by the Observer. This could be beneficial in the future to calibrate models that can be used to automate the identification of activities and movement dynamics, develop a general understanding of the behaviour of BLE, and identify useful patterns that may help in asserting the location of the pedestrian, based solely on RSSI patterns.

Measurements for the first sub-experiment were acquired on March 23, 2022 between 14:16 and 14:27 hours Irish time. These measurements were taken using a single volunteer. Measurements for the second sub-experiment followed the first sub-experiment, and hence were taken on the same day between 14:29 and 14:38 hours. The weather at 14:00 hours on the day of the experiment is presented below:

At 12:00 hours on February 10, 2023

- **Precipitation (Rain):** 0.0 mm
- **Air Temperature:** 16.8 °C
- **Wet Bulb Temperature:** 11.5 °C
- **Dew Point Temperature:** 5.9 °C
- **Vapour Pressure:** 9.3 hPa
- **Relative Humidity:** 48 %
- **Mean Sea Level Pressure:** 1027.8 hPa

Measurements for the third and final sub-experiment started after the second sub-experiment on the same day between 14:41 and 15:07 hours. The weather information at 15:00 hours on the data is as follows:

At 15:00 hours on February 10, 2023

- **Precipitation (Rain):** 0.0 mm
- **Air Temperature:** 17.4 °C
- **Wet Bulb Temperature:** 11.8 °C
- **Dew Point Temperature:** 6.0 °C
- **Vapour Pressure:** 9.3 hPa
- **Relative Humidity:** 47 %
- **Mean Sea Level Pressure:** 1027.7 hPa

2.1.4.1 Sub-experiment 1

The collected RSSI values at each location for a period of 30 seconds were plotted with RSSI on the y-axis and the order of their collection represented on the x-axis. This was performed to visually assess the strength of the signal at each of those key points for both LoS and nLoS cases. This is depicted in Figure 2.30 where the red error bars and markers depict the fluctuations in the RSS values and the median RSSI respectively at each of those locations. Likewise, the blue error bars and markers depict those parameters for the nLoS case.

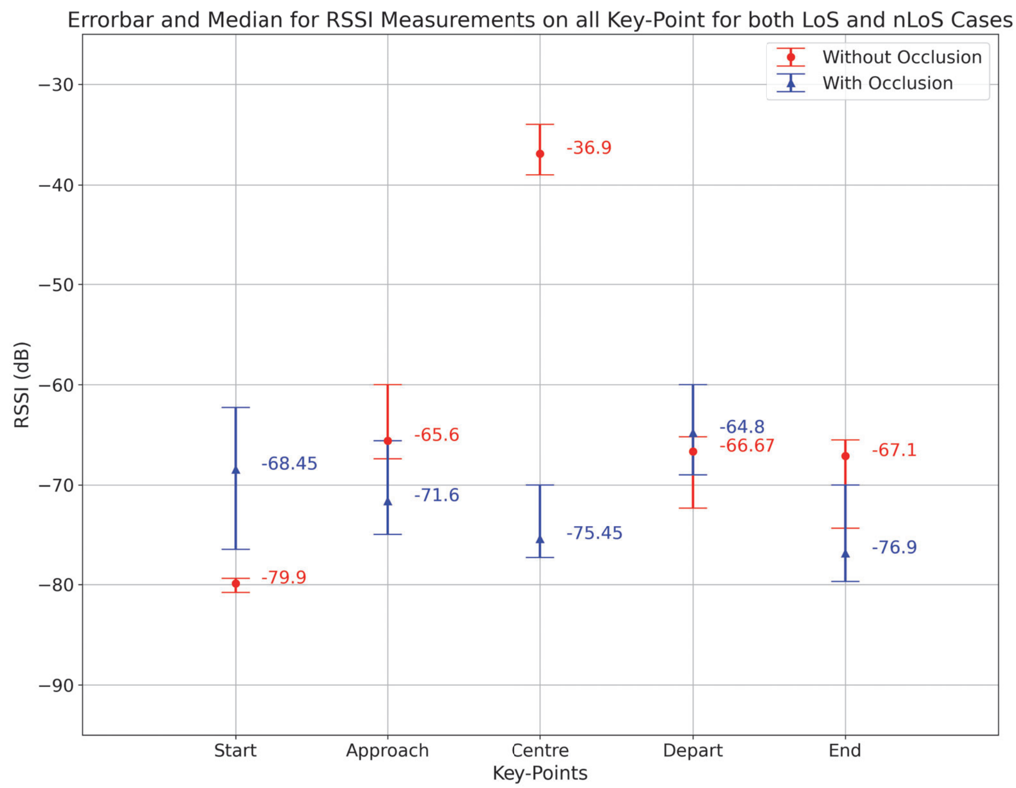


FIGURE 2.30: BLE RSSI at Key-Points *start* to *end* (LoS and nLoS) for a Period of 30 Seconds

To quantify the variation in RSS values, *MAD*, which is discussed in subsection 1.4.5 of Chapter 1, of RSSI was calculated at each key point. Table 2.8 highlights the MAD values for both LoS and nLoS cases at each of those points.

Figure 2.30 reveals that the median RSS values for the case of LoS are better at two out of five key points, viz. *start* and *depart*, on the pathway when compared against those for the case of nLoS. While empirically that is equivalent to only 40% of all the cases, the difference between the median values is significantly higher in the case of LoS at the *centre* point. This was possibly because, at the centre point, body occlusion results in full occlusion as opposed to partial occlusion at other key points, which was presented in Figure 1.21 in Chapter 1. That is, at all key points except *centre*, the Broadcaster was fairly visible or in LoS of the Observer as opposed to when at the *centre*, the Broadcaster was completely occluded by the body and the signals must travel through the body or by undergoing reflection, refraction or

Waypoint	Median Absolute Deviation (dB)	
	LoS	nLoS
Start	0.40	1.50
Approach	0.80	1.60
Centre	0.30	1.25
Depart	0.96	2.07
End	0.60	1.57

TABLE 2.8: Median Absolute Deviation at Each Key-Point, *Start* to *End*

diffraction to arrive at the Observer. However, Table 2.8 reveals a more accurate insight into the differences between the LoS and nLoS cases. The MAD values for the LoS case were lower, $< 1\,dB$, when compared against the nLoS case, $> 1\,dB$. This meant that there was more fluctuation on the signals when the Broadcaster was occluded.

2.1.4.2 Sub-experiment 2

The same analysis as for the previous sub-experiment was performed for this sub-experiment. Figure 2.31 presents the error bars and markers to depict the fluctuations and the median value of RSSI respectively in red for or LoS, and in blue for the case of nLoS. With the exception of point Q, all other points presented the situation analogous to that in the previous sub-experiment, where the case of nLoS reduced the RSS of the acquired advertisements. There was no peak formation in this case which is possibly due to the fact that the signals were travelling from a greater distance and hence were subjected to increased path loss by the time they were acquired by the Observer. It is noteworthy however that the lowest value of RSSI associated with this sub-experiment was significantly higher than the lowest values in *Sub-experiment 1*, that is where the signals are emerging from five key points on a pathway at a mere 3 *metres* deployment distance of the Observer. Moreover, as seen in Table 2.9, the MAD values for the nLoS case were better than the MAD values for the same case in *Sub-experiment 1*. While no tests were performed to unravel this occurrence, it is likely that this was due to reflection caused by the presence of metal infrastructure (as the literature suggests in Section **??** in Chapter **??**) at the experiment location, as can be seen at the bottom right corner of Figure 1.13 in Chapter 1. This metal infrastructure could have acting as an antenna to reflect the advertisements to the Observer. However, no experiments were undertaken in this PhD to further investigate this speculation.

Waypoint	Median Absolute Deviation (dB)	
	LoS	nLoS
P	0.60	1.20
Q	0.90	0.80
R	0.35	0.90
S	0.50	1

TABLE 2.9: Median Absolute Deviation at Each Key-Point, *P* to *S*

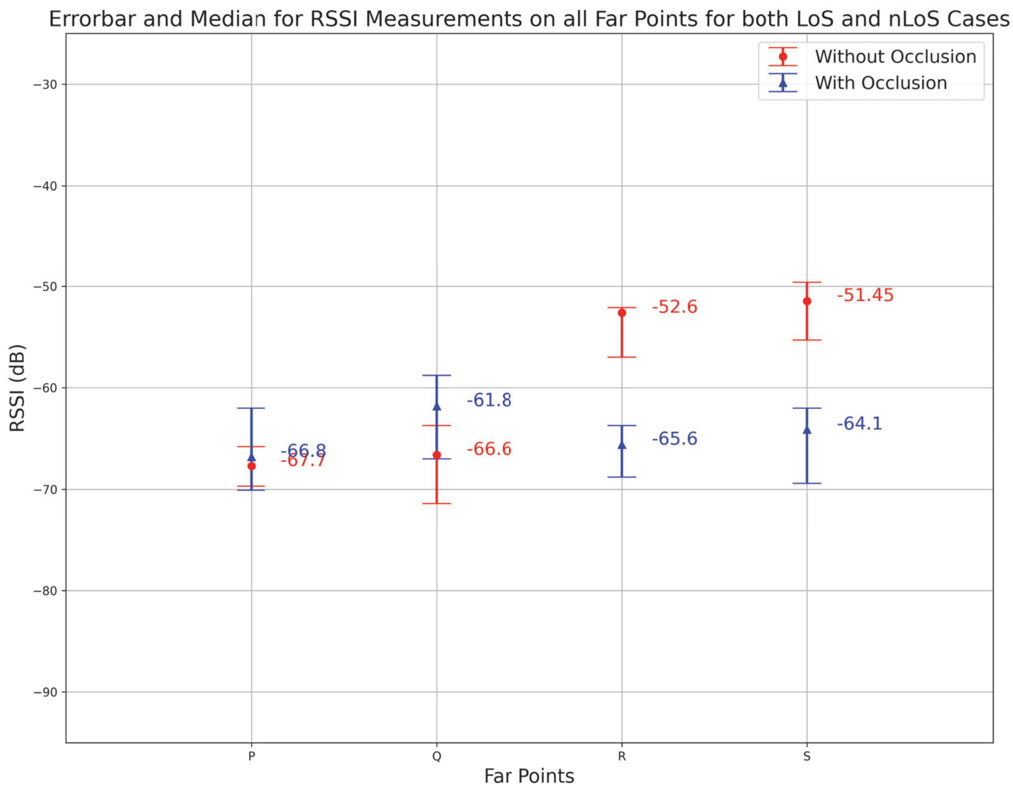


FIGURE 2.31: BLE RSSI at Key Points P to S (LoS and nLoS) for a Period of 30 *Seconds*

Finally, packet drop (as explained in Section 1.12 in Chapter 1) was observed for both the LoS and nLoS cases for all five points on the pathway, and the four far points. This analysis was identified based on the BLE advertisements process, which is briefly described here first. From the Broadcaster's point of view, advertisements are broadcasted at fixed intervals, dictated by the configured advertisement interval. This configuration of advertisement interval for the Ruuvi beacon is hard-coded by the manufacturer and for the RPi Broadcaster, it is configurable by the researcher. This configuration ensures that from the point of view of the Broadcaster, signals are sent out regularly at the set interval. If the Observer were to acquire every single advertisement that the Broadcaster has emitted, the Observer would be a recipient of a regularly-sampled signal. Since the signal is also emitted at fixed intervals, if adjusted for the delay in travel, the advertisements would correspond to a time series. Since 2.4 GHz RF signals travel at the speed of light in a vacuum, assuming there is a comparatively negligible affect of the air, the delay in signals due to travel would only be in some tens of nanoseconds for the distances under scrutiny in the experiment presented here. However all advertisements are not received by the Observer due to various reasons including path loss, reflection, refraction, and diffraction, this means the advertisements received by the Observer can be referred to as *sparsely-populated regularly-sampled time series*. This knowledge provides another means to analyse the signal. While such an assumption should facilitate the application of some Digital Signal Processing (DSP) techniques, only simple statistical techniques are employed in this experiment. However, this assumption is important to future work.

