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Design of an Electrically Small, Planar Quasi-Isotropic Antenna for Enhancement of Wireless Link Reliability under NLOS Channels

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Received: 29 July 2020; Accepted: 3 September 2020; Published: 7 September 2020

Abstract: The performance of wireless networks can be greatly influenced by the radiation pattern and polarization of the antennas at the nodes, especially when they are under non-line-of-sight (NLOS) channel environments. In this study, we designed a planar quasi-isotropic antenna based on the combination of a meandered electric dipole and an electrically small loop at a frequency of 2.45 GHz. Its electrical size (*ka*) is 0.47 and shows a gain deviation of 3.01 dB with radiation efficiency of 82.6% per the simulation. The performance of a wireless link under the line-of-sight and NLOS channels in an indoor environment was measured using the proposed quasi-isotropic antenna as a receiving antenna after validating its radiation and impedance properties experimentally (the measured gain deviation: 5.2 dB, the measured radiation efficiency: 79.2%). This study demonstrates that better properties are achieved using the quasi-isotropic antenna. The quasi-isotropic antenna shows an improved packet delivery ratio (PDR) and received signal strength indicator (RSSI) compared to the results using omni-directional antennas as a transmitting and receiving pair in the NLOS channels. To the best of our knowledge, the experimental validation of the enhancement of wireless link reliability using a quasi-isotropic antenna has not been reported before, and was first carried out in this study.

Keywords: isotropic radiation pattern; electrically small antennas; radiation pattern synthesis; mission-critical wireless network

1. Introduction

Wireless networks provide a scalable and cost-effective solution for a large number of Internet of Things applications due to the prohibitively high cost and practical difficulty of employing cables in complex control environments [1,2]. They provide considerable benefits such as simple deployment, low installation cost, and high flexibility of operation and monitoring of the control systems. There is a strong push from industrial control systems to apply wireless networks as critical infrastructure for enabling mission-critical control systems such as factory automation and power network protection [1,3]. Mission-critical wireless networks must support the right decision at the right moment, even in the presence of unexpected congestion, network failures, or external manipulations of the environment. Unreliable communication may result in significant performance degradation, and even more severe problems such as critical economic loss, human injury, and/or environmental damage [2,4].

The use of wireless networks for data transmission always introduces non-zero transmission error probability, since it is vulnerable to fading and interference. Several studies have shown the poor reliability in terms of received signal strength indication (RSSI), packet delivery ratio (PDR) degradation, and error burst length in harsh industrial environments [5,6]. One of the major technical challenges faced by industrial control applications is the non-line-of-sight (NLOS) channel in which the transmitting (Tx) and receiving (Rx) nodes cannot see each other directly due to time-varying environments of mobile nodes and obstructions [7,8]. Although several different techniques such as spread spectrum, time diversity, and channel diversity represent significant achievements of traditional networks, availability and reliability requirements of mission-critical control systems exceed what current networks can offer [1,2].

An active array antenna system with a beam-scanning feature could be an effective solution but it also increases complexity and has a larger footprint compared to a simple and compact omnidirectional antenna. Instead, the radiation pattern of the antenna at the node is worth reconsideration and should be tested as an alternative solution. The direction of the incoming signal under NLOS channels cannot be fixed or specified. Thus, a dipole antenna or a directive antenna, which have a null value at a certain point of the radiation pattern, may not be appropriate to use. That is, the antenna orientation and its polarization should have a significant effect on wireless networks [9,10]. Therefore, an antenna with an isotropic radiation pattern, which is ideally a lossless source that can radiate the same intensity of linearly polarized electric field in all directions and receive electromagnetic energy equally from every direction in space, is desirable. This perfect isotropic antenna cannot exist, however, since the transverse electric field in the far-field region cannot have the same magnitude in all directions if the field is linearly polarized everywhere [11,12]. Although a transverse electric field with a single, linearly polarized component cannot be uniform over a sphere in the far-field region, the sum of the electric fields with two polarizations is uniform [13]. The quasiisotropic radiation pattern can be generated by the pattern synthesis of small dipoles such that the null point of one dipole is along the maximum-field direction of the other dipole, consequently minimizing the blind spots of each dipole. Cross-placement, proper wrapping of electric dipoles, or a combination of small electric and magnetic dipoles are common approaches [14–20]. The reported antennae designed under this principle show a measured gain deviation from 2.6 to 12.9 dB over the entire space [16–25]. They are either in a volumetric or planar form. Whereas the volumetric antennas may have an advantage in terms of higher efficiency and more tunability in general, it is the planar ones that can be relatively thinner [26] or even conformal with a generally easier form factor to handle [27,28].

