An Empirical Study of Antenna Characteristics Toward RF-based Localization for IEEE 802.15.4 Sensor Nodes

Sungwon Yang and Hojung Cha

Department of Computer Science, Yonsei University,
Seodaemun-gu, Sinchon-dong 134, Seoul 120-749, Korea
`{swyang, hjcha}@cs.yonsei.ac.kr`

Abstract. Localization using the characteristics of the Radio Frequency (RF) in wireless sensor networks is attractive because the method does not require additional measuring devices, and hence satisfies low cost and low power consumption needs. The range information derived from Received Signal Strength (RSS), which attenuates over the distance and node connectivity, is, however, inaccurate and unpredictable in the real world due to problems caused by sensor motes and the environment of the sensor field. In this paper, through an empirical analysis, we present detailed radio signal properties of the 2.4GHz IEEE 802.15.4 radio module. We also provide the methodology of antenna design and mounting to alleviate the antenna orientation and RSS fluctuation problems, which are key factors that make RF-based ranging irregular in an obstacle-free environment. Our work is differentiated from previous work, which concludes with merely revealing the problems, ignoring them by assumptions, or even limiting the feasibility of RF utilization in localization.

1 Introduction

Although localization for Wireless Sensor Networks (WSN) has actively been studied in recent years, it is still a challenging issue. One of the simple methods for localization is to use a Global Positioning System (GPS) [1]. However, while GPS enables localization in an outdoor environment, it is costly and the energy consumption is significant. Using Received Signal Strength (RSS), or connectivity of radio communication, for localization in WSNs is attractive because of its low cost and low power consumption, and because it does not require any additional measuring devices other than the low-power radio module itself. Recently many RF-based localization algorithms have been proposed [2], [3], [4], [5], [6], [7], [8], [9]. These localization techniques, using the RSS or RF connectivity, theoretically work well in ideal conditions; however, in the real world the location error is too high to be useful in most cases. Therefore, the discrepancy of localization result between theoretical and practical conditions generates the belief that RF-based localization is useless. The main reason for the discrepancy is that most localization algorithms based on RSS or RF connectivity assume that the radio radiation pattern is perfectly circular or spherical in shape, and that the formula for RSS attenuation over distance is directly applicable. In the real world, the pattern of radio transmitted at the antenna is neither a circular nor a spherical shape, and the path loss model is not valid due to problems caused by the sensor mote and the environment of the sensor field. The study in [10] shows that the performance of RF-based localization degrades in the presence of an irregular radio range.

In this paper, we consider antenna orientation and the fluctuation of RSS as the major problems that make RF-based ranging inaccurate and unpredictable in an obstacle-free environment. Through extensive measurements, we analyze the cause of each problem and propose a methodology that eliminates the limits of RF-based localization in an obstacle-free environment. Instead of making the RF-based localization algorithm more complicated by combining with an error correction algorithm, which increases power consumption, we focus on antenna technology to solve these problems at the base level. To the best of our knowledge, our work is the first approach that shows that the irregularity of RF is not an inherent problem in WSN, and the RF irregularity can be eliminated with antenna design or mounting mechanisms. The experimental results with the various antennas clearly show the feasibility of a more accurate RF-based localization for WSN in practice.

The rest of the paper is organized as follows. Section 2 describes previous work that discusses RF irregularity. The empirical analyses of two main factors that make RF-based ranging inaccurate and the methodology for eliminating the RF irregularity with various antennas are presented in Sections 3 and 4. In Section 5, we analyze a critical consideration when deploying nodes with special antennas. In Section 6, we discuss an ideal antenna design for accurate RF-based ranging. Finally, we conclude the paper in Section 7.

2 Related Work

Early research, [11], [12], [13] mentioned link asymmetry and irregular radio range in WSNs. These phenomena were shown because of experiments to quantify the performance of packet delivery with the Berkeley Mica or Mica2 motes. They hypothesized that the irregularity of radio communication in WSNs was caused by differences in the quality of radio and hardware calibrations.

Zhou et al. [14] categorized the causes of radio irregularity into two main factors: the heterogeneous properties of devices and the non-isotropic properties of propagation media. Device properties include the antenna type (directional or ommi-directional), transmission power, antenna gains, receiver sensitivity, receiver threshold and the Signal-Noise Ratio (SNR). Media properties include the media type, background noise and various other environmental factors. They concluded that an asymmetric link is mainly caused by the variance in RF transmission power and the differences in path loss as a function of direction of propagation. However, the reason for an asymmetric link between two nodes that have the same transmitting power in an obstacle-free environment was not discussed in their work. They regarded the radio irregularity in WSNs as an inherent problem and consequently proposed the Radio Irregularity Model (RIM) to apply the radio irregularity to simulations.

Recently, Lymberopoulos et al. [15] provided a detailed analysis of radio properties of 2.4GHz RF using the IEEE 802.15.4 radio module and a monopole antenna.

They used the CC2420 [16] radio module to characterize the properties of RSS and link asymmetry in obstacle-free and indoor environments. Through extensive measurements, they showed that antenna orientation greatly affects RSS and link asymmetry in indoor and outdoor scenarios, and confirmed the presence of antenna orientation and irregular RSS attenuation problems in practice. However, a method to solve these problems was not considered in their work.

3. Antenna Orientation

Many techniques, which determine the location of an unknown node using RF, have been proposed. Most of them, however, assume ideal conditions, where the pattern of horizontal radiation is circular and the radio range is the same for each node. However, because of the presence of antenna orientation problems inherent in a real world environment, these localization algorithms only work where the assumptions hold. Antenna orientation is a problem defined as the RSS of the receiver varies as the pair wise antenna orientations of the transmitter and the receiver are changed. In this section, we analyze the cause of antenna orientation problems in WSNs, and provide solutions based on antenna characteristics. We also provide data on how the link property improves between two nodes in conditions where an antenna orientation problem does not exist.

