

Beam Switchable Vehicular Antenna for Increased Communication Range

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Abstract—In this paper, a beam switchable antenna solution for vehicular use is presented. Main objective is to improve the cellular connectivity of vehicles operating in poor coverage region. An adaptive antenna system operating in the frequency band 824–960 MHz having high gain, and full azimuth plane coverage, and main beam in elevation plane pointing towards 90°, was developed. Beam switchable antenna provides beam-steering in azimuth plane, by switching one antenna element active at a time. The concept of stacked patch antenna with L probe feed was used for a single element. This arrangement gives gain of 7.4–8.2 dBi, and total radiation efficiency of 0.11 dB, over the band, with broadside radiation pattern, and half power beam width of single element up to 80°. The field measurements for the designed antenna system were performed in poor coverage regions using commercial cellular network. Results were compared to corresponding results of conventional vehicular antenna, having omnidirectional radiation pattern and the gain of 3 dBi. The developed antenna system results in 3.5...12.7 dB higher RX level than reference antenna and increase communication range from 71 km to 109 km in open area. Similarly, in suburban area the communication range is increased from 20 km to 30.8 km. Also, the narrower beam acts as spatial filter and results in reduced fading.

1. INTRODUCTION

In a cellular network, mobile device antennas are typically omnidirectional. Because of the uniform azimuthal distribution of the radiation, these antennas have low gain and medium communication range [1]. Vehicles which operates in poor coverage region of the network, e.g., in forests or hilly terrain, are equipped with omnidirectional antennas and are sometimes range limited due to the high path loss. In order to extend the communication range, directive antenna elements can be used, e.g., as a part of an adaptive antenna system for vehicles. The directional antennas in comparison with omnidirectional antennas have higher transmission range, less interference, more spatial reuse and improved network capacity [1]. Directive antennas such as microstrip patch antennas are an attractive solution for many wireless applications because of its low profile, low cost and easy fabrication. However, patch antenna has certain limitations including narrow bandwidth [2], low efficiency and high Q value. A number of approaches has been made for enhancing the bandwidth of patch antennas which includes, the use of a thick substrate [3], and the use of parasitic patches stacked together [4, 5].

For beam switchable antenna, several antenna designs have been proposed. In [6], a reconfigurable Yagi-Uda with four-beam pattern is presented. However this antenna system have a narrow bandwidth of 10.14% and low gain of 5.01 dBi. This antenna arrangement suffers from low front to back lobe ratio which indicates strong coupling between antenna elements. In [7], double square loop antenna (DSL) and in [8], square loop steerable antenna system are reported, which claims to provide coverage to entire azimuth plane by beamsteering. However the main beam is pointing towards 30° for DSL and 35° for square loop antenna in elevation plane, due to which these antenna arrangement cannot be utilized for

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long range terrestrial communication. Long range connectivity in terrestrial communication requires the main beam pointing to an angle close to 90° in elevation plane. Similarly in [9], an electronically steerable Yagi-Uda microstrip patch antenna is reported. Because of the elevation angle of the main beam, this arrangement is best suited for satellite communication rather than long range terrestrial communication.

In this paper, the concept of a directive stacked patch antenna with an L probe feeding arrangement has been designed and modelled using CST Microwave studio. It is demonstrated here that using such antenna arrangement can result in high gain of 8.2 dBi and bandwidth upto 19.7%. This antenna arrangement provides 360° azimuthal coverage at 90° elevation angle. This paper includes the design of the developed antenna element and the beam-switchable antenna system, followed by the field measurements. The effect of the developed antenna arrangement on communication range is then evaluated by using a simple path loss model. Observation of the effect of directive radiation pattern on spatial filtering and thus reduced fading is briefly discussed.

2. ANTENNA STRUCTURE

The stacked patch antenna structure consists of three metal plates made of copper. One of them is ground plane, and remaining two are the main and parasitic patches, as shown in Fig. 1. The ground plane dimensions (W_1) are $165 \text{ mm} \times 165 \text{ mm}$, and thickness is 2 mm. The main patch of size (W_2) $131 \text{ mm} \times 131 \text{ mm}$ is stacked on top of the ground plane at the height (h_1) 14 mm, and is supported by cylinders made of Nylon. The parasitic patch of size (W_3) $123 \text{ mm} \times 123 \text{ mm}$ is stacked on top of the main patch at height (h_2) 19 mm. The thickness of both patches is 0.5 mm. Dimensions are optimized for maximum gain over the band 824–960 MHz.