In this particular analysis, using the knowledge that the Broadcaster employed had a 500 *ms* advertisement interval, that is two advertisements per second, the number of advertisements emitted by the Broadcaster for each location was calculated by doubling the duration of the round in seconds. Since the number of advertisements is a whole number, the resulting advertisement counts from the doubling process were rounded off to the nearest integer. Using this, Dropped Advertisement Percentage (DAP) and Dropped Advertisement Rate (DAR), as discussed in Sections 1.12 and 1.11 in Chapter 1, combining all key points were calculated. Table 2.10 and Table 2.11 summarises this information.

Case	Locations	Observation Duration (s)	Advertisements Emitted	Advertisements Intercepted	DAP (%)	Average DAP (%)
LoS	Start	41.973	84	17	79.76	**45.27**
	Approach	34.989	70	41	41.43	
	Centre	38.072	76	43	43.42	
	Depart	39.476	79	49	37.97	
	End	40.94	82	64	21.95	
nLoS	Start	50.434	101	58	42.57	**58.67**
	Approach	54.496	109	36	66.97	
	Centre	43.07	86	22	74.42	
	Depart	39.97	80	51	36.25	
	End	45.519	91	26	71.43	

TABLE 2.10: Advertisement Drop Percentage at Each Location on Pathway

Case	Locations	Duration of Walk (s)	Advertisements Emitted	Advertisements Intercepted	DAP (%)	Average DAP (%)
LoS	P	38.404	77	17	77.92	**56.4**
	Q	45.488	91	41	54.95	
	R	44.057	88	43	51.14	
	S	43.937	88	49	44.32	
nLoS	P	41.507	83	17	79.52	**56.52**
	Q	44.488	89	41	53.93	
	R	41.522	83	43	48.19	
	S	45.005	90	49	45.56	

TABLE 2.11: Advertisement Drop Percentage at Each Far Points, *P, Q, R, and S*

It can be seen from Table 2.10 that the DAP was considerably lower in the case of LoS compared to the case of nLoS at *approach*, *centre*, and *end* key points. However, the same did not apply to the case when the advertisements are emitted from a device at a greater distance, as can be seen in Table 2.11, where the difference was found to be marginal even if at certain key points the DAP was low. This further increased the likelihood that metal infrastructure at the far reaches of the depicted site could have acted as an antenna reflecting the signals to the Observer, thereby enabling the broadcasted advertisements to arrive at the occluded Observer just as they did without the occlusion.

2.1.4.3 Sub-experiment 3

To understand the effect of occlusion on the resulting RSSI, a ratio of the number of advertisements received within 10 percentage of the maximum values of RSSI over total number of advertisements was evaluated, as described in Subsection 1.4.10 in Chapter 1. Along with the ratio calculated in the previous step, the minimum, maximum, and median values of all the rounds for both cases were also calculated. Table 2.12 presents the data evaluated from the measured RSSI signals. The *interception rate* in the table is the ratio of total advertisements received by the Observer in the duration of the round over the total number of advertisements emitted by the Broadcaster during the walk. *Max*, *Min*, and *Median* RSSI are the maximum, minimum, and median values of all RSS values collected in each round. The mean of these values for each individual round is presented in the *Mean of Max*, *Mean of Min*, and *Mean of Median* RSSI columns. Using the maximum values of each individual round, the count of RSSI values within the 10% range of the peak was evaluated, which is presented in the *Count within 10% of Peak* column. Finally, the ratio of the number of advertisements within 10% of the peak and the total number of advertisements were calculated and are presented in the last column of the table. This ratio represents the accumulation of advertisements in the range of the peak. This empirical value helped in identifying the sharpness of the peak. If the RSSI values rose steeply, followed by a sharp decline, this ratio would be lower. Whereas, the higher value of the ratio denotes flatness around the region of the peak.

Evaluating the data provided in Table 2.12, it can be seen that the difference between the minimum and median values of the RSSI across the nLoS and LoS cases was insignificant. Whereas, the maximum value of RSSI across the two cases demonstrated a difference, with the maximum RSSI values for LoS case being -45.5 dB and -43 dB for rounds between *start* to *end* and *end* to *start* respectively, as opposed to -55 dB and -48.9 dB for the case of nLoS. The improvement in the lowest maximum RSSI of the two LoS cases, -45.5 dB, against the highest maximum RSSI of the two nLoS cases, -48.9 dB, being at 7.47%. Conversely, the improvement in the highest of the LoS case, -43 dB, over the lowest of the nLoS case, -55 dB, standing at 27.90%. Categorically, for the journeys from *start* to *end*, the maximum value of RSSI for LoS case was 20.87% over the nLoS case, whereas, for the journeys starting from *end* to *start*, the maximum value of RSSI was 13.72% better in the case of LoS. This further strengthened the likelihood of the presence of a sharper peak in the case of LoS.

The ratio of the count of RSS values within the 10% range of the peak RSSI and the total number of advertisements measured by the Observer painted a clearer picture. The highest ratio across all rounds for combined journeys in both directions for the case of LoS stood at 0.283, whereas that from the case of nLoS was 0.409. The mean of the ratios across all rounds while walking from *start* to *end* for the case of LoS was 0.235 as compared to 0.305 in the case of nLoS. The same comparison for the journeys between *end* and *start* was more significant. With the mean ratio of only 0.167 for the case of LoS against the mean of ratios of 0.305 in the case of nLoS, it was clear that *the case of nLoS results in the flatness of plateau* in the resulting pattern from the measured RSSI. Therefore, *body occlusion appears to act as a low-pass filter*.

To visualise this flatness, Figures 2.32 and 2.33 present the plot between the RSSI values against the elapsed time of the walk for the case of LoS. Whereas, Figures 2.34 and 2.35 present the chart of RSSI against elapsed time for the nLoS case. In addition to the RSSI, each plot contains horizontal lines representing the median of individual cases in respective colours, as shown in the legend of the figures, and another horizontal line in black colour representing the mean of the medians.

Sharp peaks can be visually spotted in the first two figures and plateaus can be identified in the latter two. The figures also assist in the identification of another parameter that can be used as an empirical representation for the presence of occlusion, the distance between the peak and the median value. The empirical values of this distance are presented in Table 2.13. It can be seen that the distance between the

Case	Direction, round	Duration (s.sss)	Advertisements Emitted	Advertisements Intercepted	Interception Rate (Hz)	Max RSSI (dB)	Mean of Max RSSI (dB)	Min RSSI (dB)	Mean of Min RSSI (dB)	Median RSSI (dB)	Mean of Median RSSI (dB)	Count within 10% of Peak[1]	Ratio[2]	Mean of Ratios
LoS	Start to End, 1	43.984	88	46	1.0458	-53.4		-77		-63.65		13	0.283	
	Start to End, 2	40.97	82	40	0.9763	-52.8		-76.1		-65.7		11	0.275	
	Start to End, 3	36.635	73	43	1.1737	-45.5	-45.5	-69.4	-77	-59.7	-62.47	7	0.163	0.235
	Start to End, 4	40.989	82	44	1.0735	-47.1		-70.3		-62		10	0.227	
	Start to End, 5	38.029	76	48	1.2622	-52.6		-68.6		-61.3		11	0.229	
	End to Start, 1	42.277	85	49	1.159	-45.2		-69		-62.2		8	0.163	
	End to Start, 2	40.006	80	53	1.3248	-43.2		-83		-59.8		7	0.132	
	End to Start, 3	36.816	74	48	1.3038	-49.3	-43	-73	-83	-59.2	-59.84	10	0.208	0.167
	End to Start, 4	39.988	80	51	1.2754	-45.1		-75		-60		9	0.176	
	End to Start, 5	38.5	77	51	1.3247	-43		-65.6		-58		8	0.157	
nLoS	Start to End, 1	41.5	83	40	0.9639	-59.5		-82		-68.45		14	0.350	
	Start to End, 2	41.017	82	49	1.1946	-55		-75		-64.7		16	0.327	
	Start to End, 3	37.009	74	40	1.0808	-56.1	-55	-81	-82	-65.65	-66.986	13	0.325	0.305
	Start to End, 4	40.067	80	41	1.0233	-56.5		-71.8		-67.33		10	0.244	
	Start to End, 5	37.736	75	43	1.1395	-60.7		-78		-68.8		12	0.279	
	End to Start, 1	41.402	83	42	1.0144	-50.2		-67		-60.1		11	0.262	
	End to Start, 2	39.035	78	39	0.9991	-50.9		-68.25		-59.7		15	0.385	
	End to Start, 3	39.488	79	44	1.1143	-53.6	-48.9	-76.3	-76.3	-62.4	-61.83	18	0.409	0.305
	End to Start, 4	40.494	81	49	1.2101	-48.9		-75		-65.4		7	0.143	
	End to Start, 5	41.906	84	46	1.0977	-53.5		-70.5		-61.55		15	0.326	

TABLE 2.12: Parameters of Observed Advertisements During Walk

[1] Number of Advertisements within the 10% value of the peak or maximum of RSSI.

[2] Ratio of count of advertisements intercepted within 10% range of the peak or the maximum RSSI and the total number of advertisements received.

median and the peak value of RSSI in the case of nLoS is less, which further supports the finding that occlusion results in a plateau or flatness pattern in the RSSI, and the techniques presented here are useful in quantifying these plateaus.

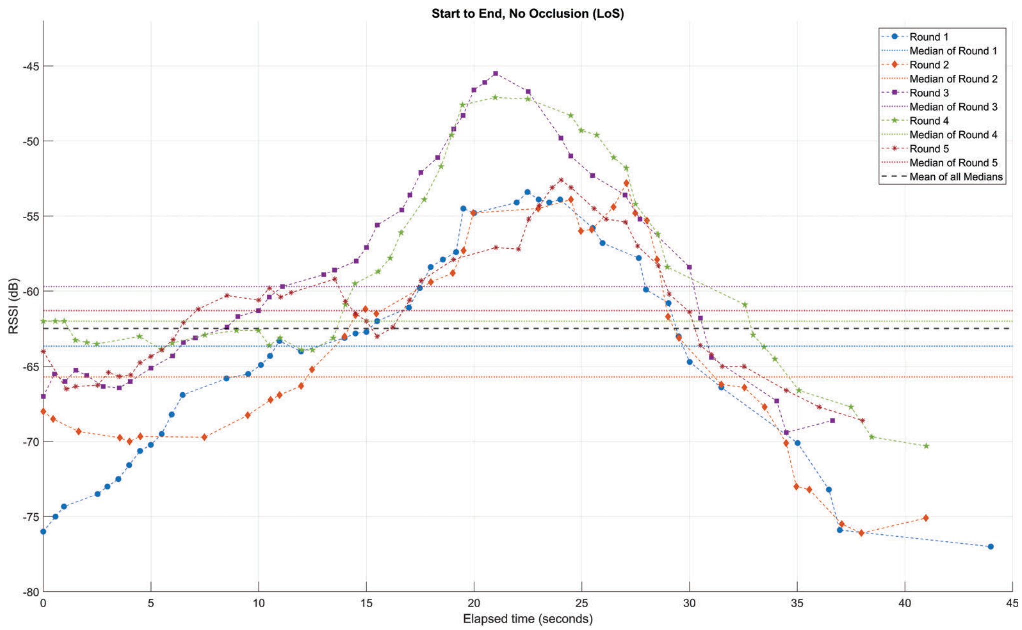


FIGURE 2.32: RSSI, Medians and Mean of all Medians for all Five rounds of Walk from Start to End in case of LoS