3.1 Cause of Antenna Orientation

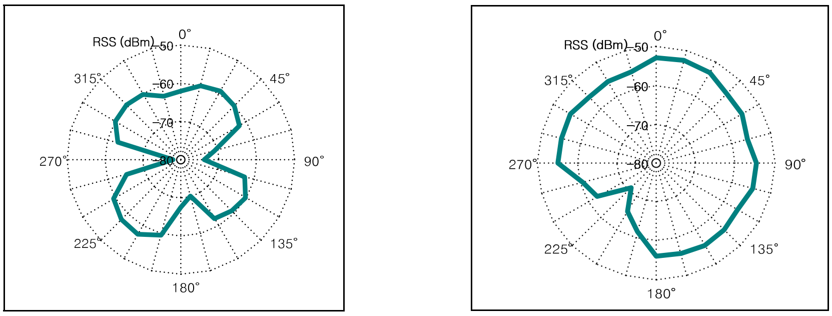
Most off-the-shelf sensor motes use a $\frac{1}{4}$ wavelength monopole antenna, which is mounted in either an internal or external type configuration. A $\frac{1}{4}$ wavelength monopole antenna shows the same radiation pattern of a $\frac{1}{2}$ wavelength dipole antenna whose horizontal radiation pattern is omni-directional. However, this omni-directional radiation pattern is distorted when an antenna is mounted on sensor motes. An irregular radiation pattern means that the measured RSS may vary according to the orientation of the transmitting and receiving nodes, although both the transmitter and the receiver are located in a fixed position. To quantify the distorted radiation pattern, we measured average RSS values in 24 different degrees with a fixed receiver node and a rotating transmitter node at a 1.5m distance and output power of -10dBm using "Tmote Sky[*]" [17] in a relatively obstacle-free environment (No obstacles making reflections within three meters).

As shown in Figure 1(a), the radiation pattern of the internal antenna is so jagged that the difference in the measured RSS is up to 20dBm, which is impossible for use in obtaining propitious distance information for localization. In the case of $\frac{1}{4}$ wavelength external monopole antenna, the radiation pattern is still biased and the maximum difference of RSS is 15dBm, as shown in Figure 1(b), although the pattern is more circular compared to the internal antenna case.

---

[*] All experiments using real sensor motes in this paper were conducted with "Tmote Sky" from the Moteiv cooperation.

One of the main factors that cause the antenna orientation phenomenon is the small size of the ground plane inside the PCB (Printed Circuit Board). The widely-used $\frac{1}{4}$ wavelength monopole antenna is formed by replacing one half of a dipole antenna with a ground plane at right-angles to the remaining half. If the ground plane is large enough, the monopole behaves exactly like a dipole, as if its reflection in the ground plane formed the missing half of the dipole. The ground plane of a sensor mote, however, may not satisfy the ideal ground conditions. Another factor, which affects the radiation pattern, is the circuit design and devices on a sensor mote. In other words, the electric field of the antenna is distorted by the interference from other devices, which are close to it.

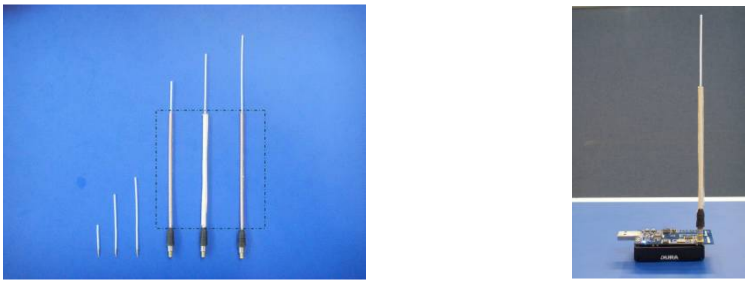


(a) (b)

Fig. 1. Horizontal radiation patterns of (a) internal inverted-F $\frac{1}{4}$ wavelength antenna and (b) external $\frac{1}{4}$ wavelength monopole antenna mounted on a sensor mote

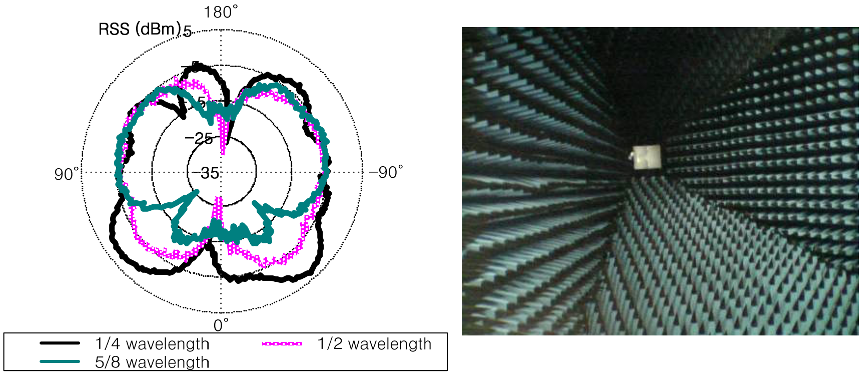
3.2 Length of Antenna

To validate whether the antenna orientation problem is indeed caused by interference from electric devices on a sensor mote, we kept the distance between the antenna and the sensor mote to a wavelength height (12.5cm at 2.4GHz) using a coaxial cable whose impedance is 50Ω . Since the vertical angle of radiation gets narrower as the length of the antenna gets longer from $\frac{1}{4}$ wavelength to $\frac{1}{2}$ or $\frac{5}{8}$ wavelength [18], we also changed the length of the antenna to $\frac{1}{2}$ and $\frac{5}{8}$ wavelengths. Three antennas of different lengths both with and without a coaxial cable are shown in Figure 2. Figure 3(a) shows the measured vertical radiation patterns for each antenna, which shows the longer antenna has narrower angle of vertical radiation. Measurements were conducted in the anechoic chamber, as shown in Figure 3(b), which does not generate a reflection of electromagnetic waves, and a device which takes a measurement of RSS from the antennas in every single degree used.