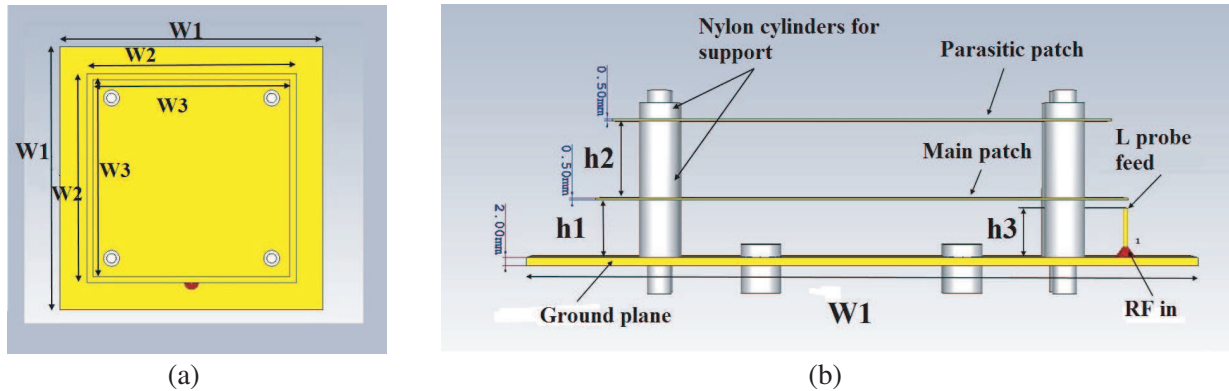


Figure 1. (a) Front and (b) side views of the stacked patch antenna.

Main patch is excited through coupling of signal from the L probe feed. Both the main and parasitic patches will result in dual resonance behavior [10]. With increase in the ratio of lengths of the two radiating patches, dual resonance occurs instead of broadband behavior [5], so in our case the dimensions are selected so that both resonances occur close to each other which results in wide bandwidth.

2.1. Simulated and Measured Results for Single Element Antenna

The simulated impedance matching of the antenna is shown in Fig. 2(a) along with the measured results of the prototype. Simulated and measured S_{11} -parameters are below -10 dB over the band 824–960 MHz. The maximum measured gain over the band is 8.2 dB with a decrease of 0.85 dB for lower frequencies of the band, as shown in Fig. 2(b). The simulated azimuth plane radiation pattern of vertically oriented antenna, for different frequencies is shown in Fig. 2(c) with the maximum gain of 8.36 dB. The 3 dB beam width equals approximately 80° with the main beam pointing towards 90° in elevation plane.