Case	Direction, round	Peak (dB)	Median (dB)	Distance between Peak and Median (dB)	Mean of Distances (dB)
LoS	Start to End, 1	-53.4	-63.65	10.25	
	Start to End, 2	-52.8	-65.7	12.9	
	Start to End, 3	-45.5	-59.7	14.2	12.19
	Start to End, 4	-47.1	-62	14.9	
	Start to End, 5	-52.6	-61.3	8.7	
	End to Start, 1	-45.2	-62.2	17	
	End to Start, 2	-43.2	-59.8	16.6	
	End to Start, 3	-49.3	-59.2	9.9	14.68
	End to Start, 4	-45.1	-60	14.9	
	End to Start, 5	-43	-58	15	
nLoS	Start to End, 1	-59.5	-68.45	8.95	
	Start to End, 2	-55	-64.7	9.7	
	Start to End, 3	-56.1	-65.65	9.55	9.426
	Start to End, 4	-56.5	-67.33	10.83	
	Start to End, 5	-60.7	-68.8	8.1	
	End to Start, 1	-50.2	-60.1	9.9	
	End to Start, 2	-50.9	-59.7	8.8	
	End to Start, 3	-53.6	-62.4	8.8	10.41
	End to Start, 4	-48.9	-65.4	16.5	
	End to Start, 5	-53.5	-61.55	8.05	

TABLE 2.13: Gap Between Median RSSI and the Maximum (Peak) RSSI

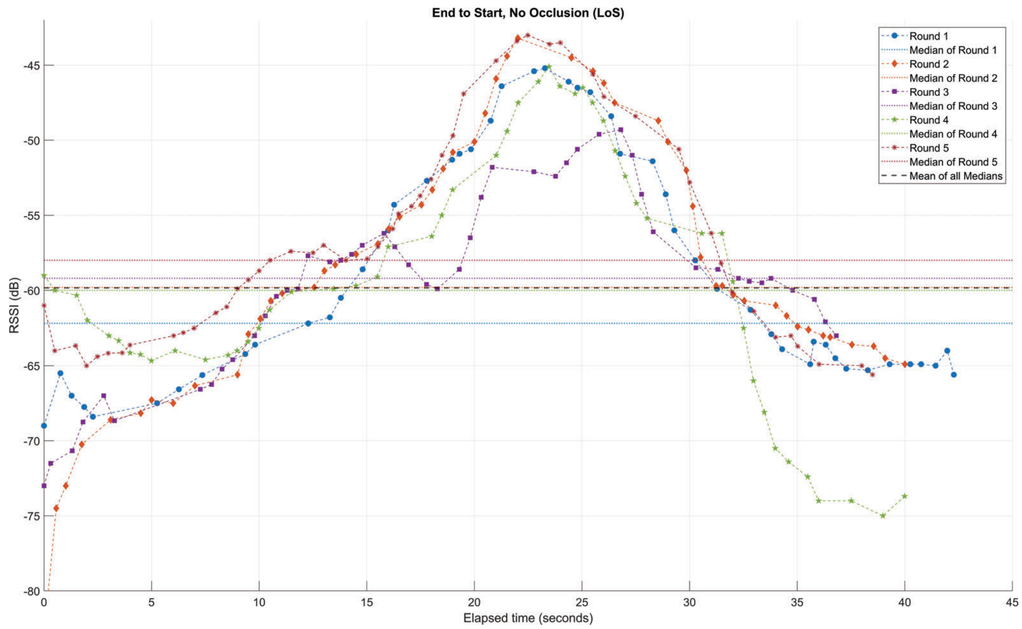


FIGURE 2.33: RSSI, Medians and Mean of all Medians for all Five rounds of Walk from End to Start in case of nLoS

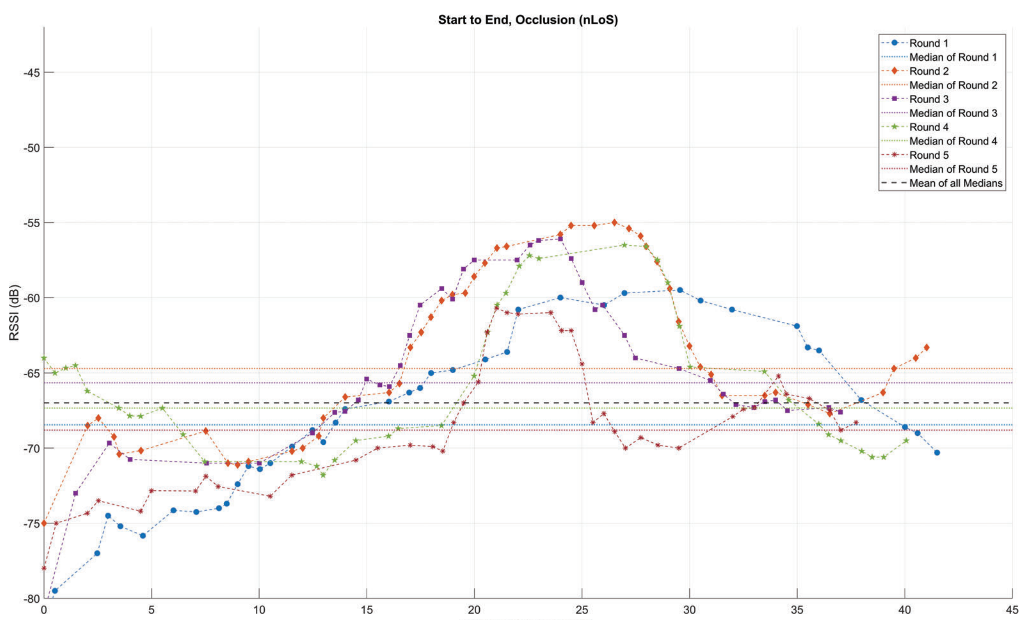


FIGURE 2.34: RSSI, Medians and Mean of all Medians for all Five rounds of Walk from Start to End in case of nLoS

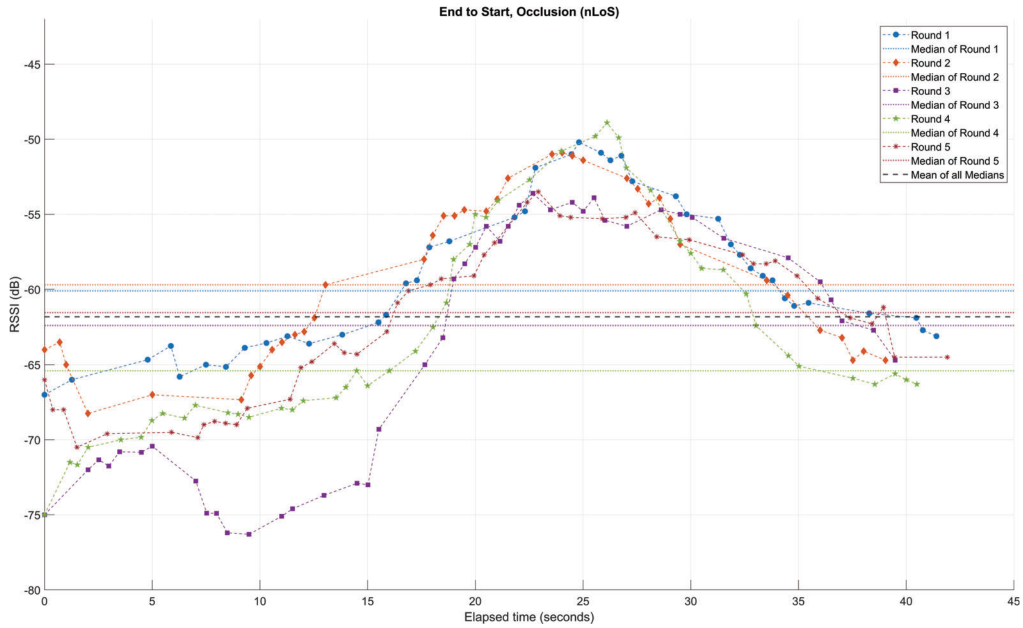


FIGURE 2.35: RSSI, Medians and Mean of all Medians for all Five rounds of Walk from End to Start in case of nLoS

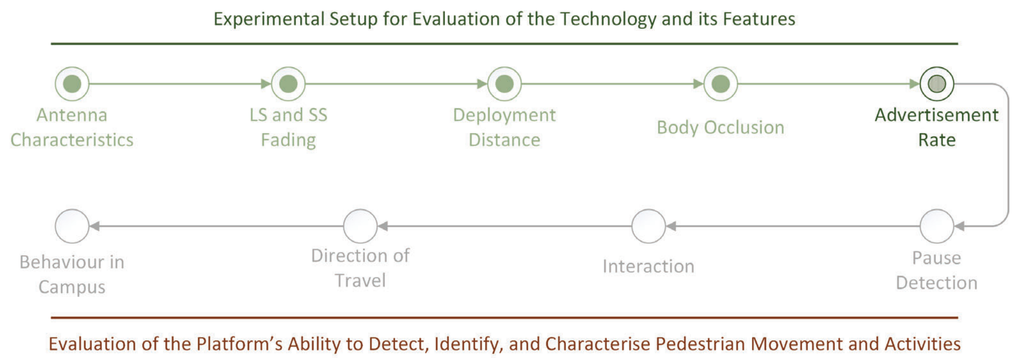
Section Summary

The experiment conclusively shows that occlusion introduces an effect akin to a "clipping" filter, suppressing the peak on the RSSI time series in the presence of body occlusion. This subsequently results in a characteristic plateau in the shape of RSSI when plotted against elapsed time. Using common statistical methods, median and MAD, the results prove the possibility of identifying the plateau and therefore assert the possible presence of occlusion in most of the cases. This is true in both the scenarios where the pedestrian is stationary and where the pedestrian is moving on a linear path. As seen in figure 2.30, the RSSI is significantly higher near the Observer (point C) in the LoS scenario when compared against the RSSI at other locations on the path, whereas, in the nLoS scenario, RSSI near the Observer remains in the same range as on the other points on the path.

It is also seen that the likelihood of the presence of body occlusion, as detected by the MAD analysis, can be further verified by measuring the difference between the median of all the collected RSS values during the walk and the maximum RSSI of those collected values. For the case of body occlusion, since there should be an absence of a sharp peak, the difference obtained between the median and peak RSSI must be smaller than the difference between the median and the peak of RSSI when there is no occlusion. Finally, the DAR is also an aid to detect occlusion. This is because with occlusion there is an increased probability of the advertisements losing their strength while traversing through the obstruction and thus not reaching the Observer. However, the DAR measure can only be employed in conjunction with other analysis methods if the advertisement rate of the Broadcaster is known. Otherwise, there is no way of knowing the number of advertisements emitted during the time the Broadcaster was *visible* to the Observer.

The work described in this section is presented in a paper titled, "Effects of Body Occlusion on Bluetooth Low Energy RSSI in Identifying Close Proximity of Pedestrians in Outdoor Environments" (Parmar, Kelly, and Berry, 2022).

2.1.5 Effect of Advertisement Interval of BLE Broadcaster on Acquisition Capabilities of the Observer



Understanding the effect of the advertisement interval or the advertisement rate is crucial. The range of BLE is limited and the strength of the signal reduces with distance. Therefore, when deployed in an outdoor pathway, an observing device is capable of producing useful results only for short distances. For example, a pathway of 50 *metres* with a BLE Observer deployed at 25 *metres* from each end, can be traversed by a casual walker at a speed of 1.4 *metres* per *second* in 35 *seconds*. During this time, the greater the number of advertisement packets received, the finer the granularity of the captured observations of the walk. However, there could be other bottlenecks with a very aggressive advertisement rate from a BLE Broadcaster. There could be competing packets on the same channel, resulting in more packet collisions, or the rate of packets intercepted could be too much for the Observer to process. On the other hand, a lazy advertisement rate might produce only two or three measurements for the entire journey, resulting in insufficient data for any analysis of the type presented in this chapter to be possible. Therefore, an optimal advertisement rate must be investigated to ensure that a balance between the advertisement rate and the usefulness of the acquired data is maintained.