(a) (b)

Fig. 2. (a) $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{5}{8}$ wavelength monopole antennas with and without a coaxial cable. The area designated by the dotted-line indicates a wavelength coaxial cable. (b) A sensor mote with an external antenna.



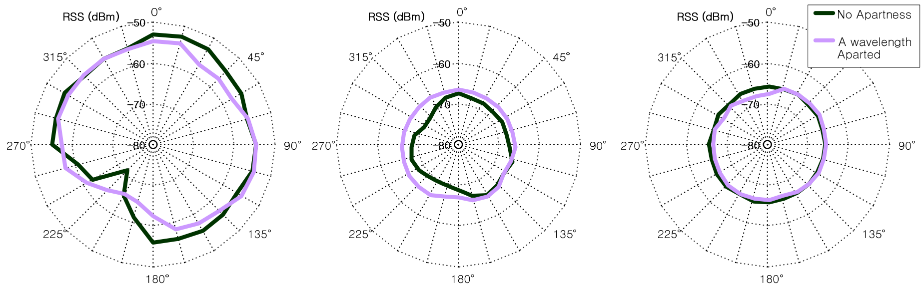
(a) (b)

Fig. 3. (a) Radiation patterns of $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{5}{8}$ wavelength monopole antenna on side view. (b) Picture of the anechoic chamber where the measurements of radiation pattern were conducted.

Figure 4(a) shows that the null radiation zone, where a radically weaker radiation than in other areas occurs, is eliminated when the $\frac{1}{4}$ wavelength optimal antenna is mounted a wavelength height farther from a sensor mote. With a $\frac{1}{2}$ wavelength monopole antenna, we obtained more circular radiation patterns, especially when the antenna was a wavelength away from the mote. In case of a $\frac{5}{8}$ wavelength antenna, it shows an almost perfect circular radiation pattern although it is mounted without a coaxial cable. Note that the radiation pattern gets more circular with a $\frac{1}{2}$ or $\frac{5}{8}$ wavelength monopole antenna, however the RSS gets weaker when compared to a $\frac{1}{4}$ wavelength antenna.

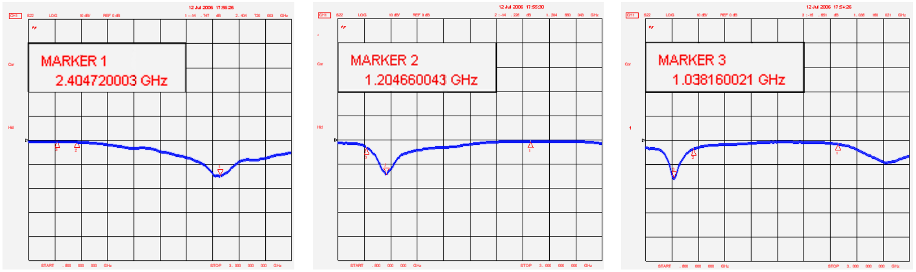
As shown in Figure 4, the antenna orientation problem can be eliminated with a $\frac{1}{2}$ wavelength monopole antenna, which keeps a wavelength distance away from a sensor mote or a $\frac{5}{8}$ wave length one. In other words, the antenna orientation problem can be solved by minimizing the electrical interference from devices of a sensor mote and matching the ground plane with the proper length of antenna. The horizontally omni-directional radiation pattern is obtained by simply keeping enough distance between an antenna and a sensor mote or changing the antenna to a longer one. In practice, however, the distance between an antenna and a sensor mote cannot be as far away as is theoretically needed.

Using a $\frac{1}{2}$ or $\frac{5}{8}$ wavelength antenna is also inefficient because as the length of an antenna deviates from the optimal length, the antenna does not resonate at the given frequency. Figure 5 shows the resonant point, measured with a network analyzer, of three monopole antennas whose length is $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{5}{8}$ wavelength of 2.4GHz respectively. In Figure 5(a), the $\frac{1}{4}$ wavelength monopole antenna causes maximum resonance at the frequency of 2.4GHz, however, $\frac{1}{2}$ and $\frac{5}{8}$ ones do not. The attenuation of RSS, which is caused by changing the antenna length from an optimal $\frac{1}{4}$ wavelength to others, is about 10dBm as shown in Figure 4. An antenna whose length does not match the given frequency receives weak signals, and consequently shortens the communication range. To solve this problem, an antenna that has an analogous radiation pattern to $\frac{1}{2}$ or $\frac{5}{8}$ wavelength antenna without attenuation of RSS is required.



(a) (b) (c)

Fig. 4. The horizontal radiation patterns of (a) $\frac{1}{4}$ wavelength, (b) $\frac{1}{2}$ wavelength, and (c) $\frac{5}{8}$ wavelength antenna mounted on a sensor mote. Measurements were conducted at a 1.5m distance between two motes and output power of -10dBm. Both the transmitter and receiver used exactly the same length of antenna.