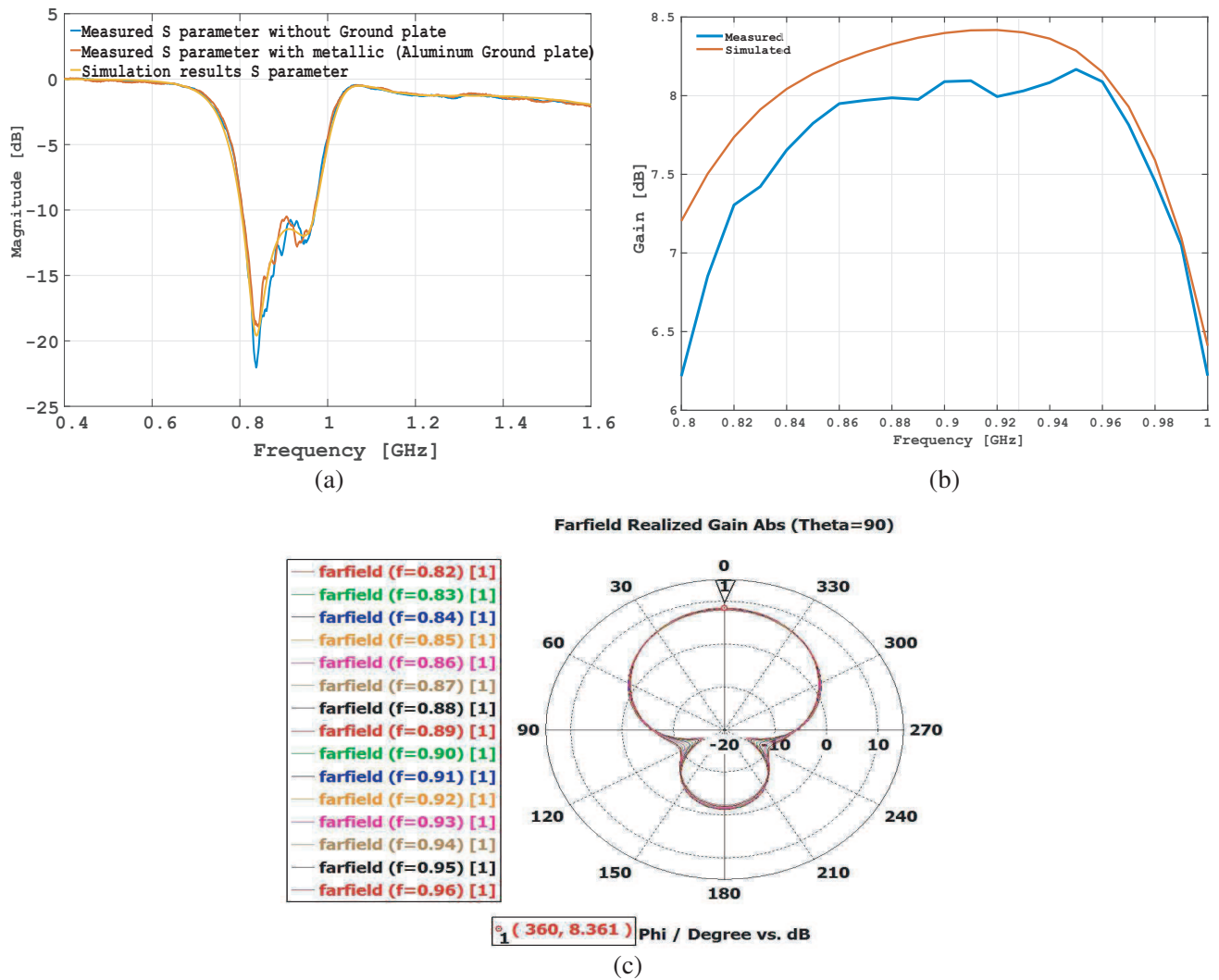


Figure 2. (a) Simulated and measured S_{11} -parameter. (b) Simulated and measured gain over frequency and (c) Azimuth plane pattern.

3. SWITCHED BEAM ANTENNA

By using four identical antenna elements pointing in different directions as shown in Fig. 3(a) the antenna system can cover whole azimuthal plane with reasonable high gain. This concept has been earlier used in [11]. In the simulations, the antenna structure is placed on metallic plate (Aluminum) which serves as a rooftop of vehicle, having dimension $L \times W = 1700 \text{ mm} \times 1100 \text{ mm}$. The height of antenna element above the rooftop is optimized to get maximum broadside gain and better azimuth plane pattern. Because of the rooftop reflection the optimized height is 100 mm. Decreasing the height results in an increase in side lobe and back lobe levels. The spacing between the antenna elements on opposite sides to each other is also optimized and set to 230 mm. Decreasing spacing, increases the coupling between antenna elements. The S -parameters for this antenna structure and the azimuth plane pattern are shown in Fig. 3(b) and Fig. 3(c), respectively. The effect of rooftop is small, and the input matching is below -10 dB level. The isolation between antenna elements is below -27 dB over the band. The azimuth plane pattern shows the radiation patterns of all four antenna elements.