Here, three advertisement interval candidates, viz. 100 *ms*, 500 *ms*, and 1000 *ms* (or advertisement rate of 10 *Hz*, 2 *Hz*, and 1 *Hz* respectively) were investigated at a deployment distance of 3 *metres*. Since the Broadcaster in this experiment was based on a RPi, the advertisement interval could be modified through reprogramming. Each advertisement packet emitted by the Broadcaster was supplemented with the sequence number of the advertisement itself so the receiver could identify the order of the packet it received. The advertisement record was also stored on the Broadcaster to enable a comparison between the transmitted advertisement and the received advertisement.

The measurements were collected on April 2, 2024 starting at 12:50 hours and lasting at 13:39 hours Irish time. A single volunteer pedestrian was required to partake in the experiment. The weather conditions at the time of the experiment is described below:

At 13:00 hours on April 2, 2024

- **Precipitation (Rain):** 0.0 mm
- **Air Temperature:** 11.3 °C

- **Wet Bulb Temperature:** 9.1 °C
- **Dew Point Temperature:** 6.6 °C
- **Vapour Pressure:** 9.8 hPa
- **Relative Humidity:** 73 %
- **Mean Sea Level Pressure:** 1000.2 hPa

The most direct approach was comparing the total number of emitted advertisements against the total number of received advertisements. This comparison highlighted the number of packets dropped for each advertisement interval candidate. The hypothesis was that a smaller advertisement interval or an aggressive advertisement rate results in greater packet collision and an unmanageable workload on the Observer. To address this, the total count of advertisements, obtained through the last sequence number of the advertisement packet on the Broadcaster, was compared against the total count of advertisements observed by the Observer, obtained through counting the number of acquired advertisements.

Table 2.14 shows the number of advertisements sent, the number of advertisements received, the repetition of advertisements received, and the percentage of dropped advertisements by the Observer. Figures 2.36 and 2.37 also illustrate the percentage of dropped advertisement in the cases of LoS and nLoS respectively for each advertisement rate. The repetition of advertisements signified the advertisement packets that were received more than once due to reflected transmissions arriving at the Observer from a different route. The percentage of dropped advertisements was found to be substantially higher for the advertisement interval of 100 *ms*, ranging in the high 80s and 90s. The performance of 500 *ms* and 1000 *ms* advertisement interval were comparable where almost half of the advertised signals were captured. Regardless, the number of intercepted signals with a 100 *ms* advertisement interval, barring one LoS travel from *end* to *start* were also comparable to the other advertisement intervals. So, the question then is, is there any significance of testing the advertisement rate/advertisement interval?

Advert Interval	Case	Travel Direction	Adverts Sent	Adverts Received	Repeated Packets Received	Drop percentage
100 *ms*	LoS	S -> E[1]	295	18	0	93.89%
		E -> S[2]	290	2	0	99.31%
	nLoS	S -> E	312	16	0	94.87%
		E -> S	222	40	0	81.98%
500 *ms*	LoS	S -> E	45	24	1	46.66%
		E -> S	44	26	0	40.90%
	nLoS	S -> E	46	20	0	56.52%
		E -> S	45	22	0	51.11%
1000 *ms*	LoS	S -> E	26	14	0	46.15%
		E -> S	23	11	0	52.17%
	nLoS	S -> E	23	13	0	43.47%
		E -> S	29	18	0	37.93%

TABLE 2.14: Percentage Dropped Advertisements by Observer

[1] Travelling from the *start* point to the *end* point on the pathway.
[2] Travelling from the *end* point to the *start* point on the pathway.

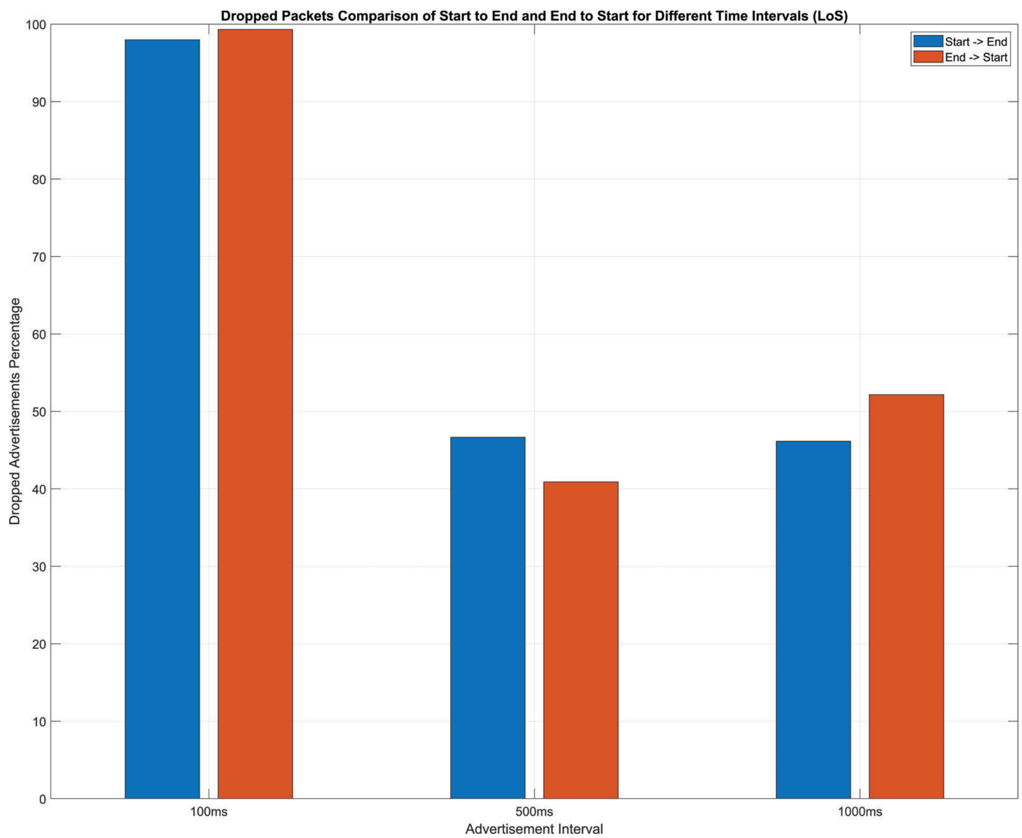


FIGURE 2.36: Comparison of Dropped Advertisements at Different Advertisement Intervals in LoS Case

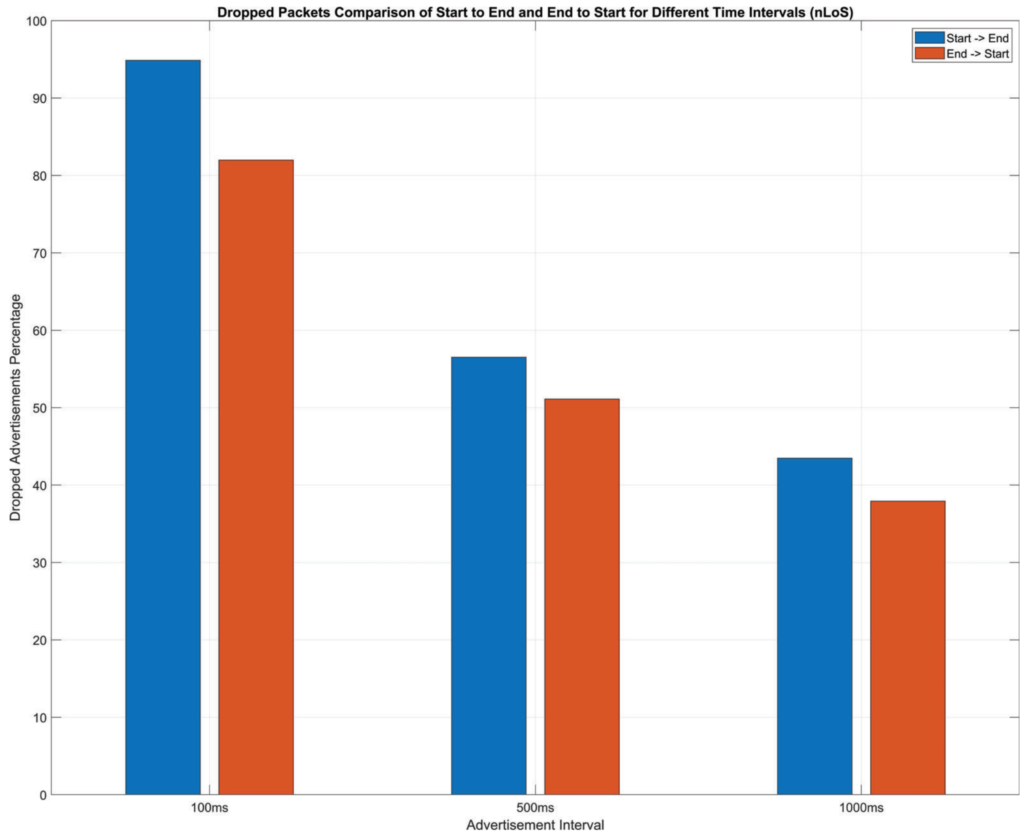


FIGURE 2.37: Comparison of Dropped Advertisements at Different Advertisement Intervals in nLoS Case

To investigate further, a comparison of the number of signals acquired concerning the course of the walk of volunteer pedestrians was charted on a *geoplot*. The data markers on the geoplot represent the measurement of location from the GPS and the number next to the markers represents the sequence number of the advertisements emitted by the Broadcaster around that region. Alongside each geoplot, the RSSI and the sequence number collected by the Observer for the respective round was plotted on a scatter chart. The marker on the graph represents the RSSI of the captured signal and the horizontal axis depicts the sequence number of the captured advertisement. For the case of 100 *ms* advertisement interval, Figures 2.38, 2.39, 2.40, and 2.41 represents the aforementioned geoplots for LoS *start* to *end* case, nLoS *start* to *end* case, LoS *end* to *start* case, and nLoS *end* to *start* case respectively. It can be observed that the interception of advertisements for the 100 *ms* advertisement interval was patchy, especially in Figures 2.39, 2.40. This indicates a failure to acquire significant measurements between the walks to result in useful patterns. However, there was also the case in Figure 2.41, where the advertisements were evenly distributed, however, that is the best result out of all the rounds. While the advertisement interval of 100 *ms* does provide valuable information, its likelihood of working reliably is lower. Referring back to Table 2.14, the percentage of dropped advertisement packets was observed to be extremely high for the 100 *ms* advertisement interval to be considered reliable.