In this study, we designed a highly efficient and electrically small quasi-isotropic planar antenna at 2.45 GHz and examined its feasibility in improving wireless link reliability under NLOS channels. The proposed antenna design is compact and shows a good quasi-isotropic pattern. The simulated results of the impedance and radiation properties were successfully verified experimentally. Wireless link reliability was evaluated using the proposed antenna under line-of-sight (LOS) and NLOS channels. The comparison group used an omni-directional antennas pair, and the possible and simple solution of improving PDR and RSSI is discussed here.

2. Antenna Design

An electrically small planar antenna having a quasi-isotropic radiation pattern was designed as shown in Figure 1a,b. The design parameters are also listed. The antenna is composed of a small meander dipole and arcs extended from each end of the dipole as in [18]. The arc at the top of the substrate rotates in a counterclockwise direction, while the arc at the bottom rotates in a clockwise direction, and they form a small loop together. Each meander arm is also placed at the top and bottom of the substrate, and the whole configuration is fed by a coaxial cable at the center. The signal line of the cable is connected at the arm on the top and the outer conductor is connected at the bottom. The material characteristic of a ferrite bead is characterized and implemented in a full-wave electromagnetic simulation to prevent current flowing over the outer layer of the feeding conductor. This helps to minimize the effect from the feed line such that the radiation pattern is not distorted. Ansys HFSS (High Frequency Structure Simulator) was used for the full-wave electromagnetic simulations.



Figure 1. The proposed antenna design with the design parameters: (a) 3D and (b) top views.

Rogers RT/duroid 5880TM with a thickness (h) of 0.72 mm (ε_r = 3 and tan δ = 0.0009) was used for the substrate. Since the radius of the substrate r was 0.07 λ g at 2.45 GHz, the electrical length of the meander line and arc was also short. Therefore, the current distributions on each configuration of the meander part and arcs were nearly constant, as shown in Figure 2a, and are referred to as perpendicularly placed electrically small electric dipole (\vec{J}) and magnetic dipole (\vec{M}) , having TM and TE mode radiation patterns, respectively. Consequently, their summed pattern was nearly isotropic, as shown by the simulated 3D radiation pattern in Figure 2b. The radiation pattern of the proposed antenna differs from the unidirectional radiation pattern of a Huygens source antenna that is also composed of the crossed electric and magnetic dipoles [29–31]. The main idea relies on the phase difference between the two dipole sources. When the phase difference is 180°, a unidirectional radiation pattern can be created since the fields are constructively added at one direction whereas they are canceled at the opposite side (see Figure 1 of [29]). According to the theory, the total radiated electric fields from the two dipoles are summed to have the isotropic radiation pattern when the phase difference is 90° [14]. For this reason, the circular polarization is created at certain points of the radiation space. This will be discussed more with the axial ratio plot of the proposed antenna (See Figure 6).



Figure 2. Design concept: (a) current distribution and (b) 3D radiation pattern.

The radiation properties of the designed antenna are dependent on its profile. When carrying out the parameter study on h with all other design parameters being fixed, we observed that the resonant frequency of the antenna shifted down with a thinner height of the substrate, as seen in Figure 3a. This occurred because the capacitance of the structure increased as the metallic parts at the top and bottom of the substrate grew closer. Such phenomena can also be seen from the input reactance plotted in Figure 3b, where it decreased to negative values when h was smaller. The parameter study result is summarized in Table 1. The gain deviation worsened slightly when the height of the substrate h was thicker. This was due to the increased vertical current flowing through the substrate, which was not shielded by the ferrite bead. The table also shows that the radiation efficiency increased as the electrical size of the antenna increased with a thicker h.