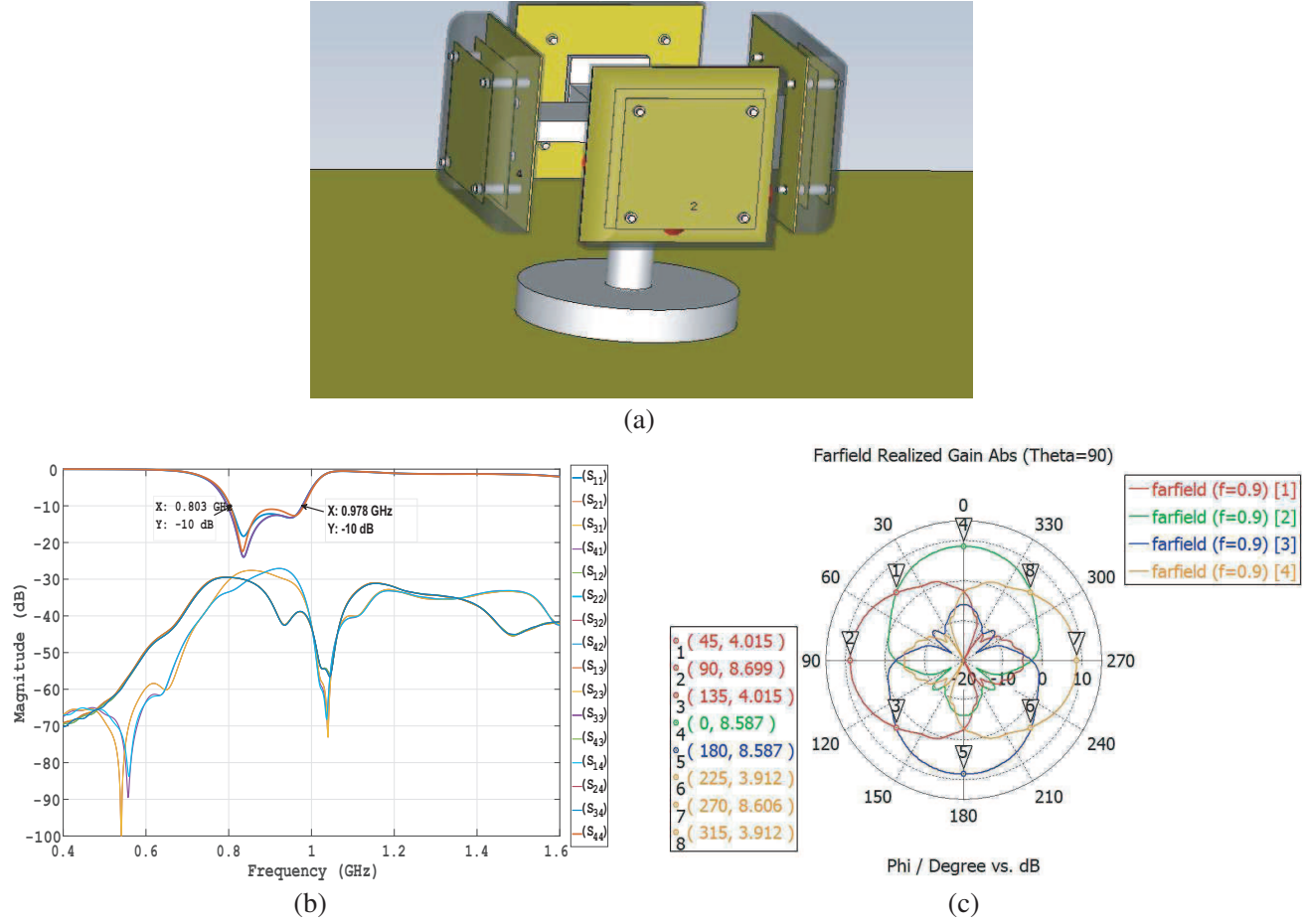


Figure 3. (a) Beam switchable antenna structure. (b) Simulated S_{11} -parameter for beam switchable antenna on the vehicle rooftop of size 1700 mm \times 1100 mm. (c) Azimuth plane patterns for four-element antenna.

4. FIELD MEASUREMENT RESULTS

4.1. Measurement Setup

Measurements for the designed antenna system were performed in actual environment using connection to commercial 2G base stations, and omnidirectional vehicular antennas were used as references. Different suburban and deep forest locations were selected for measurements. Measurements were performed in areas of weak signal strength and sparsely located base stations, in order to get clear picture of antenna performance. During the measurements, antennas were placed on rooftop of vehicle on a ground metal sheet of size 1700 mm \times 1100 mm and the measurements were static. Measurements were performed using 2G cellular network with frequencies 824–960 MHz and the device for recording the RX level was a commercial mobile phone with Nemo Handy Software by Keysight Technologies [12]. Mobile phone was equipped with an external coaxial connection instead of its internal antenna. The RX levels for different antennas were recorded and compared. Two different reference antennas, shown in Fig. 4. (namely Huber and Suhner Sencity Road antenna having gain of 3 dBi, and TW-LTE/4G antenna having gain of 5 dBi [13]) were used along with the beam switchable antenna. A SP4T switch [14] is used with the designed beam switchable antenna, for switching an individual antenna element, active at a time. Switching was done manually, during the field measurements. This switch has low insertion loss of 0.4 dB and high isolation between output ports up to 40 dB over the band. The cable losses for reference antennas, Huber and Suhner Sencity Road Antenna and TW-LTE/4G antenna are 3.7 dB

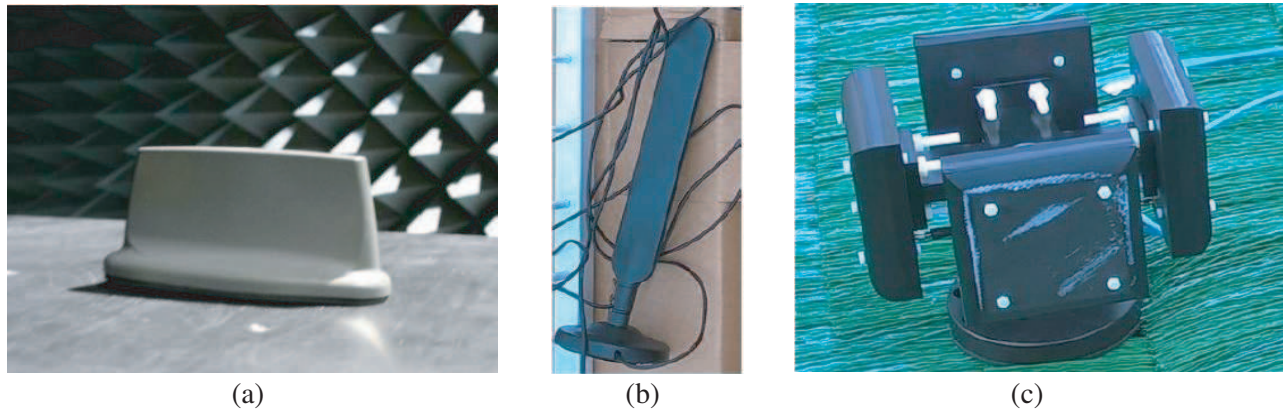


Figure 4. (a) Huber and Suhner Sencity Road antenna, (b) TW-LTE/4G antenna, (c) and beam switchable antenna.

and 2.6 dB, respectively. The combined cable and switch losses for the designed antenna are 1.7 dB. All these losses are removed during data analysis to ensure accurate comparison between the antenna performances.

4.2. Observation and Results

The recorded RX level for antennas varied much at the time of measurements. This is because of multipath fading effect, which is especially happening due to movement of trees and their leaves. Variation was in the range of 10–15 dB. The results for RX levels were recorded in particular traffic channels of a base station for all antennas under observation. This ensures a fair comparison of RX levels for different antennas. In first measurement location, reference antenna was Huber and Suhner Sencity Road antenna while for third measurement, the reference antenna was Tw-LTE/4G.

4.3. First Measurement in Talvivaara, Kajaani

Figure 5 shows the recorded RX level for the reference and the beam switchable antenna. Horizontal axis shows the time, and vertical axis shows RX level in dBm scale. For this and for all other measurements, first the reference antenna is measured following the 4 different states of the four-element antenna. Along with the measurement, a mean value over time is shown as horizontal line. Time gaps between measurements are due to antenna switching and measurement software restarts.