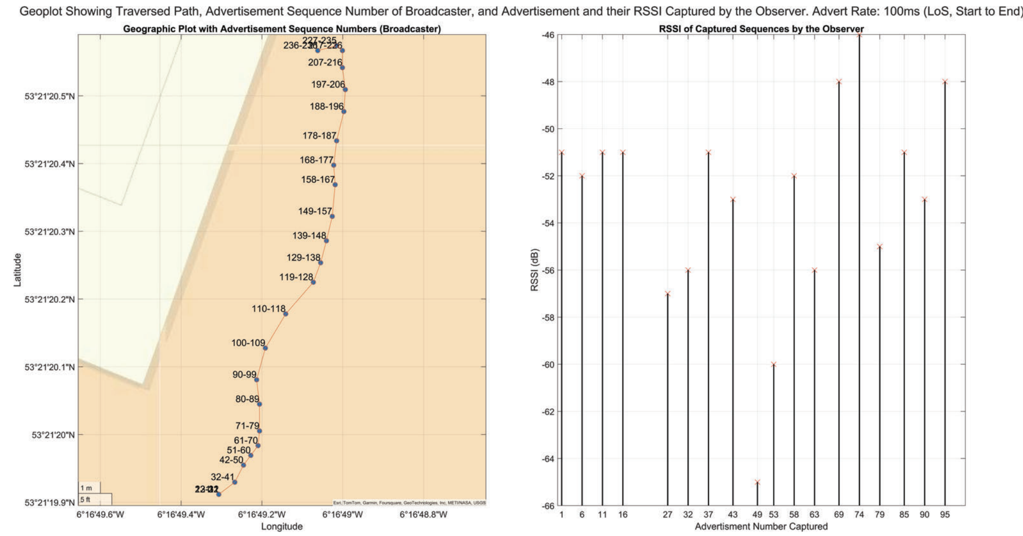


FIGURE 2.38: Geoplot and Captured Advertisement for 100 *ms* Advertisement Interval on a Walk from *Start* to *End* in LoS case

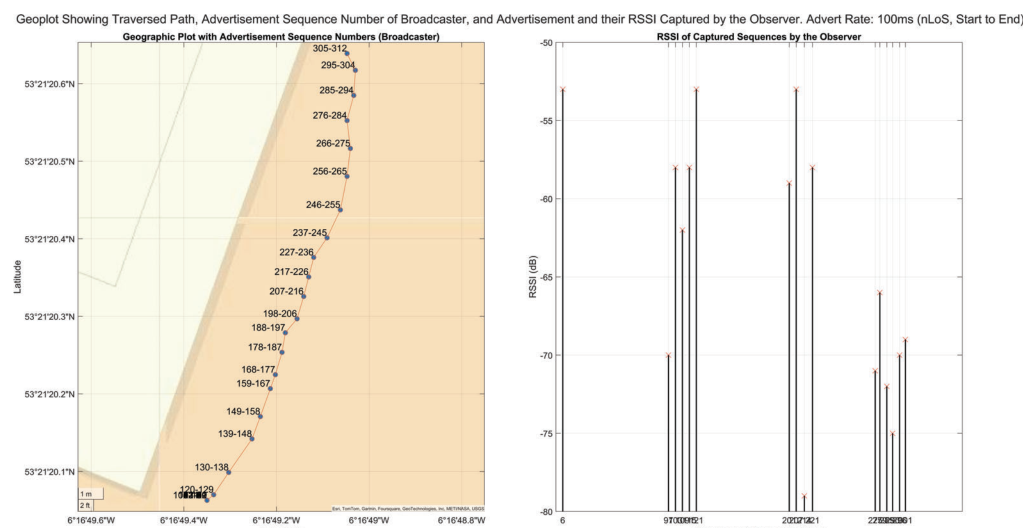


FIGURE 2.39: Geoplot and Captured Advertisement for 100 *ms* Advertisement Interval on a Walk from *Start* to *End* in nLoS case

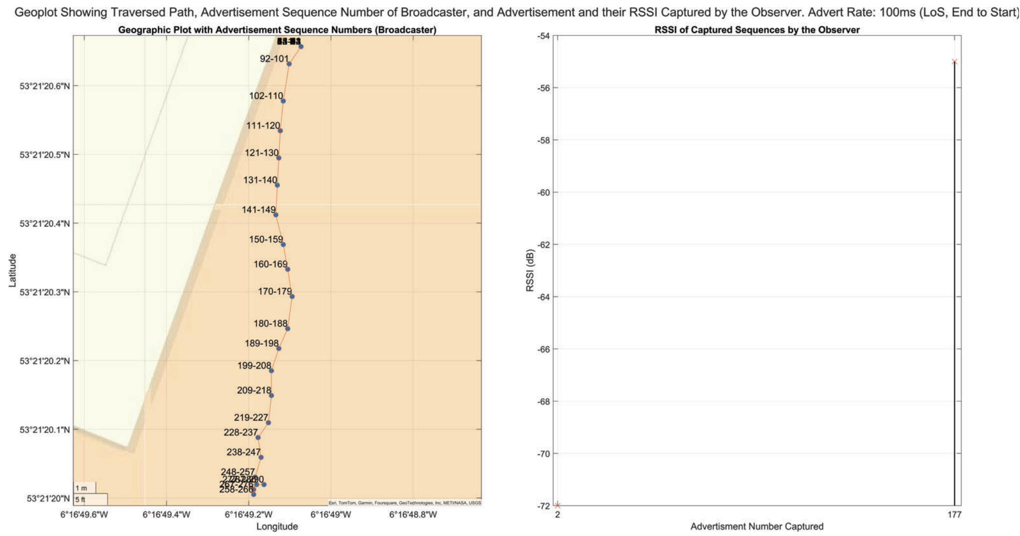


FIGURE 2.40: Geoplot and Captured Advertisement for 100 *ms* Advertisement Interval on a Walk from *End* to *Start* in LoS case

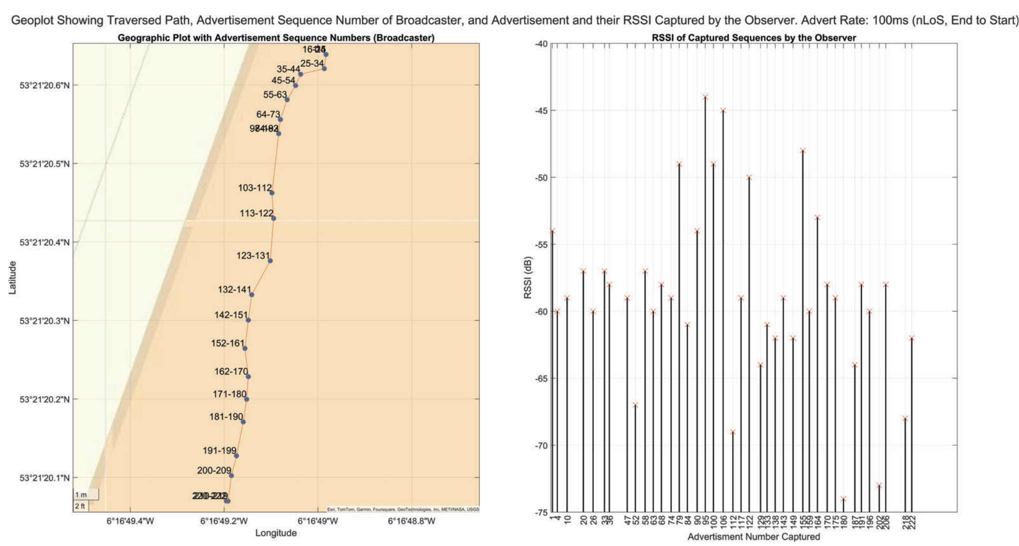


FIGURE 2.41: Geoplot and Captured Advertisement for 100 *ms* Advertisement Interval on a Walk from *End* to *Start* in nLoS case

Similarly, Figures 2.42, 2.43, 2.44, and 2.45 represents the geoplots for LoS *start* to *end* case, nLoS *start* to *end* case, LoS *end* to *start* case, and nLoS *end* to *start* case respectively, for the advertisement interval of 500 *ms*. In this case, while empty patches can be seen just as in the case of the 100 *ms* advertisement interval, they were equally distributed to generate meaningful patterns.

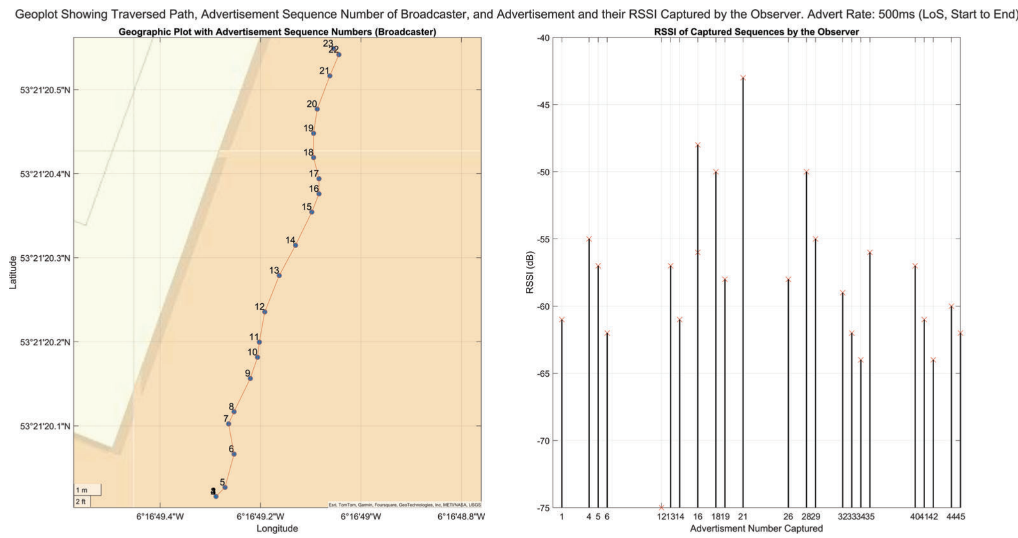


FIGURE 2.42: Geoplot and Captured Advertisement for 500 *ms* Advertisement Interval on a Walk from *Start* to *End* in LoS case

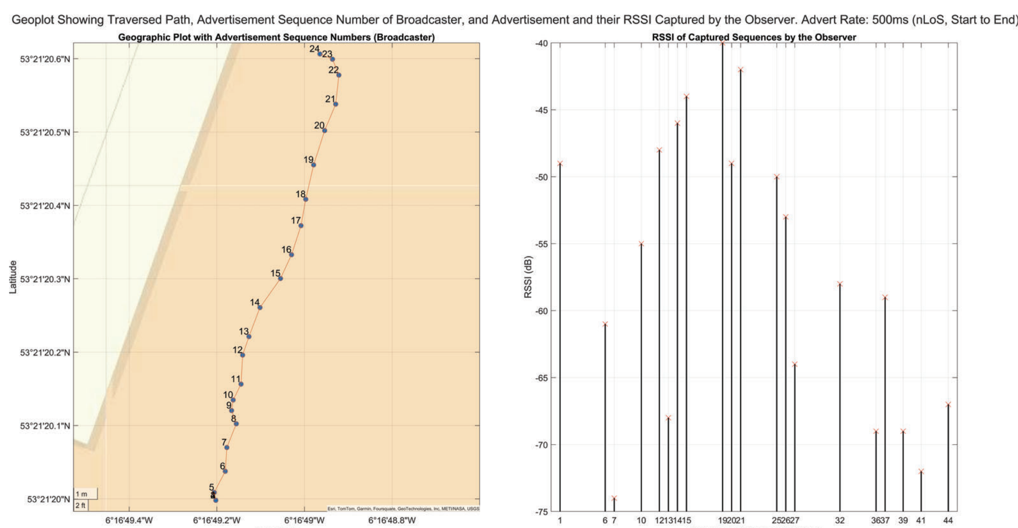


FIGURE 2.43: Geoplot and Captured Advertisement for 500 *ms* Advertisement Interval on a Walk from *Start* to *End* in nLoS case

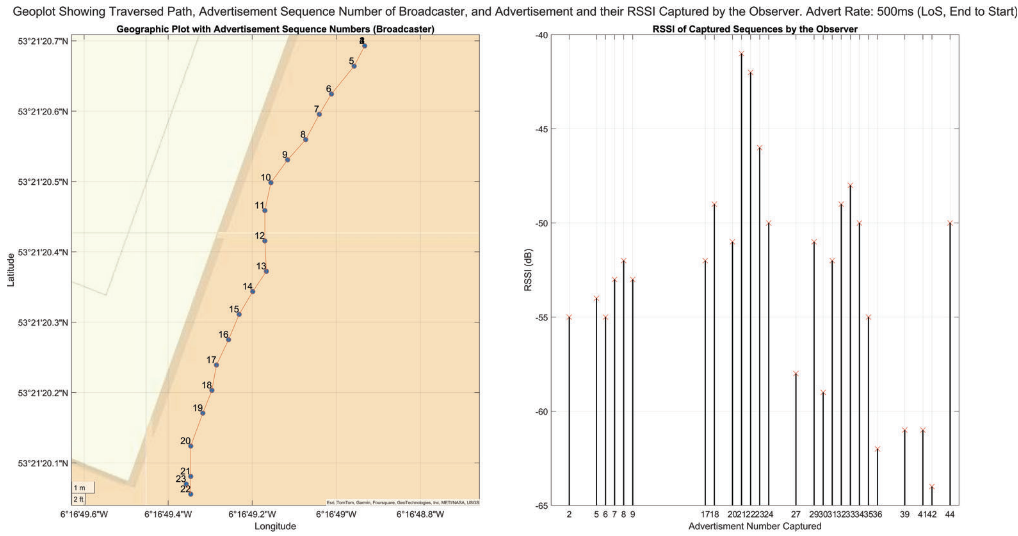


FIGURE 2.44: Geoplot and Captured Advertisement for 500 *ms* Advertisement Interval on a Walk from *End* to *Start* in LoS case