Parameter (mm)	h = 0.32	h = 0.72	h = 1.12
Frequency (GHz)	2.30	2.45	2.51
Gain deviation (dB)	2.66	3.01	3.09
Radiation Efficiency (%)	81.3	82.6	88.6

Table 1. Parameter study results on h.



Figure 3. Parameter study results on h: (a) Reflection coefficient. (b) Input impedance.

The final design parameters are presented in Table 2. The antenna resonated at 2.45 GHz with an impedance bandwidth of 1.2% with a -10 dB criterion, as shown in Figure 4. It was electrically small with its electrical size (*ka*) of 0.47 at the resonant frequency (*k*, free-space wave propagation constant; *a*, radius of the imaginary sphere enclosing the antenna). The simulated radiation pattern at the elevation and azimuth planes will be shown in a later section with the measurement results. The designed antenna showed a quasi-isotropic radiation pattern with a maximum gain deviation of 3.01 dB as shown in Figure 5.

Parameter	Value	Parameter	Value
M1	8.4	W3	2.4
M2	13.8	W4	2
M3	12.1	W5	3.15
M4	6.7	r	9.25
W1	2.2	h	0.72
W2	2	α	271.06°

Table 2. Final design parameters of the proposed quasi-isotropic antenna design.

Note that all the units are in millimeters except α , which is in degrees.



Figure 4. Simulation and measurement results of the reflection coefficients of the proposed antenna.



Figure 5. Simulation result of a gain deviation over the entire space at the resonant frequency.



Figure 6. Simulation results of the axial ratio over the entire space.

Lastly, the axial ratio (AR) of the antenna at the resonant frequency was calculated in a spherical space and is plotted in Figure 6 to show the spatial polarization dependency. We found that a circular polarization with AR < 3 dB was created at certain points but overall linear polarization was formed. This can be explained by the antenna configuration with the electric dipole and magnetic dipole being along the *x*-axis and the *z*-axis, respectively. The antenna was linearly polarized when the field

components of the two dipoles were in the same magnitude and phase in the xy-plane (i.e., $\theta = 90^{\circ}$) and the yz-plane (i.e., $\phi = 90^{\circ}$). This showed a circular polarization at the points in the xz-plane, such as when θ is 45° and 135° and ϕ is 0° and 180°. These occurred where the electric field components of the electric dipole E_{θ} and magnetic dipole E_{ϕ} met with same magnitude and 90° phase shift. This showed that the proposed antenna can generate the quasi-isotropic radiation pattern from the sum of two different polarizations from the two different dipole configurations. This also can be verified from the pattern measurement (See Figure 9c). Thus, the proposed antenna shows a quasi-isotropic radiation pattern not only in terms of its magnitude but also in terms of polarization.

3. Fabrication and Measurements

The proposed antenna was fabricated by etching both sides of the same Rogers substrate used in the simulation and shown in Figure 7a. A U.S. quarter was placed for size comparison. The impedance resonance characteristic was measured using an Anritsu MS46522B vector network analyzer. As shown by the dashed line in Figure 4, it resonated at 2.47 GHz, showing very good agreement with the computed expectation with only negligible deviation. The gain, radiation efficiency, and patterns were measured in an anechoic chamber. The two-dimensional electric field radiation pattern measurement was carried out in the far-field measurement chamber as shown in Figure 7b. It had dimensions of $14 \times 7 \times 6.7$ m and was available for the frequency range from 200 MHz to 20 GHz with an E5071C ENA series network analyzer (Agilent Technologies). The threedimensional gain and efficiency measurements were carried out in the mobile antenna measurement chamber shown in Figure 7c. Its dimensions were $8 \times 4 \times 4$ m and it covered the frequency range from 200 MHz to 6 GHz with an E8362B PNA network analyzer from Agilent Technologies. The proposed antenna was used as a receiver and the standard horn antenna was used as a source antenna. The radiation pattern of each plane was measured for both horizontal and vertical polarization by rotating the orientation of the source antenna. The simulated and measured peak gains and efficiencies are plotted in Figure 8. The figure shows that the measured maximum peak gain and efficiency are 0.8 dBi and 79.2%, respectively, which shows similar performance to the simulation results.