In Fig. 5, the mean value of recorded RX level for the reference antenna is -82.05 dBm while for element 1 of four-element antenna system, the mean value of RX level is -65.72 dBm. For element 4 the mean RX level is -65.52 dBm. This shows that RX level is greater at beam switchable antenna than reference antenna. The variation in signal strength is quite low for four-element antenna in comparison to that of reference antenna, which indicate less fading of the signal. Because of more directive beam in some specific direction and nulls or smaller side lobes in other directions, this results in reduced multipath propagation. The amount of fading of signal is smaller when the signal is strictly in the main beam of the antenna. From the figure the fading for reference antenna is 3.6 dB while for element 1 of the beam switchable antenna fading is 0.63 dB and for element 4 it is 1.22 dB.

4.4. Second Measurement in Venejärvi, Kajaani

Same measurement with the same setup was performed at Venejärvi. The findings of this measurement are shown in Fig. 6. For reference antenna, the mean recorded RX level is -97.95 dBm, while for element 1 of the beam switchable antenna the mean RX level is -91.96 dBm. For rest of the antenna elements the recorded RX level is low. This indicates that signal is in the main beam of element 1. Fading for reference antenna is 1.95 dB, and for element 1 of the beam switchable antenna it is 1.5 dB.

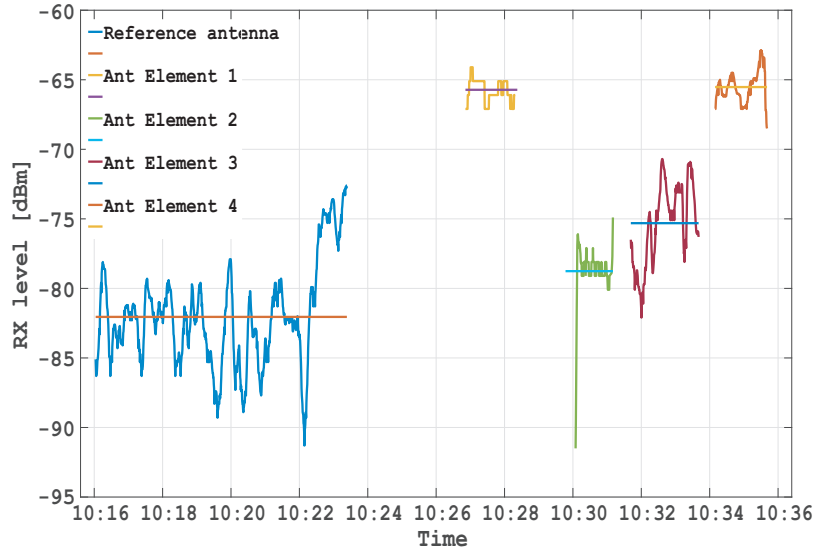


Figure 5. Measured RX level in Talvivaara Kajaani.

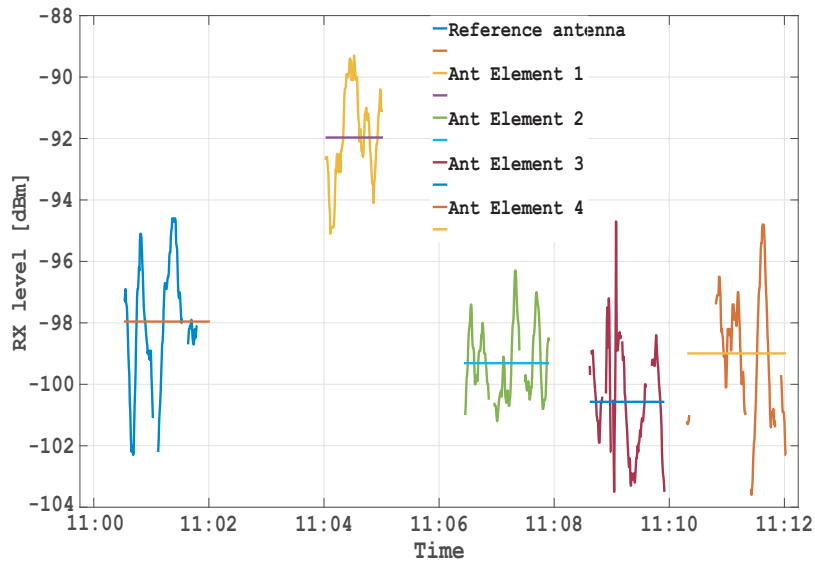


Figure 6. Measured RX level in Venejärvi, Kajaani.

4.5. Third Measurement in Virpiniemi

At this location, measurements were performed, at top of ski jump tower (roughly 60 meters above ground level), below median ground level (a few meters), and at the median ground level. These measurements were performed without a conducting ground plane.