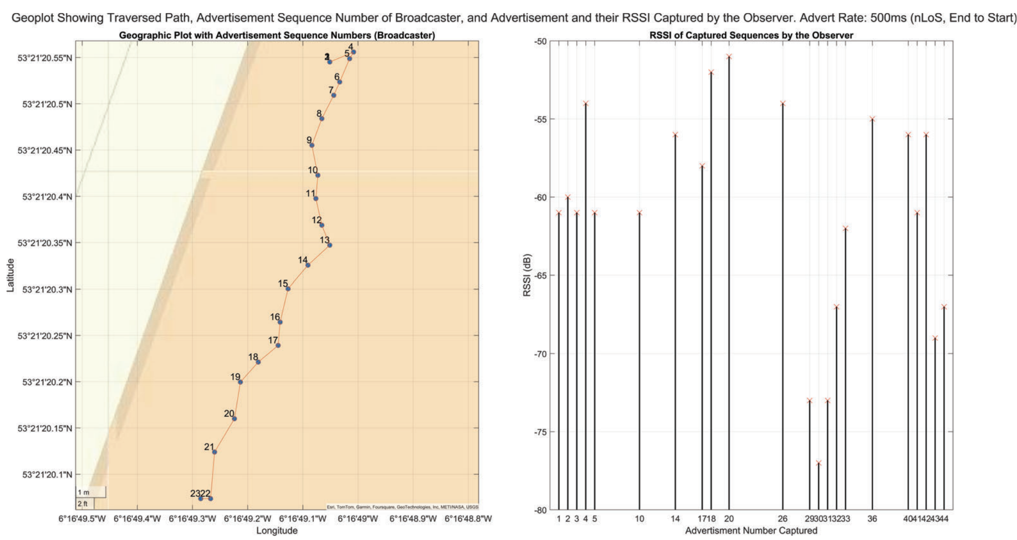


FIGURE 2.45: Geoplot and Captured Advertisement for 500 *ms* Advertisement Interval on a Walk from *End* to *Start* in nLoS case

Finally, from Figures 2.46, 2.47, 2.48, and 2.49, representing the geoplots for LoS *start* to *end* case, nLoS *start* to *end* case, LoS *end* to *start* case, and nLoS *end* to *start* case respectively for the advertisement interval of 1000 *ms*, it can be seen that the intercepted advertisements were evenly spread out throughout the duration of the walk, as was also the case for 500 *ms* advertisement interval. Note, that while the patches appear to have large empty spaces in the figure, they are evenly spread and only appear larger because of the scale of the x-axis. While the space of the x-axis could be kept uniform for all the observations, it is intentionally auto-adjusted to ensure that the axis is no too tightly packed and is readable.

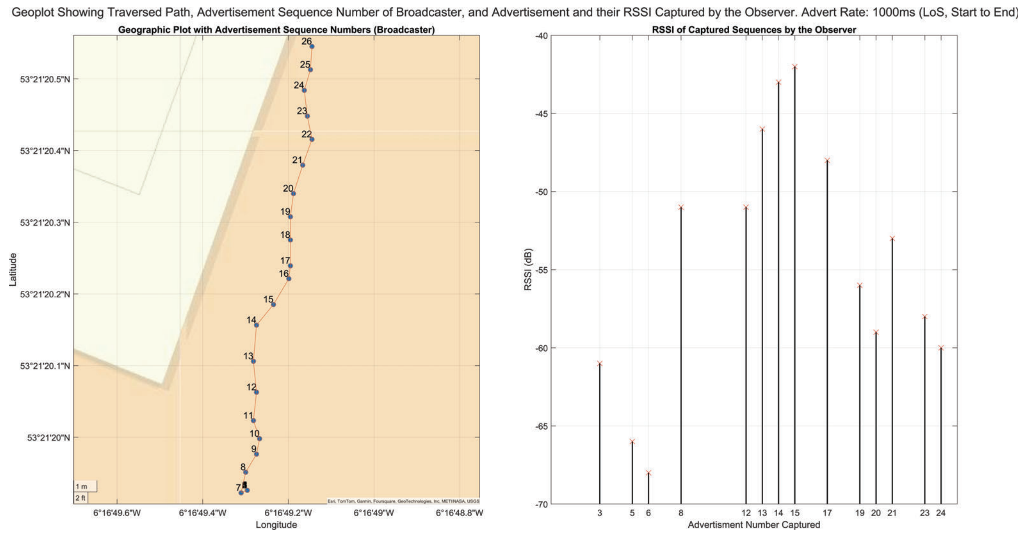


FIGURE 2.46: Geoplot and Captured Advertisement for 1000 *ms* Advertisement Interval on a Walk from *Start* to *End* in LoS case

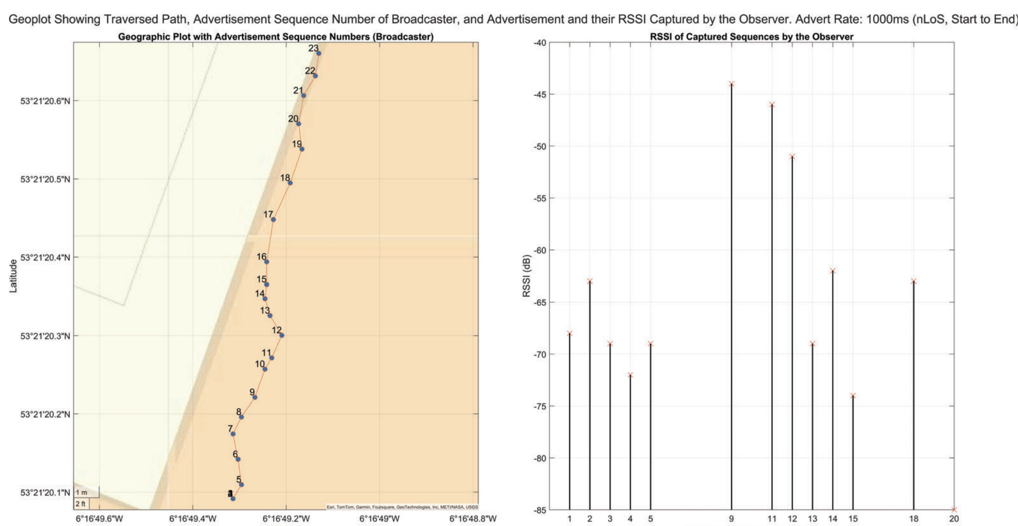


FIGURE 2.47: Geoplot and Captured Advertisement for 1000 *ms* Advertisement Interval on a Walk from *Start* to *End* in nLoS case

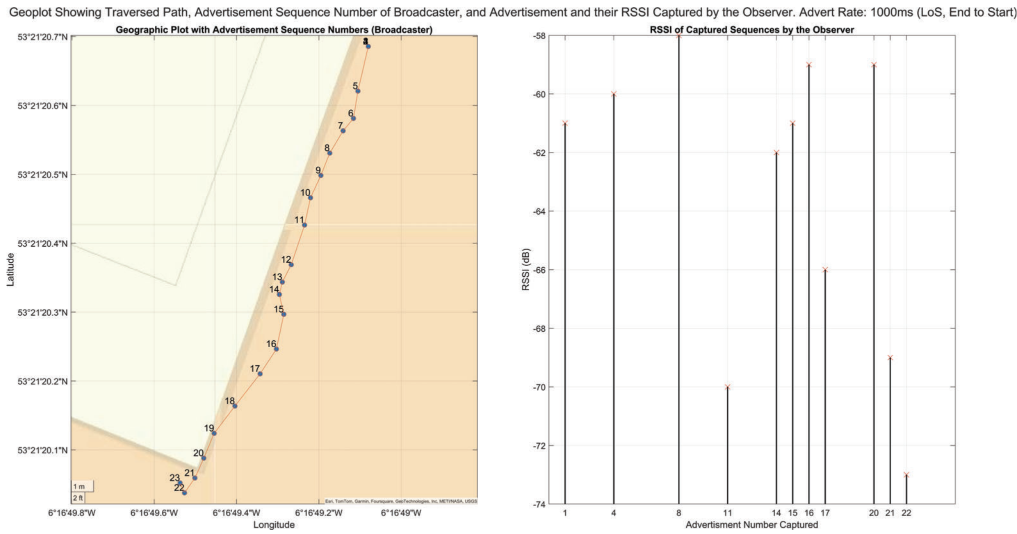


FIGURE 2.48: Geoplot and Captured Advertisement for 1000 *ms* Advertisement Interval on a Walk from *End* to *Start* in LoS case

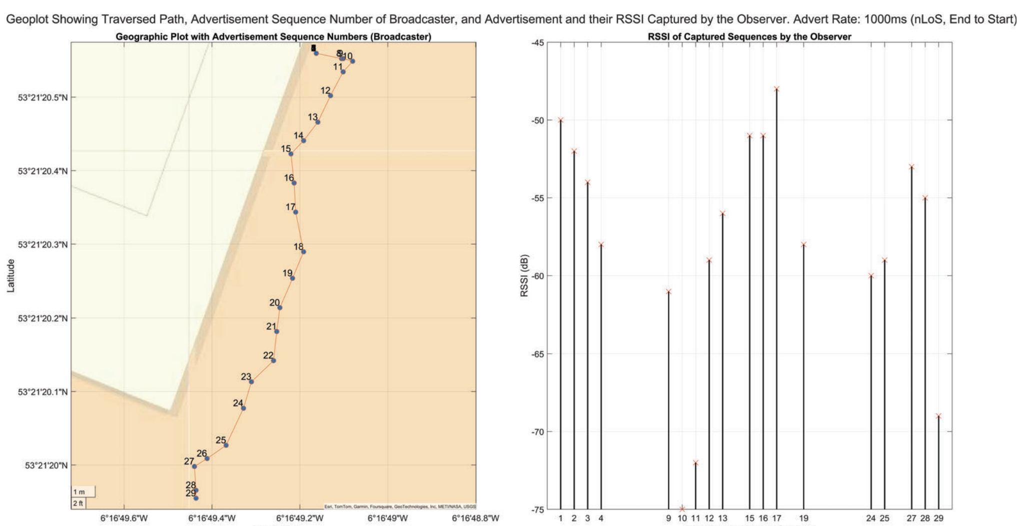


FIGURE 2.49: Geoplot and Captured Advertisement for 1000 *ms* Advertisement Interval on a Walk from *End* to *Start* in nLoS case

The issue with the uneven scaling of the x-axis on the geoplots, as mentioned earlier, was however tackled by directly analysing the number of advertisements initiated by the Broadcaster at each location marker along the path measured by the *GPS Logger* and the number of those advertisements captured by the Observer. For instance, say at the third GPS marker, the Broadcaster emitted 10 advertisements at a 100 *ms* advertisement interval, how many of those 10 advertisements emitted by the Broadcaster are captured by the Observer? Figures 2.50, 2.51, 2.52, and 2.53 compare the number of advertisements emitted against the number of advertisements captured at each point during a walk in the LoS case *start* to *end*, nLoS case *start* to *end*, LoS case *end* to *start*, and nLoS case *end* to *start* respectively, for the 100 *ms* advertisement interval. As seen in the figures, despite broadcasting ten advertisements every second, the Observer failed to retrieve them in three of the four presented cases. This may be due to the repeated interception of advertisement messages creating a bottleneck for the RPi Observer such that the overload resulted in momentary freezes in the system.

