

REAL-TIME AUTOMATIC BEAM-TRACKING FOR NB-IOT

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Received: April 29, 2020; Revised: July 10, 2020; Accepted: July 12, 2020

Abstract

In this paper, the better performance of Narrow Band Internet of Thing (NB-IoT) system is in focus. The patch antenna having low back lobe is developed to overcome the use of monopole antenna. Also, the self-adaptive steering system for NB-IoT is developed in order to give the best mobility performance to NB-IoT system. The improved performance for the proposed system is confirmed by computer simulation and experiment in real environment both for static and dynamic cases.

Keywords: Narrow Band Internet of Things (NB-IoT), indoor coverage, mobility, Received Signal Strength Indicator (RSSI)

Introduction

Nowadays, lots of mobile communication operators have a huge interest in Internet of Things (IoT) technology in order to provide connectivity among devices utilizing Low Power Wide Area Network (LPWAN) technology. So far, Narrowband Internet of Thing (NB-IoT) being one kind of LPWAN technology has been rapidly developed (Chen *et al.*, 2017; Hoglund *et al.*, 2017; Ratasuk *et al.*, 2017). The NB-IoT based on LTE networks is currently in focus as the advantages of an improved indoor coverage, low delay-sensitivity, low cost and power consumption. The NB-IoT devices can support over 100,000 IoT devices per base station and operate in three modes: the LTE as guard-band or in-band, and the GSM carrier as standalone as its features is shown in Table 1.

The NB-IoT system investigation shown in Lauridsen *et al.* (2016); Beyene *et al.* (2017); Wan *et al.* (2017) has been used in several applications such as smart city including smart metering, smart parking, smart home, etc. These applications are in

an indoor scenario; therefore, the received signal strength is low due to building structure, or distance between devices and base station. Also, the environment alters all the time which has a direct effect to the received signal strength. Moreover, some applications need the continuous connection between NB-IoT base station and devices.

Table 1. The features of NB-IoT

Feature	NB-IoT technology support
Standard	3gpp
Modulation	QPSK and BPSK
Coverage range (theoretical values)	10-15 Km (Rural)
Data Rate	UL: 150 Kbps, DL: 100 Kbps
Topology	star
Frequency Band	Cellular band
Channel width	180 kHz
Spectrum	licensed
Duplex	Half
Mobility support	High and complex
Mobility latency	High (1.6-10 s)
Battery life	~10 years

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According to this, a stable signal strength is strongly required.

Although most of NB-IoT devices are used in fixed position, there are some NB-IoT applications used in mobility condition with the speed of 50 km/h (Moon *et al.*, 2017). Also, some applications in smart industry and smart life cases employ the devices to track or monitor some parameters such as cattle monitoring, logistic tracking, motor tracking, pet tracking, etc. (Ayoub *et al.*, 2018; Kim *et al.*, 2019). For these cases, the connection of the NB-IoT devices may be lost when the devices are moving away from the base station. However, NB-IoT is appropriate for low-speed communications. To maintain the connectivity, the devices are limited not excess 80 km/h (Thailand IoT Industry White Paper, 2019). Another one impairment is the utilization of omni-directional antenna such as monopole antenna at NB-IoT devices. This results in a weak received signal strength. According to this, the mobility of the system is limited.

So far, there have been several methods to analyze the performance of NB-IoT signal. One case study was placed in indoor environment such as smart metering to study the attenuation of signal strength due to material of structure or underground areas (Pennacchioni *et al.*, 2017). Also, the work presented in Malik *et al.* (2019) has revealed the superior benefit of outdoor usage over indoor usage. This is because there are lots of obstacles in an indoor environment. Moreover, the study of positioning performance for outdoor NB-IoT has been discussed in the work presented in Tong *et al.* (2018). Furthermore, the investigation of NB-IoT performance in different elevation levels has been studied in Khan *et al.* (2019). However, those mentioned works have been concerned only fixed position scenario. The issue of mobility effect has been left to be studied. Therefore, this paper investigates into theoretical study and also experimental study for NB-IoT both in indoor scenario and mobility in outdoor environment.

In this paper, there are two cases to be studied in this paper: i) the NB-IoT devices are static, not moving while measuring the signal strength and ii) the devices are moving while connecting to the base station. The aims of this analysis are to test indoor coverage and mobility performance. Firstly, in static case, the device positions are fixed to study the effects of distance between device and base station both in elevation and azimuth aspects. For the dynamic case, the devices randomly move away from base station. In this case, the directional antenna has to be automatically steered to the direction of base station to keep receiving the best signal strength all the time. This self-adaptive algorithm is herein proposed in this paper.

Furthermore, a microstrip patch antenna having low back lobe is developed in this paper in order to give the maximum gain at boresight direction. The performance of proposed antenna is compared with the use of conventional monopole antenna in terms of signal strength.

Methods

A: Antenna Architecture

In wireless system, antenna is one of important components converting current and voltage to electromagnetic waves. The antenna design is significant to improve system performance in so many ways. It is desirable for antennas to have a simple structure, low cost, lightweight, and conformable configuration for the ease of installation (Tamilselvan *et al.*, 2012; Lee *et al.*, 2017). So far, a microstrip patch antenna has been popular for wireless communication when attached to vehicles (Nyunt *et al.*, 2018).