Figure 7 shows the recorded RX levels at top of the ski jump tower. It is observed that recorded RX level for reference antenna is -54.88 dBm while for element 1 of the beam switchable antenna system, recorded RX level is -46.81 dBm which is 9 dB higher than that of reference antenna. In this measurement, the fading for reference antenna is 0.48 dB and for element 1 of the beam switchable antenna it is 0.49 dB which is low, indicating line-of-sight (LOS) propagation channel. However, small variation in signal strength exists because of metallic structure of the tower and movement of people which cause multipath propagation in close proximity of the receiving antenna.

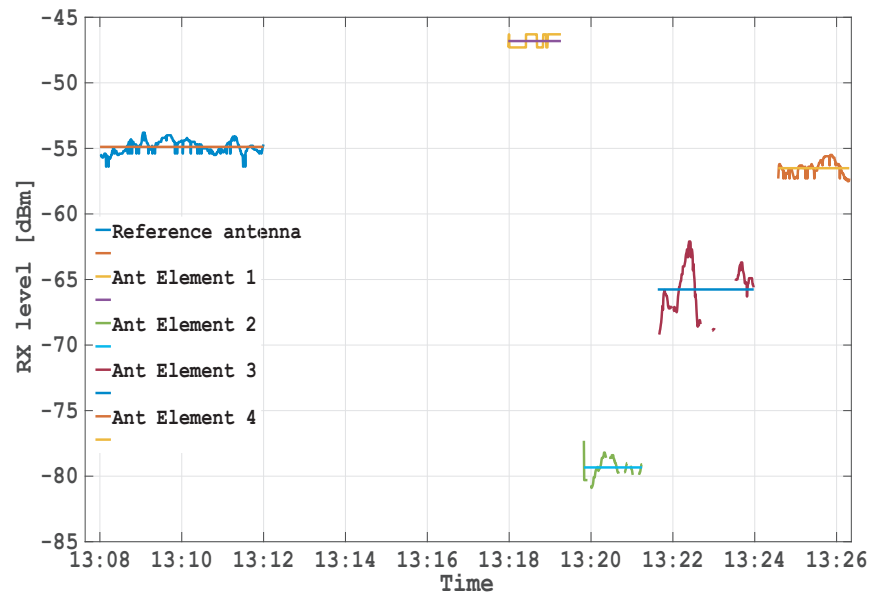


Figure 7. RX level measurement at top of ski jump tower (60 meters above ground level).

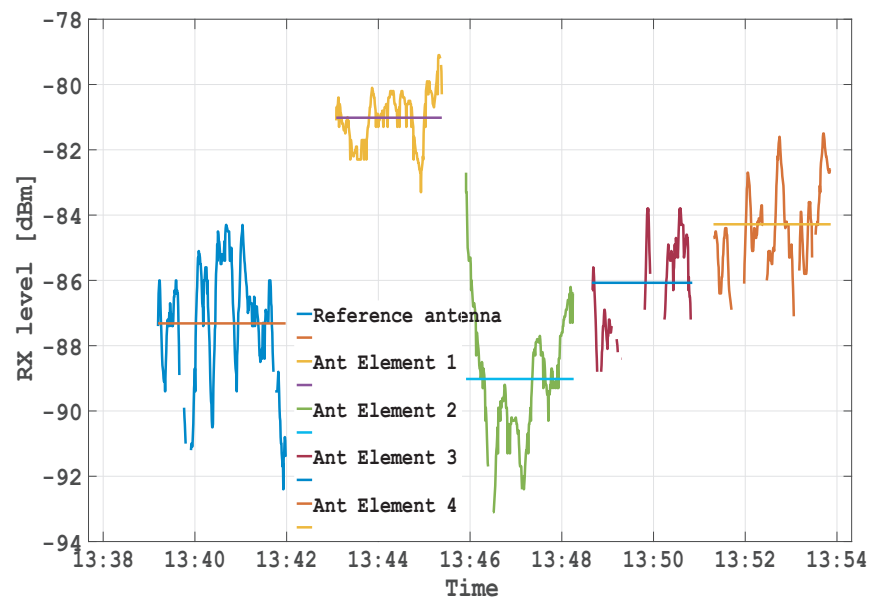


Figure 8. RX level measurement below ground level (a few meters).

Another measurement was performed at a few meters below median ground level in non-line of sight (NLOS) condition, with the results shown in Fig. 8. All recorded signal are multipath propagated, reflected or diffracted components. Fading for element 1 of the beam switchable antenna is 0.79 dB, and for reference antenna, fading is 1.81 dB. The recorded RX level for reference antenna is -87.32 dBm while for element 1 of the beam switchable antenna system the recorded RX level is -81.02 dBm which is 6.3 dB higher than mean of reference antenna.