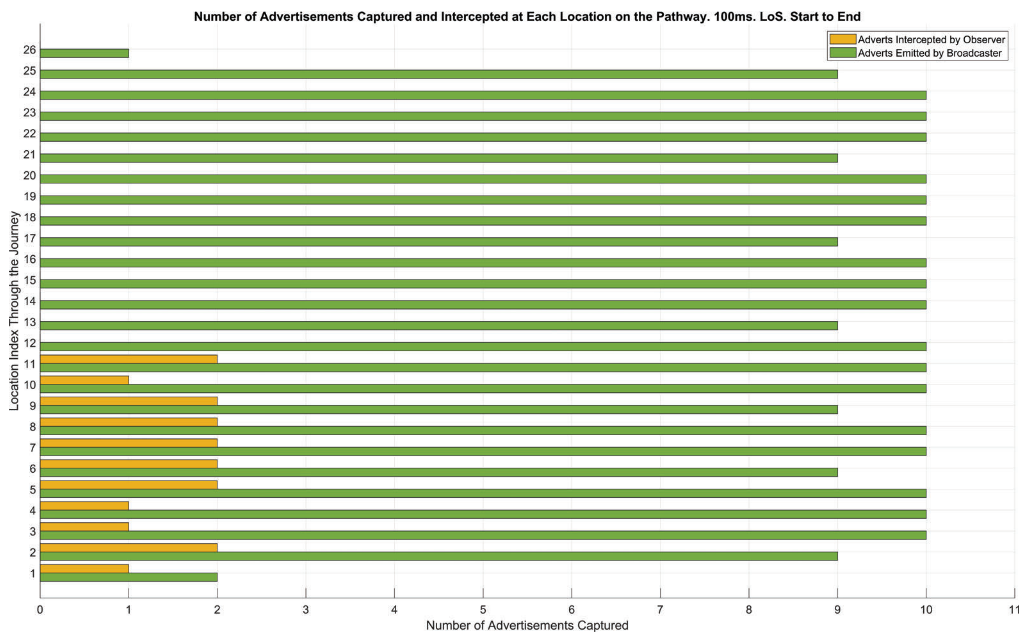


FIGURE 2.50: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 100 *ms* Advertisement Interval on a Walk from *Start* to *End* in LoS case

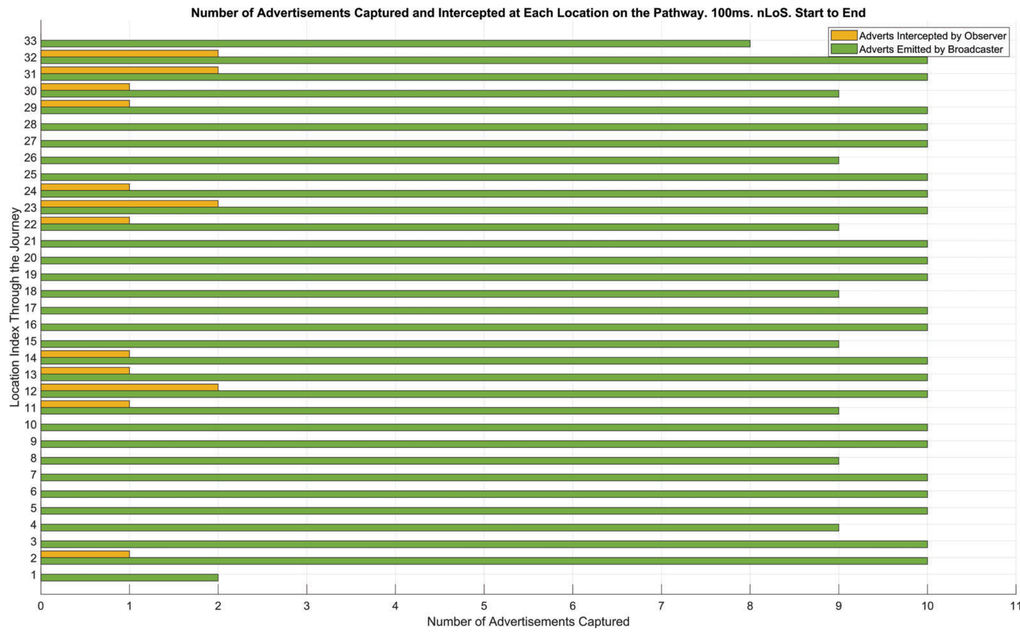


FIGURE 2.51: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 100 *ms* Advertisement Interval on a Walk from *Start* to *End* in nLoS case

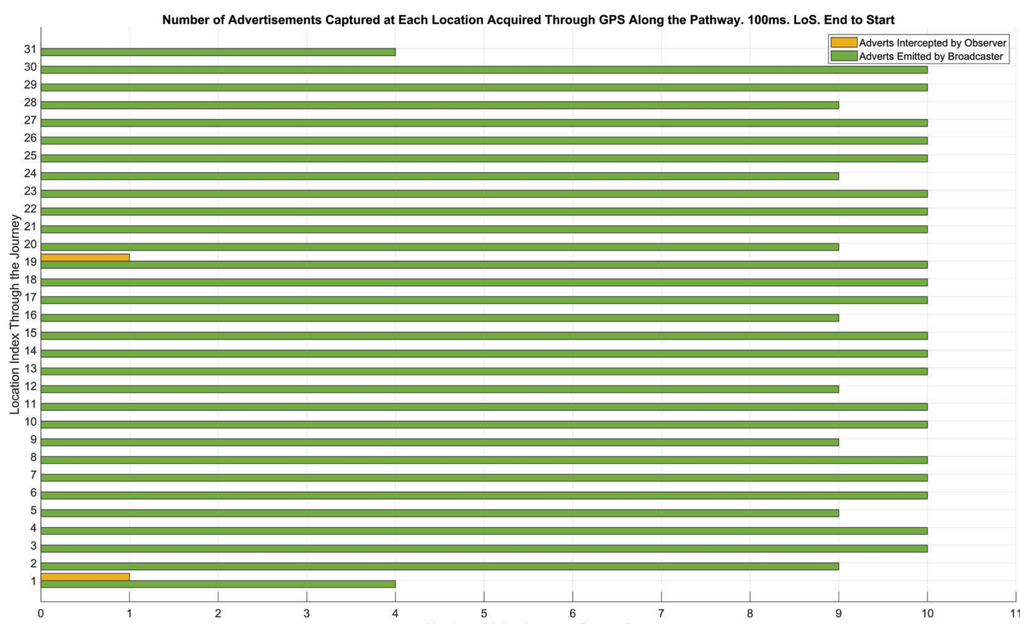


FIGURE 2.52: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 100 *ms* Advertisement Interval on a Walk from *End* to *Start* in LoS case

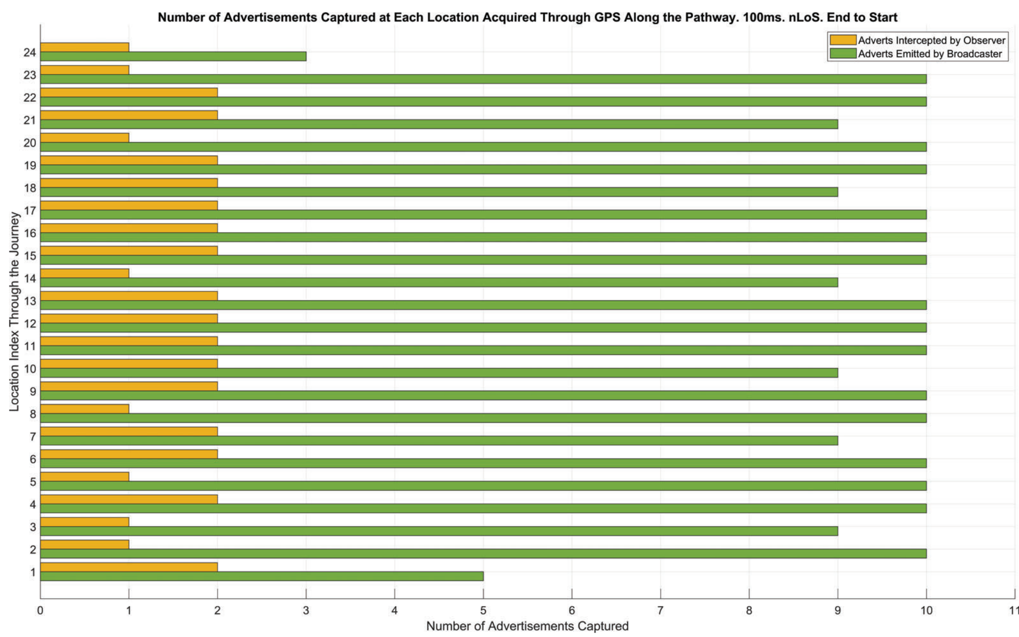


FIGURE 2.53: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 100 *ms* Advertisement Interval on a Walk from *End* to *Start* in nLoS case

Likewise, Figures 2.54, 2.55, 2.56, and 2.57 compare the number of advertisements emitted against the number of advertisements captured at each point during a walk in LoS case *start* to *end*, nLoS case *start* to *end*, LoS case *end* to *start*, and nLoS case *end* to *start* respectively, for the 500 *ms* advertisement interval. It is apparent from the figure that the advertisements in this case were more evenly captured. In many locations, at least one of the two broadcasts was acquired by the Observer. The results suggest the superiority of the 500 *ms* advertisement interval over the 100 *ms* advertisement interval, and perhaps, this is the reason that 500 *ms* is generally the minimum advertising interval on available beacons.

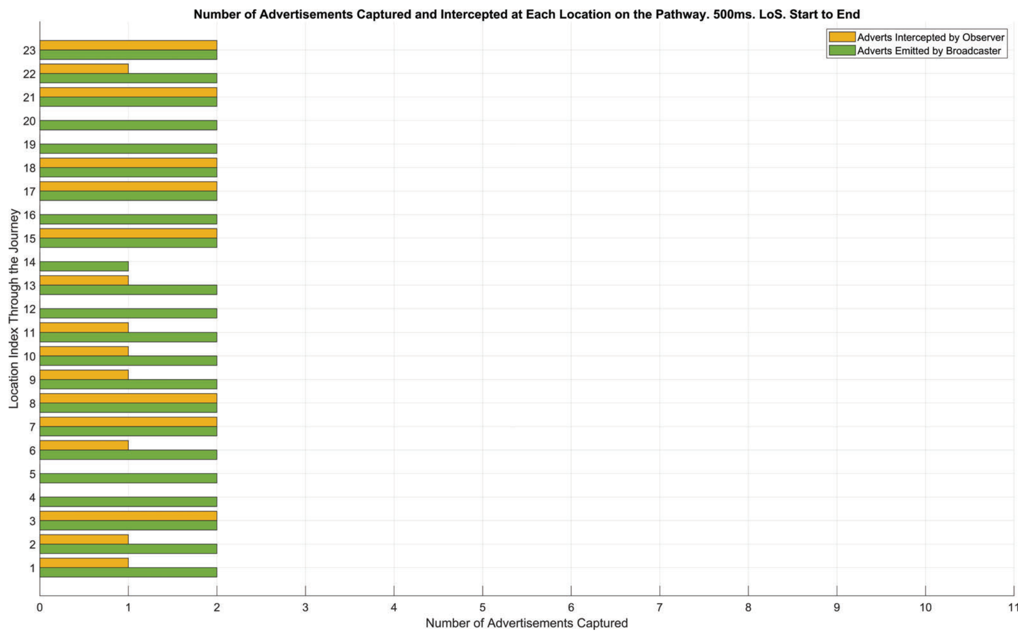


FIGURE 2.54: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 500 *ms* Advertisement Interval on a Walk from *Start* to *End* in LoS case