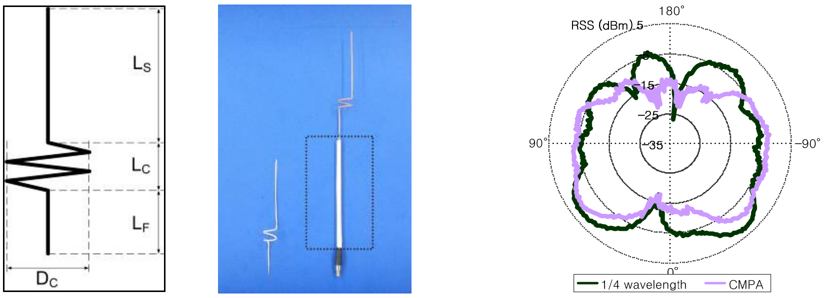
MARKER 1
2.404720003 GHz

MARKER 2
1.204660043 GHz

MARKER 3
1.038160021 GHz

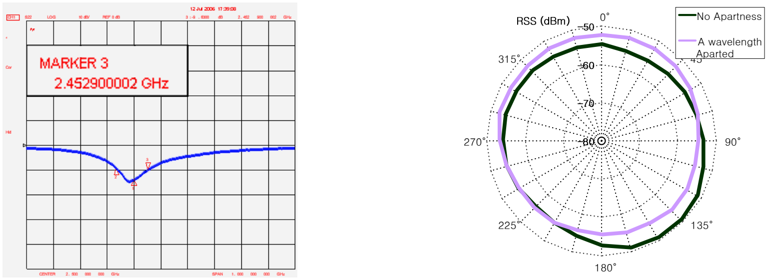
(a) (b) (c)

Fig. 5. Return loss of (a) $\frac{1}{4}$ wavelength, (b) $\frac{1}{2}$ wavelength, and (c) $\frac{5}{8}$ wavelength monopole antenna. The minimum peak indicates the return loss at maximum resonant frequency.



(a) (b) (c)

Fig. 6. (a) Configuration of collinear monopole antenna with loading coil, (b) Designed collinear monopole antenna. The area designated by the dotted-line indicates a wavelength coaxial cable, and (c) Vertical radiation pattern of the designed CMPA. Measurements of the vertical radiation pattern were conducted in an anechoic chamber.



(a) (b)

Fig. 7. (a) Return loss of designed CMPA. The minimum peak indicates the return loss at maximum resonant frequency. (b) Horizontal radiation pattern of the designed CMPA mounted on a sensor mote. Measurements were conducted at a 1.5m distance between two motes and an output power of -10dBm. Both the transmitter and receiver used exactly the same length of antenna.

3.3 Collinear Monopole Antenna

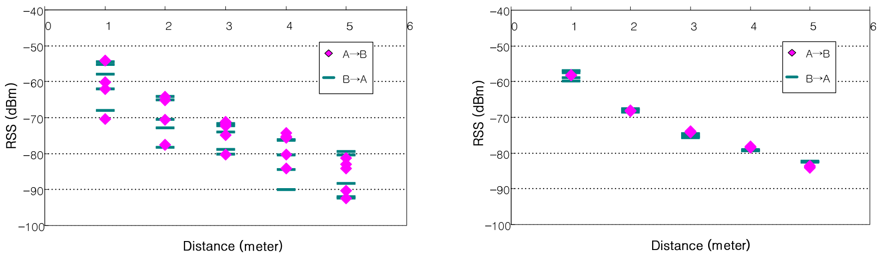
Since in spite of satisfying the regular radiation pattern, the longer than optimal length of antenna does not satisfy the normal communication range, we are required to find an antenna guaranteeing both a regular radiation pattern and no decrease in communication range.

The Collinear MonoPole Antenna (CMPA) is used to obtain a higher performance level [19]. It is composed of two linear wires connected with a loading coil and it has a narrower vertical radiation pattern than a $\frac{1}{4}$ wavelength default antenna. Figure 6(a) shows the configuration of a CMPA with a loading coil and Figure 6(b) shows the CMPA we have built where the length of the first antenna element L_F is 2.8cm, the length of the second antenna element L_S is 6cm, the uncoiled length of the coil arm L_C is 5.6cm, and the coil diameter D_C is 0.7cm. Figure 6(c) presents the measured vertical radiation pattern of our CMPA, which is narrower than a $\frac{1}{4}$ wavelength optimal monopole antenna. The resonant frequency of our CMPA is around 2.4GHz as shown in Figure 7(a). Figure 7(b) shows that the CMPA guarantees the omni-directional radiation pattern horizontally and the higher RSS than the case of measurement with not only $\frac{1}{2}$ or $\frac{5}{8}$ wavelength monopole antenna but also a $\frac{1}{4}$ wavelength optimal one.

3.4 Asymmetric Link

Through the various experiments, we have discovered why the antenna orientation problem occurs and subsequently provided solutions through antenna design and mount methods. In this section, we show the improvement of link symmetry through antenna replacement. An asymmetric link is defined as one in which the connectivity of “node A” to “node B” is significantly different from that of “node B” to “node A” on condition that the transmission power of node A and B is the same. The link asymmetry is caused by factors such as the presence of obstacles, the asymmetric multi-path effect, and the antenna orientation. Since we consider the obstacle-free environment, we focus on the asymmetric link problem caused by antenna orientation.

The asymmetric link has been regarded as an inherent problem in WSNs. However, for accurate localization in both range-free and range-based techniques; it is essential that this issue be resolved. Figure 8 shows that the asymmetric link of the RSS problem can be eliminated by solving the antenna orientation problem. With a $\frac{1}{4}$ wavelength monopole antenna, which has the horizontally irregular radiation pattern, the maximum deference of RSS from “node A” to “node B” and from “node B” to “node A” is 15dBm as shown in Figure 8(a). Conversely, the maximum difference of RSS between two links is only 1.7dBm, as shown in Figure 8(b), for nodes with a $\frac{5}{8}$ wavelength monopole antenna, which transmits almost the same strength of radio signal to all horizontal directions. Consequently, the asymmetric link problem in WSNs is not an independent issue, but a problem that is dependent on the antenna orientation problem.