The last measurement in Virpiniemi was performed at median ground level. Fig. 9 shows the recorded RX level, which is -78.41 dBm for the reference antenna, while for element 1 of the beam switchable antenna, it is -68.9 dBm. Now there is 9.5 dB advantage over the reference antenna. The

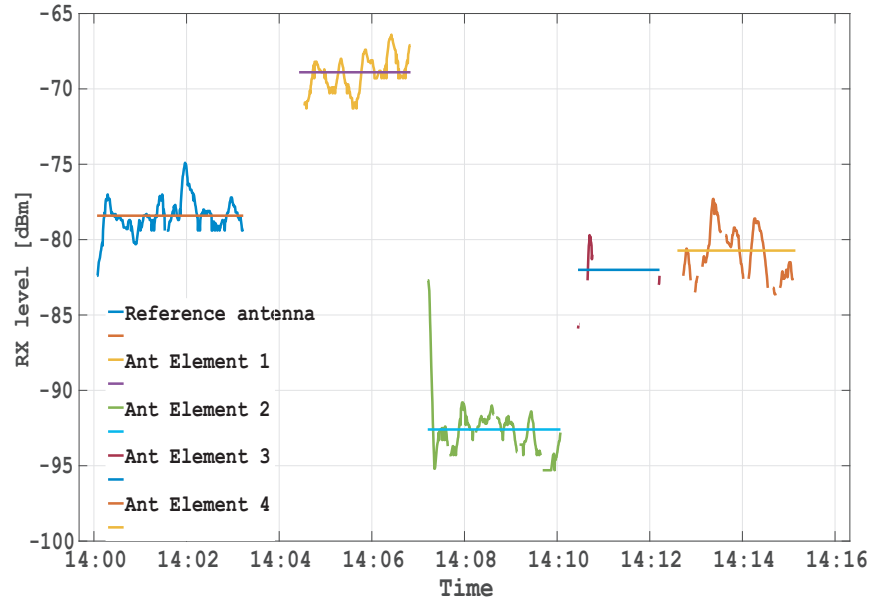


Figure 9. RX level measurement at ground level.

fading for reference antenna and element 1 of the beam switchable antenna is the same which is 1.10 dB.

Mean RX levels from all locations are combined in Fig. 10. The black line shows the reference antenna performance at all the measurement locations whereas the green points show the maximum received RX level by any antenna element of the beam switchable antenna system. This figure presents the obtainable benefit of beam switchable antenna system, in terms of received signal strength in comparison with reference antennas. At some points, the four-element antenna system and reference antenna have same RX level, but most of the time the beam switchable antenna results in increased RX level.

Mean values of the recorded RX levels from different measurements are listed in Table 1. The RX level resulting from the beam switchable antenna system is 3.5...12.7 dB higher than that of the reference antennas. On average 6.3 dB higher signal strength was recorded during the described field measurements. This indicates the gain difference between the reference and the beam switchable antenna and reduction in fading in the case of beam switchable antenna system.

Table 1. Mean RX level [dBm] for reference and beam switchable antenna in measurement locations.

Location	Ref RX [dBm]	Beam switchable antenna RX [dBm]*	Δ RX level
Talvivaara	-88.8	-76.1	12.7
Venejärvi	-89.81	-86.08	3.5
Virpiniemi Top	-60.1	-51.2	4.8
Virpiniemi Below Gnd level	-85.9	-79.6	6.4
Virpiniemi Gnd level	-74.1	-65.2	8.9

*Maximum value of four elements

5. RANGE ESTIMATION

The benefit in terms of extended range by using beam switchable antenna system in comparison with reference antenna is analyzed using a simple path loss model. Two different propagation environments