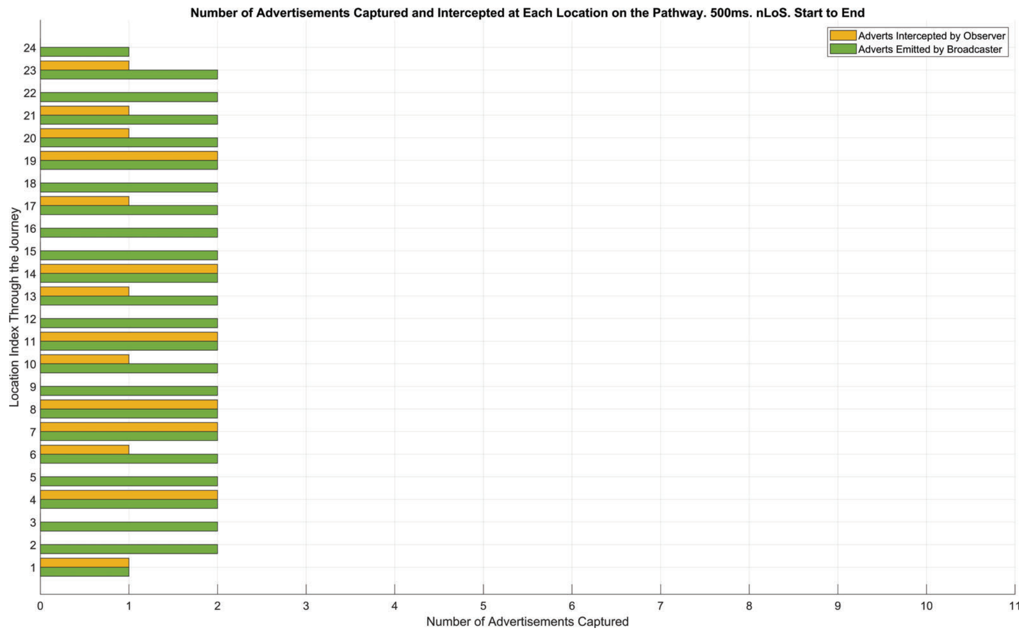


FIGURE 2.55: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 500 *ms* Advertisement Interval on a Walk from *Start* to *End* in nLoS case

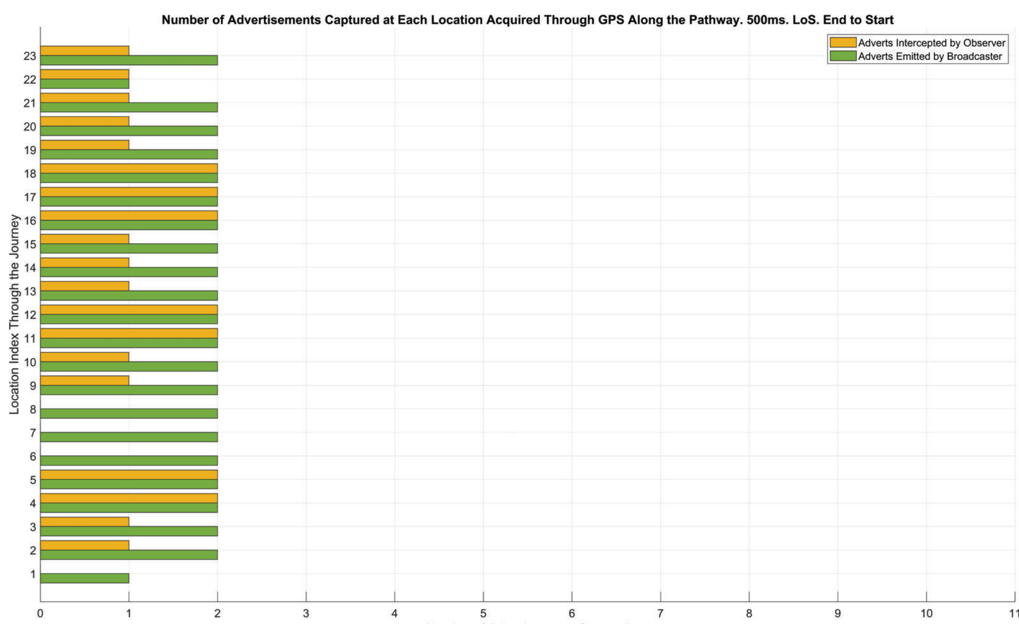


FIGURE 2.56: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 500 *ms* Advertisement Interval on a Walk from *End* to *Start* in LoS case

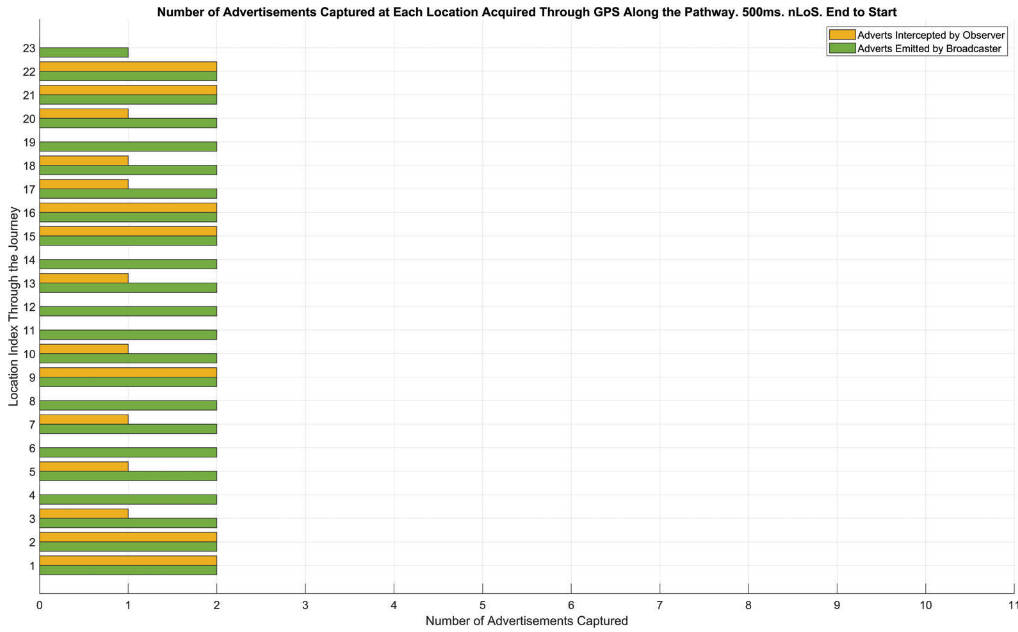


FIGURE 2.57: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 500 *ms* Advertisement Interval on a Walk from *End* to *Start* in nLoS case

And finally, from Figures 2.58, 2.59, 2.60, and 2.61, representing the LoS and nLoS *start* to *end* walk and LoS and nLoS *end* to *start* walks, for the 1000 *ms* advertisement interval, it can be seen that the acquired advertisements were just as evenly spread as in the case of the 500 *ms* advertisement interval. The results suggest the superiority of the 1000 *ms* advertisement interval over the 100 *ms* advertisement interval. The percentage of dropped advertisements, as seen in Table 2.14, for both 500 *ms* and 1000 *ms*, are comparable, as is the acquisition of the broadcasts by the Observer at both these advertisement intervals. The choice of the 500 *ms* advertisement interval should be more useful than the 1000 *ms* interval because the finer measurement of granularity could provide insights into nuances in the measured walks.

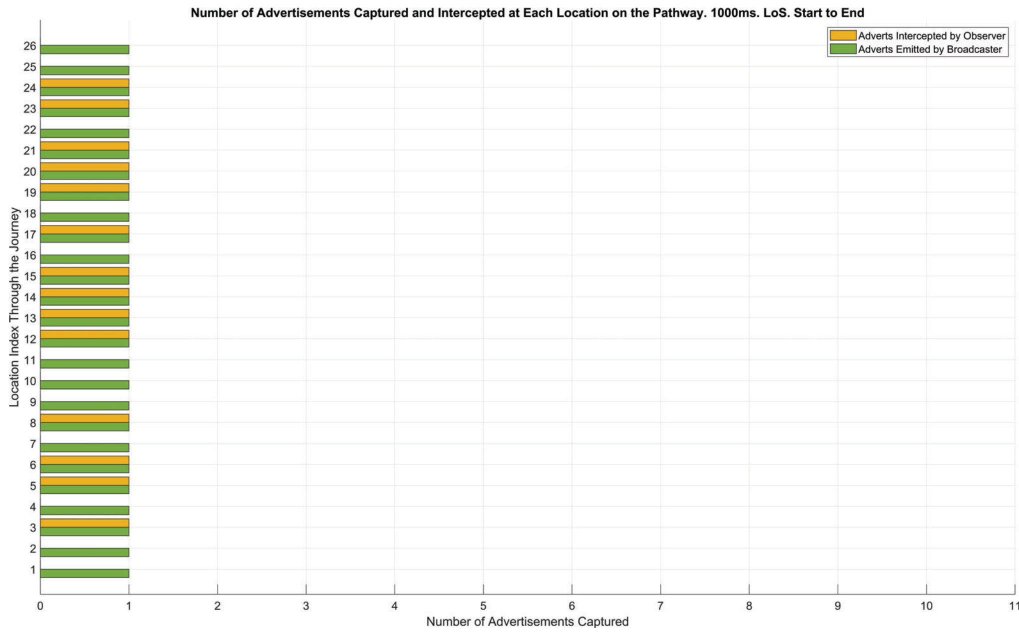


FIGURE 2.58: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 1000 *ms* Advertisement Interval on a Walk from *Start* to *End* in LoS case

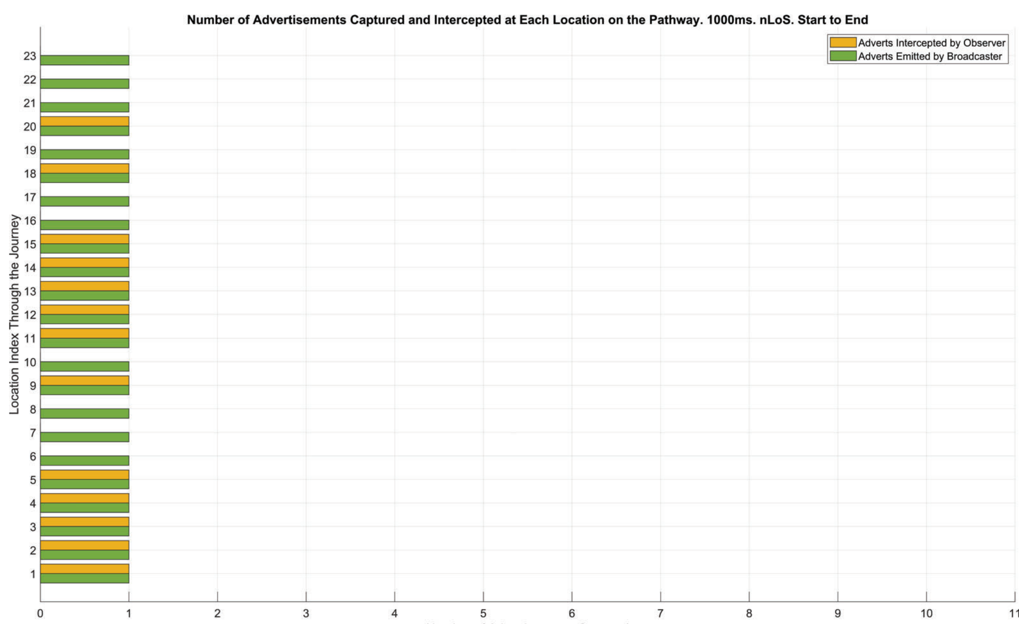


FIGURE 2.59: Advertisements Emitted vs Advertisements Captured at Each GPS Measurement for 1000 *ms* Advertisement Interval on a Walk from *Start* to *End* in nLoS case