The normalized simulated and measured radiation patterns along the xy, yz, and xz planes are shown in Figure 9. The figure shows that the radiation patterns in the xy- and yz-planes are nearly uniform. The pattern in the xz-plane contains two orthogonal omni-directional E_{θ} and E_{ϕ} patterns generated by the x-oriented electric dipole and the z-oriented magnetic dipole, respectively (Figure 2a), and the total radiated field shows a quasi-isotropic radiation pattern. The measured result is generally in good agreement with the simulation results. Finally, the measured gain deviation of the built antenna is shown in Figure 10. The maximum gain deviation is 5.2 dB with the highest and lowest gains of 0.8 and -4.4 dB, respectively. It differs by 2.2 dB from the computed expectation but is still acceptable and shows a similar distribution as compared to Figure 5. The non-perfect shielding of the measurement cable in an anechoic chamber that is perpendicular to the antenna could have caused the deviation. Note that the vertical current component has a non-negligible effect on the gain deviation.

There is considerable research on the planar quasi-isotropic antenna focusing the frequencies around 900 MHz and 2.4 GHz. In Table 3, the performance of the proposed design is compared with the previously published measured results around the 2.4 GHz frequency. Table 3 shows that the proposed design is electrically smaller and lower-profile. Even though the antenna size is small, it still shows comparable performance in comparison with electrically larger quasi-isotropic antennas. This proposed compact and planar quasi-isotropic antenna could be an effective design for miniature devices.





Figure 7. Photos of the built antenna and the radiation performance measurement setup. (**a**) The built prototype of the proposed antenna. (**b**) The anechoic chamber for the radiation pattern measurement. (**c**) The anechoic chamber for the three-dimensional gain and efficiency measurement.



Figure 8. Simulation and measurement results of the peak gain and radiation efficiency.



Figure 9. Simulation and measurement radiation pattern of the proposed antenna: (**a**) xy, (**b**) yz, and (**c**) xz planes.



Figure 10. Measurement result of the gain deviation over the entire space.

Reference	Frequency (GHz)	Height (λ _s)	ka	Gain deviation (dB)
[14]	2.465	0.116	1.05	5.6
[20]	2.45	0.0063	0.73	3.14
[21]	2.465	0.0065	1.63	5.75
[22]	2.45	0.008	1.16	6.67
[23]	2.01	0.024	2.73	12.9
[24]	2.4	0.11	5.37	7.6
[25]	2.4	0.016	1.28	2.6
This work	2.47	0.006	0.47	5.2

Table 3. Antenna	performance com	parison of p	proposed design	n with the r	previously i	published design.
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4. Link Reliability Evaluation

The PDR and RSSI are the main metrics used to characterize the reliability of wireless links in the indoor environment. In this section, we demonstrate whether PDR and RSSI could be improved using the quasi-isotropic antenna compared to the Tx and Rx pair of antennas with omni-directional patterns. The performance evaluation setup based on IEEE 802.15.4 is as follows: The RE-Mote from Zolertia [32] was used as an evaluation board together with Contiki-NG software [33]. The transmit power was 5 dBm and the receiver sensitivity was –95 dBm. The inter-packet transmission interval was 50 ms and each experimental point ran for 10 min. That is, there were 12,000 packet transmissions. The comparison group used the commercial antenna with an omni-directional radiation pattern for both the transmitter and the receiver as a reference. We replaced the receiver with the built prototype of the quasi-isotropic antenna to evaluate the PDR and RSSI performance. The photos of the antenna are shown in Figure 11. The PDR and RSSI values are all measured at 2.47 GHz.



(a)

(b)

Figure 11. Antennas for the performance evaluation setup: (**a**) Zolertia board with default omnidirectional antenna and (**b**) Zolertia board with quasi-isotropic antenna.

The measurement under the LOS environment was carried out in a typical corridor with a concrete wall and glass windows as shown in Figure 12a. The distance (d) between the transmitter and receiver was varied from 3.6 to 36 m, with a step size of 5.4 m. For the NLOS environment, the transmitter and receiver were blocked by a thick concrete wall and metal door, as shown in Figure

12c. Its associated photo is shown in Figure 12b. We also evaluated the link reliability when the transmitter and receiver were located at different floor levels of the building.