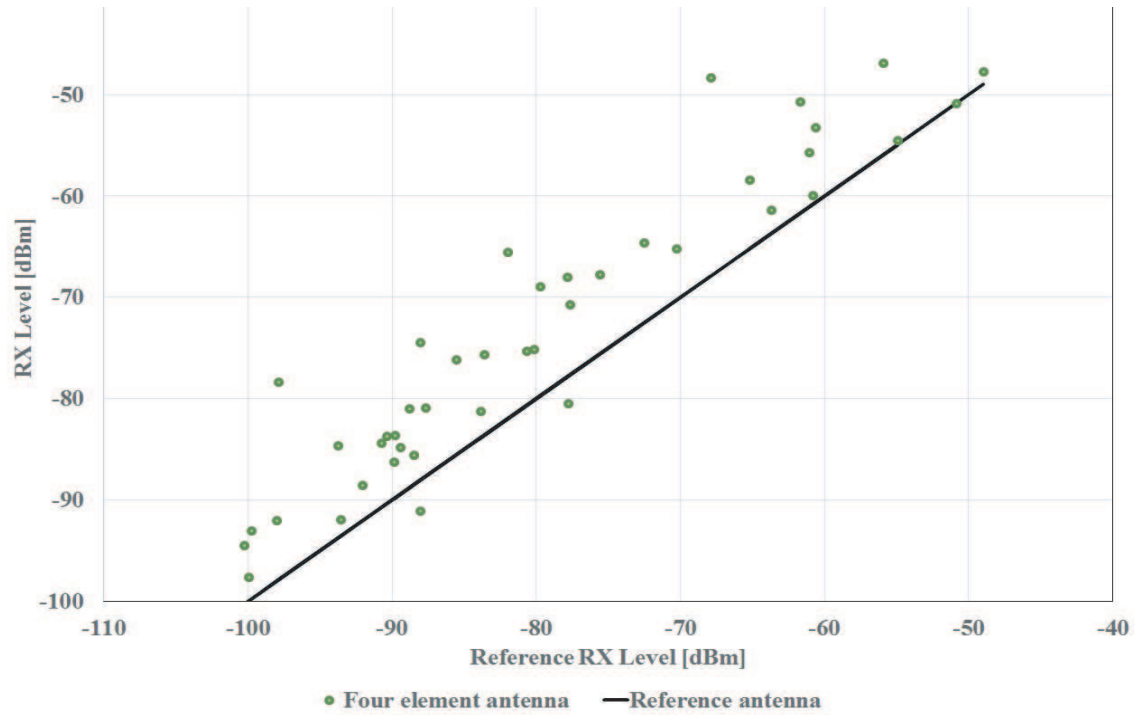


Figure 10. The beam switchable antenna and reference antenna performance as a function of the maximum measured RX levels in different measurement locations.

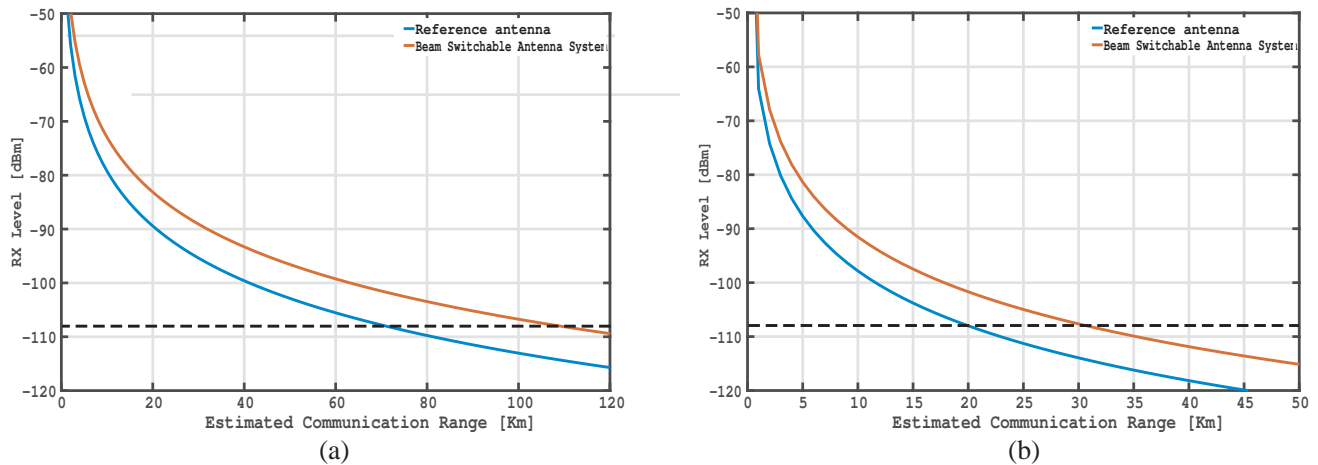


Figure 11. Communication range estimation using (a) Okumura-Hata model for open area, and (b) Okumura-Hata model for Suburban area.

are considered which are open area and suburban area. Okumura-Hata models [15] are used for both propagation environments, for prediction of the achievable communication range. This is because path loss models specifically for forest area does not exist in cellular network. Reference antenna and beam switchable antenna gains are 3 dBi and 8 dBi, respectively. The gain difference between the reference antenna and four-element antenna system is 5 dB, while field measurements indicated 6.3 dB gain difference. This 1.3 dB more gain is due to spatial filtering of the beam switchable element system. Results for range estimation are shown in Fig. 11. Fig. 11(a) shows the range estimation for open area environment. The horizontal black line represents the receiver sensitivity level in GSM 900 MHz

Table 2. List the parameters used for propagation model in open area and suburban area.

Parameter	Open And Suburban Area
Frequency [MHz]	900
G Tx [dB]	15
G Rx [dB]	Ref 3 dBi, Beam switchable 8 dBi
RX Sensitivity level [dBm]	−108
P Tx [dBm]	30
h Rx [m]	2
h Tx [m]	50

which is −108 dBm. Range estimation for reference antenna is represented by blue curve while orange curve is for the beam switchable antenna system. The gain increase of 6.3 dB results in an increase in communication range from 71 km to 109 km in open area. A corresponding communication range calculation for suburban area is presented in Fig. 11(b), which shows an increase from 20 km to 30.8 km in communication range. Path loss calculation parameters are listed in Table 2.

6. CONCLUSION

In this paper, a beam switchable antenna system for vehicles operating in poor coverage regions of the network, e.g., forest machines, is proposed, in order to enable higher connectivity. The design of beam switchable antenna system is presented along with its field measurements at different poor coverage locations, to find the benefits in comparison with conventional omnidirectional vehicular antennas. The designed antenna achieves 6.3 dB higher RX power level than that of reference antenna.

It has been shown that by using the beam switchable antenna system the fading of received signal is reduced due to spatial filtering. Also, by using the developed solution the range extension is achieved and presented in this paper. It is shown that the designed antenna solution can achieve 38.0 km range extension in open area and 10.8 km in suburban area. The range extension is predicted using Okumura-Hata model for open area and suburban area propagation environments.

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