(a) (b)

Fig. 8. Average RSS vs. distance plot for (a) $\frac{1}{4}$ wavelength monopole antenna and (b) $\frac{5}{8}$ wavelength monopole antenna. Nodes were placed with random orientation for each measurement. All measurements were conducted with a transmission power of -7dBm.

From the viewpoint of link connectivity, link symmetry, which is the most important factor in many range-free localization methods, can also be guaranteed with a horizontally omni-directional antenna. Srinivasan et al. [20] presented the relationship between RSS and Packet Reception Rate (PRR), which shows that PRR varies rather radically where RSS is less than -87dBm. Figure 9 shows the similar result, which is re-experimented. As shown in Figure 8(a), the difference in RSS is up to 15dBm where the antenna of sensor motes is $\frac{1}{4}$ wavelength monopole whose horizontal radiation pattern is irregular. Hence, a node may receive all packets or nothing according to the directions of the nodes in the case where the average RSS value is close to -87dBm, which is an entrance of a gray region. Conversely, an antenna that guarantees the horizontally omni-directional radiation pattern satisfies a certain level of PRR although the average RSS value is near -87dBm.

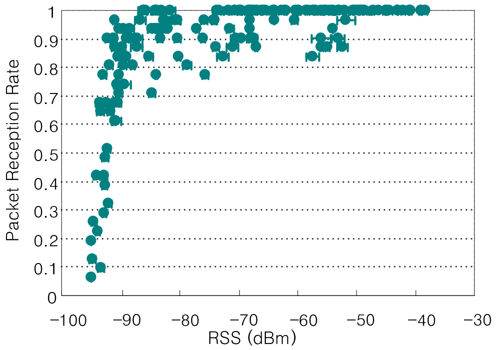


Fig. 9. RSS vs. Packet Reception Rate plot. 150 measurement cases were randomly picked where the distance between a transmitter and a receiver is 50 to 2000cm and the transmission power is -25 to 0dBm

4. RSS Fluctuation

Theoretically, RSS attenuates over distance in free space. However, this is not valid in practice due to multi-path fading. In the real environment, RSS attenuates by a certain distance, and then starts fluctuating. This fluctuation leads to unreliable distance information because the same RSS can be measured at different distances. In this section, we validate that the distance guaranteeing RSS attenuation without fluctuation can be extended through antenna replacement. Based on an experiment using parabolic antennas, we also provide insight on how the accuracy of range-based ranging improves under the circumstance such that the cause of RSS fluctuation is eliminated through a special antenna.

4.1 Ground Reflection

Figure 10 shows the RSS values versus distance for five different output power levels. The measured RSS attenuates almost linearly by the distance d_R as shown. Here, d_R is a distance that guarantees the validity of the path loss model so that mapping RSS to distance information for localization can be possible within d_R. However, beyond this reliable distance, RSS begins fluctuating. Note that the RSS starts fluctuation at the same distance for all cases of different output power, and each peak for different output power after the distance of d_R is generated at the same distance. This implies that the output power of the transmitter is not a factor that affects d_R. Since the object, which generates multi-path fading, is only the ground in an obstacle-free environment, the ground reflection is the main factor which generates the RSS fluctuation problem.

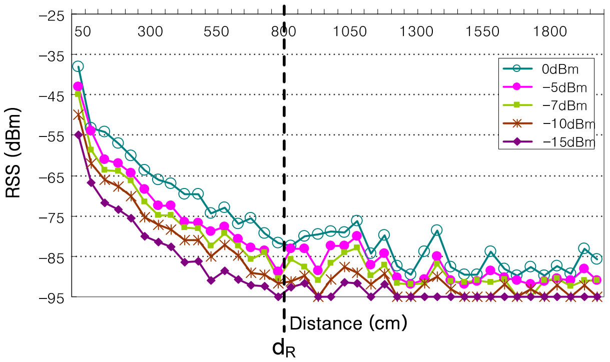


Fig. 10. RSS vs. distance for five different output powers on soil ground. Measurements were conducted with $\frac{1}{4}$ wavelength optimal monopole antennas. The top of the antenna was at 20cm height. -95dBm of RSS value indicates no communication between receiver and transmitter.

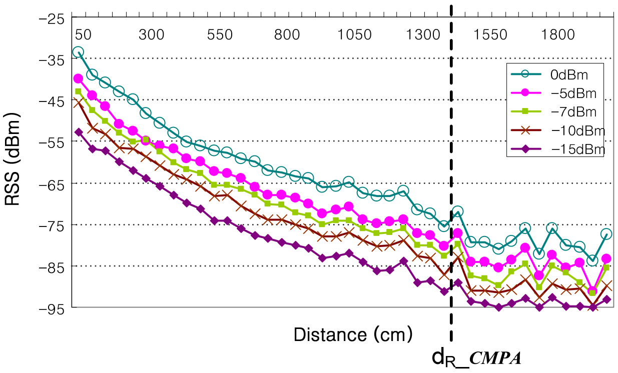


Fig. 11. RSS vs. distance for five different output powers on soil ground. Measurements were conducted with the designed CMPA. The top of the antennas was at 20cm height. -95dBm of RSS value indicates no communication between receiver and transmitter.