Figure 12. Measurement setup. (a) Photo for the LOS environment. (b) Photo for the NLOS environment. (c) Floor map for the NLOS environment.

The measured PDR and RSSI values are given in Figure 13. In Figure 13a, where the PDR across the distance under LOS is plotted, there is comparable performance between the different pairs of the antennae. Next, RSSI across the distance was measured under LOS, and is plotted in Figure 13b. There still did not appear to be a big difference between the two pairs, but the one with a quasi-isotropic antenna at the receiver generally performed better. This is because there were still scattered fields from the ground and walls despite the transmitter and receiver directly seeing each other. The measured values under NLOS are shown in Figure 13c,d. The position of the receiver was moved from position 1 to 6 in Figure 12c. Note that LOS was still achieved when the receiver is at position 1. In Figure 13c, PDR degradation is observed when the omni-directional antenna is at position 4 due

to the metal obstacle and weak multipath signal. Note that the PDR was better at position 4 when the designed quasi-isotropic antenna was used. It generally provided robust performance for various NLOS positions. The same situation can be observed in the case of measuring the RSSI again in Figure 13d. The RSSI was again degraded for the omni-directional antenna at position 4, which was due to the metal obstacle and weak multi-path signal, whereas the antenna pair with the quasi-isotropic antenna generally provided robust performance for different NLOS positions. Consequently, we demonstrate that the quasi-isotropic radiation pattern would be useful in improving communication performance under NLOS.



(c)



Figure 13. Measured PDR and RSSI. (a) PDR under LOS, (b) RSSI under LOS, (c) PDR under NLOS, and (d) RSSI under NLOS.

We also evaluated the link reliability when the transmitter and the receiver were deployed at the different floors of the building. The transmitter was at the lower level of the floor. The vertical distance between the two nodes was around 3.7 m. Figure 14 shows the average PDR and RSSI measurement as a function of various transmit powers between –13 and 7 dBm. A significant improvement was observed when the developed quasi-isotropic antenna was used. One interesting observation is that the proposed antenna provides around 3 dB gain of average RSSI with respect to those using the omni-directional antenna pair when the transmit power is greater than –9 dBm. It also provides PDR greater than 70 for transmit power between –11 and –9 dBm while the omni-directional antenna pair has low PDR of less than 35%.



Figure 14. Measured (a) PDR and (b) RSSI under NLOS at different floor levels of the building.

5. Conclusions

In this paper, we proposed an electrically small and planar quasi-isotropic antenna and demonstrated its feasibility of improving the wireless link reliability under NLOS channel environments. The antenna had an electrical size *ka* less than 0.5 and showed a measured gain deviation around 5 dB, which is good enough to be considered as a quasi-isotropic antenna. Its performance in terms of the electrical size and gain deviation was compared with other planar quasi-isotropic antennas in the literature. Furthermore, from the wireless link reliability test in indoor NLOS channels, we demonstrated that PDR and RSSI can be enhanced by the simple use of the proposed antenna, in comparison to the use of omni-directional antennas. To the best of our knowledge, the usefulness of the quasi-isotropic antenna in real communication measurement was first demonstrated by this work. The exact analysis of the link reliability evaluation according to the different gain deviation values and the polarization dependency of the quasi-isotropic antennas remains a possibility for future work.

Author Contributions: Conceptualization, S.M.R. and I.-J.Y.; methodology, S.M.R., M.J., P.P., and I.-J.Y.; software, S.M.R., M.J., P.P., and I.-J.Y.; validation, S.M.R., M.J., P.P., and I.-J.Y.; formal analysis, S.M.R., M.J., P.P., and I.-J.Y.; investigation, S.M.R., M.J., P.P., and I.-J.Y.; resources, S.M.R., M.J., P.P., and I.-J.Y.; data curation, S.M.R., M.J., P.P., and I.-J.Y.; writing—Original draft preparation, S.M.R.; writing—Review and editing, P.P and I.-J.Y.; visualization, S.M.R.; supervision, I.-J.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the Basic Research Laboratory of the National Research Foundation funded by the Korean government under Grant NRF-2017R1A4A1015744, and in part by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No. 2017-0-00659).

Conflicts of Interest: The authors declare no conflict of interest.

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