Since d_R depends on where the first reflection by ground occurs, extending the distance of the first reflection is required to extend d_R for obtaining useful distance information at a longer distance. We changed the antenna from an optimal $\frac{1}{4}$ wavelength monopole to CMPA in Figure 6(b) to extend d_R. The vertical radiation pattern of designed CMPA is narrower than an optimal $\frac{1}{4}$ wavelength monopole antenna as shown in Figure 6(c). Therefore, the angle of incidence of CMPA is narrower than a $\frac{1}{4}$ wavelength one. Since the narrower angle of incidence means that the reflection on the ground occurs at a greater distance and the reflected RF also interferes with directly-propagated RF at a further distance, d_R is extended.

Figure 11 shows the RSS values versus that of distance with CMPA. Compared with a $\frac{1}{4}$ wavelength monopole antenna, the distance that guarantees obtaining useful distance information directly from RSS is extended from 8m to 14m. Note that we adjusted the top of both antennas to the same height to minimize the side-effect caused by different antenna heights. The adjustment of antenna height was essential because the difference of $\frac{1}{4}$ wavelength monopole and the designed CMPA is about 7cm.

4.2 Experiment using Parabolic Antennas

In the previous section, we validated that the distance, which guarantees the path loss model can be extended by changing into an antenna whose vertical radiation angle is narrower than the case of a $\frac{1}{4}$ wavelength optimal antenna. We now focus on how long d_R can be extended under the environmental conditions where the ground reflection does not exist. To measure RSS value over a distance satisfying the condition of no ground reflection, we used a parabolic antenna [21], which has a very sharp radiation pattern in both the horizontal and vertical planes.

We placed two sensor motes in an obstacle-free space, connecting them with parabolic antennas whose gain is 15dBi, and satisfying the line-of-sight as shown in Figure 12. The parabolic antenna transmits a radio signal to an extremely narrow direction so that the reflection of RF caused by ground almost never occurs. As shown in Figure 13, in the condition where there is no ground reflection, RSS attenuates linearly over distance without fluctuation. In an obstacle-free environment where the ground reflection is removed by using an antenna whose radio signal is not radiated to the ground, the reliable distance d_R can be extended to the communication range itself. In case of our experiment with the parabolic antenna of 15dBi gain, the reliable distance was over 50m.

Through this experiment, we noticed that remarkably accurate performance of localization can be achieved even with RSS-based localization techniques, which translate RSS to actual distance between nodes, provided that an antenna, which eliminates the RSS fluctuation problem is used.

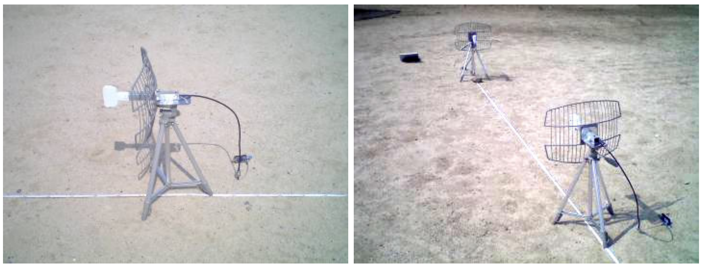


Fig. 12. An experimental setup for RSS measurement with parabolic antennas. The transmission power is 0dBm and the line of sight is satisfied at a height of 50cm.

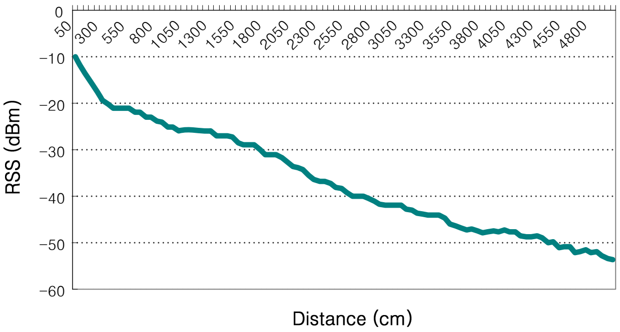


Fig. 13. RSS vs. Distance with parabolic antennas of 15dBi gain at a height of 50cm

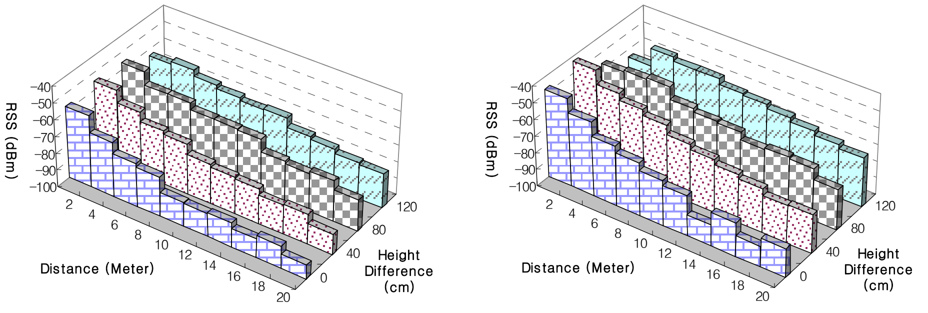
5. Deployment Consideration

So far, we have validated that both antenna orientation and RSS fluctuation problems can be alleviated by changing the antenna into one whose vertical radiation pattern is less than a $\frac{1}{4}$ wavelength optimal antenna. Experimental results in a relatively flat and obstacle-free environment show better performance in terms of regular radiation pattern and obtaining a longer distance range which is applicable to the path loss model. The problem which is occurred when changing an antenna from a $\frac{1}{4}$ wavelength optimal one to an antenna with a narrower angle of vertical radiation, is that the RSS attenuation over distance is less reliable than the case of using a $\frac{1}{4}$ wavelength optimal monopole antenna in the environment where the heights of a transmitter and a receiver are different.

In order to analyze how the comparatively narrower vertical radiation than $\frac{1}{4}$ wavelength monopole antenna affects the localization performance in an environment where a height difference exists, we measured RSS over distance with different heights between a receiver and a transmitter. Figure 14 shows RSS values versus distance for four cases. The height differences of the transmitter and the receiver are

0cm, 40cm, 80cm, and 120cm respectively. In the case of a $\frac{1}{4}$ wavelength monopole antenna, the path loss model was valid for the height difference of 0cm, 40cm, and 80cm. For the height difference of 120cm, the measured RSS value at a 2m distance was weaker than the RSS value at a 4m distance. However, the difference of the RSS value was slight for 2dBm.

In the case of our CMPA, the path loss model was slightly broken at a height difference of 80cm, and the RSS difference between 2m distance and 4m distance was 10dBm at a height difference of 120cm as shown in Figure 14(b). To identify the height difference, which guarantees the path loss model, we measured RSS at the distance of 2m between a transmitter and a receiver by changing the height difference from 0 to 120cm. As shown in Figure 15, for a $\frac{1}{4}$ wavelength optimal antenna, the RSS value decreases dramatically at a height difference of 90cm. On the other hand, the RSS value starts dramatically decreasing at a height difference of 70cm for the CMPA. The vertical boundary which guarantees the path loss model can be represented about 24.5° for a $\frac{1}{4}$ wavelength monopole antenna and about 19.5° for the CMPA.



(a) (b)

Fig. 14. RSS vs. Distance in four cases that the transmitter and receiver are placed at different heights for (a) a $\frac{1}{4}$wavelength monopole antenna and (b) our CMPA. Measurements were conducted with a transmitter of fixed height and a receiver on a tripod, which can adjust height.

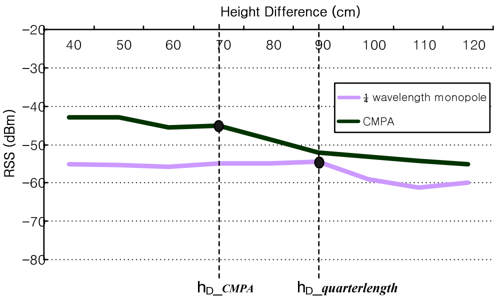


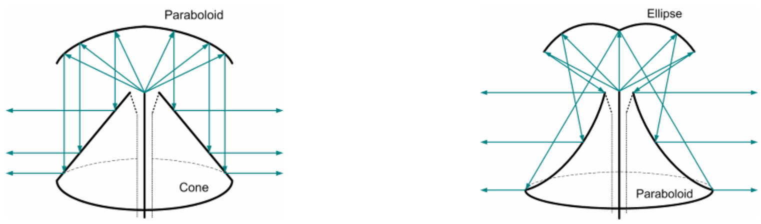
Fig. 15. RSS vs. height difference of the transmitter and receiver at 2m distance

In an RSS-based localization technique, the $\frac{1}{4}$ wavelength optimal antenna consequently presents reliable localization performance where the angle with a transmitter and a receiver is only lower than 24.5°. Moreover, when using a special antenna such as the CMPA to alleviate antenna orientation and RSS fluctuation problems, more restrictions on node-deployable environment, in terms of height difference, are imposed because the vertical radiation angle gets narrower.

6. Discussion

In Section 4.2, we showed that the RSS attenuates over distance without any fluctuation when using a parabolic antenna whose vertical radiation pattern is very sharp so that the reflection by ground does not occur. The problem of a conventional parabolic antenna is that it radiates RF only to the particular direction. Satisfying no RSS fluctuation caused by ground reflecting, some special antennas make it possible to obtain a horizontally omni-directional radiation pattern. Figure 16(a) shows the schematic diagram of omni-directional antenna with dual reflectors of a paraboloid and a cone [22]. Figure 16(b) shows another antenna design to satisfy both horizontally omni-directional and horizontal-only radiation, which consists of an ellipse and a paraboloid as a sub-reflector and a main-reflector respectively [23]. The problem in constructing an antenna including a paraboloid is the size of the paraboloid. Since the diameter of paraboloid requires it being larger than a wavelength of RF, it is not possible to apply a conventional dual reflector antenna directly to a WSN.

With a collinear antenna, it is also possible to reduce vertical radiation and increase antenna gain such as with dual reflector antennas by increasing the number of coils or loops. The problem with the collinear antenna, which satisfies the problem of a narrow angle of vertical radiation making no ground reflection, is the increased length of antenna. The length of collinear antenna used in this paper is about 10cm, and the length increases to 25cm if making an antenna that includes two loops to obtain 6dBi gain. The length of antenna may get longer over 100cm for much less vertical radiation. We expect that a ceramic antenna can solve this length problem because the size of an antenna made with ceramic can be over 60% smaller than a conventional monopole antenna [24], [25].



(a) (b)

Fig. 16. Schematic diagram and radiation direction on side view of dual reflector omni-directional antenna consisting of (a) a paraboloid and a cone [22], and (b) an ellipse and a paraboloid [23].

7. Conclusions and Future Work

In this paper, we analyzed why the RF-based localization techniques do not work well in practice and the corresponding solutions. Based on extensive experiments with the widely-used CC2420 IEEE 802.15.4 compliant radio and various antennas, we conclude our work as follows:

- Factors involved with the antenna orientation problem include a small ground plane size and an electrical effect caused from other devices on a sensor mote. Therefore, the antenna orientation problem can be eliminated by mounting an antenna keeping a certain vertical distance away from a sensor mote or using an antenna which has less radiation toward the downside to minimize distortion of electrical fields.
- The asymmetric link in an obstacle-free environment is an incidental problem caused by antenna orientation. Hence, it can be easily solved by removing the cause of the antenna orientation.
- The RSS fluctuation is a problematic phenomenon in that the RSS attenuation over distance is not held out at a certain reliable distance, and is caused by multi-path fading, especially reflection by the ground in an obstacle-free environment. The reliable distance can be extended by replacing an antenna with one having a narrow vertical radiation pattern, which leads the first reflection of RF on the ground to occur at a greater distance.
- Dual reflector antenna or high-gain collinear antenna can be used for eliminating both antenna orientation and RSS fluctuation problems in cases where sensor motes are deployed in a relatively flat ground environment. We expect to reduce the size of those antennas by building them of ceramic.

In future work, we plan to make a ceramic collinear antenna, which has similar characteristics to that of a dual reflector antenna, satisfying the appropriate size specifications in WSNs. With a specially made antenna, we hope to analyze and evaluate the improvement of the accuracy in RF-based localization techniques for relatively flat and obstacle-free environments.

Acknowledgments

This work was supported by the National Research Laboratory (NRL) program of the Korea Science and Engineering Foundation (2005-01352), and the MIC(Ministry of Information and Communication), Korea, under the ITRC(Information Technology Research Center) support program supervised by the IITA(Institute of Information Technology Advancement)" (IITA-2006-C1090-0603-0015).

References

1. Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J.: *Global Positioning System: Theory and Practice.* 4th Ed., Springer Verlag (1997)

2. Patwari, N., and Hero III, A. O.: Using Proximity and Quantized RSS for Sensor Localization in Wireless Networks. ACM International Workshop on Wireless Sensor Networks and Applications (WSNA) (2003)
3. Savarese, C., Rabay, J., and Langendoen, K.: Robust Positioning Algorithms for Distributed Ad-Hoc Wireless Sensor Networks. USENIX Technical Annual Conference (2002)
4. Savvides, A., Park, H., and Srivastava, M.: The Bits and Flops of the N-Hop Multilateration Primitive for Node Localization Problems. ACM International Workshop on Wireless Sensor Networks and Applications (WSNA) (2002)
5. Shang, Y., and Ruml, W.: Improved MDS-Based Localization. INFOCOM (2004)
6. Ji, X., and Zha, H.: Sensor Positioning in Wireless Ad-hoc Sensor Networks with Multidimensional Scaling. INFOCOM (2004)
7. Bulusu, N., Heidemann, J., and Estrin, D.: GPS-less Low-Cost Outdoor Localization for Very Small Devices. IEEE Personal Communications Magazine (2000)
8. Niculescu, D, and Nath, B.: Ad hoc Positioning System (APS). IEEE GLOBECOM (2001)
9. Yedavalli, K., Krishnamachari, B., Ravula, S., and Srinivasan, B.: Ecolocation: A Sequence Based Technique for RF Localization in Wireless Sensor Networks. Information Processing in Sensor Networks (IPSN) (2005)
10. He, T., Huang, C., Blum, B. M., Stankovic, J. A., and Abdelzaher, T.: Range-Free Localization Schemes for Large Scale Sensor Networks. ACM International Conference on Mobile Computing and Networking (MobiCom) (2003)
11. Ganesan, D., Krishnamachari, B., Woo, A, Culler, D., Estrin, D., and Wicker, S.: Complex Behavior at Scale: An Experimental Study of Low-Power Wireless Sensor Networks. Technical Report, UCLA/CSD-TR 02-0013 (2002)
12. Cerpa, A., Busek, N., and Estrin, D.: SCALE: A Tool for Simple Connectivity Assessment in Lossy Environments. CENS Technical Report 0021 (2003)
13. Zhao, Y. J., and Govindan, R.: Understanding Packet Delivery Performance in Dense Wireless Sensor Networks. ACM Conference on Embedded Networked Sensor Systems (SenSys) (2003)
14. Zhou, G., He, T., Krishnamurthy, S., and Stankovic, J. A.: Impact of Radio Irregularity on Wireless Sensor Networks. International Conference on Mobile Systems, Applications, and Services (MobiSys) (2004)
15. Lymberopoulos, D., Lindsey, Q., and Savvides, A.: An Empirical Analysis of Radio Signal Strength Variability in IEEE 802.15.4 Networks using Monopole Antennas. European Workshop on Sensor Networks (EWSN) (2006)
16. CC2420 Data sheet. http://www.chipcon.com/files/CC2420_Data_Sheet_1_3.pdf.
17. MoteIV, Tmote-Sky-Datasheet, http://www.moteiv.com/products/docs/tmote-sky-datasheet.pdf.
18. Joseph, C. J.: *Practical Antenna Handbook*. 4th Ed., McGraw Hill (2001)
19. Taguchi, M., Yamashita, K., Tanaka, K., and Tanaka, T.: Analysis of coil-loaded thin-wire antenna. IEEE International Symposium on Antennas and Propagation (1989)
20. Srinivasan, K., and Levis, P.: RSSI is Under Appreciated. 3rd Workshop on Embedded Networked Sensors (EmNets) (2006)
21. Pacific Wireless, http://www.pacwireless.com/products/GD24_datasheet.pdf.
22. Orefice, M., and Pirinolli, P.: Dual Reflector Antenna with Narrow Broadside Beam for Omnidirectional Coverage. Electron Letters Vol. 29 (1993) 2158-2159.
23. Bergmann, J. R., and Moreira, F. J. S.: An Omnidirectional ADE Reflector Antenna. Microwave and Optical Technology Letters Vol. 40 (2004)
24. Choi, W., Kwon, S., and Lee, B.: Ceramic Chip Antenna using Meander Conductor Lines. Electronics Letters, Vol. 37, No. 15 (2001)
25. Moon, J., and Park, S.: Small Chip Antenna for 2.4/5.8-Ghz Dual ISM-Band Applications. IEEE Antennas and Wireless Propagation Letters, Vol. 2 (2003)