Antenna design: Many researchers are currently working on the system enhancement in terms of gain and directivity for microstrip patch antennas employing different designs and materials. One of general methods to enhance gain and directivity is the use of reflector planes. Also, the impedance matching improvement to enhance the antenna efficiency has been considered using slot design and inset feed.

In this paper, a microstrip patch antenna is designed, simulated, and fabricated. The effects of the slot design, inset feed and reflector plane on the gain and directivity are evaluated. Furthermore, the air gap thickness between the microstrip patch and reflector is also investigated. In order to obtain the desired characteristics, the designed antenna including some tuning optimization are introduced. The previously designed antenna presented in Kamolklang *et al.* (2019) has been adopted in this paper. The proposed antenna is designed at 900 MHz. The antenna theory equations are used for calculating the length and width of substrate and the patch of antenna. The substrate used for the proposed antenna is FR-4 with dielectric constant of 4.3 and thickness of 1.6 mm. As a design procedure, the dielectric constant (ϵ_r), height (h) of substrate and resonant frequency (f_r) are used to calculate patch width (W_p) and patch length (L_p) with the following formula: the designed patch width antenna is determined using (1). In order to calculate the patch length, the effective dielectric constant (ϵ_{eff}) is considered as shown in (2). Then, the efficient length of patch (L_{eff}) and the length extension (ΔL) are determined as shown in (3) and

(4). Therefore, the actual length of patch is determined using (5).

$$W_p = \frac{c}{2f_0\sqrt{\frac{\epsilon_r+1}{2}}} \quad (1)$$

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} \frac{1}{\sqrt{1+12\frac{h}{W_p}}} \quad (2)$$

$$L_{eff} = \frac{c}{2f_0\sqrt{\epsilon_{eff}}} \quad (3)$$

$$\Delta L = 0.412h \frac{(\epsilon_{eff}+0.3)(\frac{W_p}{h}+0.264)}{(\epsilon_{eff}-0.258)(\frac{W_p}{h}+0.8)} \quad (4)$$

$$L_p = L_{eff} - 2\Delta L \quad (5)$$

Moreover, width and length of ground plane are calculated as shown in (6) and (7):

$$W_g = 6h + W_p \quad (6)$$

$$L_g = 6h + L_p \quad (7)$$

The proposed antenna is fed by the SMA connector. Overall dimension is 120×150 mm². From comparison results between previous and proposed antenna, although dimension of proposed patch that consists of the height and width of patch about 77×110 mm² is smaller than previous antenna, dimension of ground plane is larger. Therefore, the directivity of proposed antenna is higher than previous work. Moreover, reflector plane using ammonium material is sized of 170×150 mm². A reflector plane redirects the propagation density from back lobe to the main lobe in order to give rise to gain and directivity. Table 2 shows the summary of the simulated results for the proposed antenna.

Simulated and measured results: The configuration of proposed antenna is shown in Figure 1 and also the fabricated one is shown in Figure 2. The comparison of return loss between simulated and measured results is shown in Figure 3. The simulated one provides -24.67 dB while the

measured result provides -17.76 dB at 908 MHz. Furthermore, Figure 4(a) shows the simulated 3D radiation pattern of the proposed antenna. Its E-plane and H-plane radiation are shown in Figures 4(b) and 4(c), respectively. As we can see, the proposed antenna radiates in a particular direction.

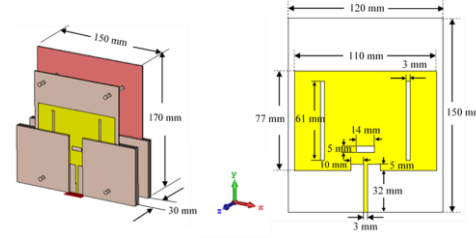


Figure 1. The simulated structure of microstrip patch antenna with blocks

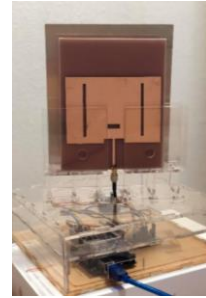


Figure 2. The Photograph of fabricated antenna

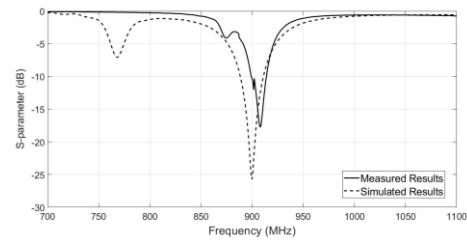


Figure 3. The return loss of microstrip patch antenna

Table 2. The summary of the simulated result for the proposed antenna

Parameters	Previous (Kamolklang <i>et al.</i> , 2019)	Proposed
Material of substrate	FR-4	
Dielectric constant	4.3	
Dimensions of substrate (mm ²)	120*150	120*150
Dimensions of patch (mm ²)	120*102	110*77
Resonant frequency (MHz)	900	900
Return Loss (S ₁₁)	-23.29	-24.67
Directivity (dBi)	4.32	7.09
Gain (dB)	4.11	2.38
Radiation efficiency (dB)	-0.2	-4.78
Total efficiency (dB)	-0.21	-5.1

Also, the back lobe is relatively small with the help of reflector plane. Table 3 shows the summary of the simulated and measured results for the proposed antenna. These results confirm the utilization of the proposed antenna for NB-IoT system. Also, it provides gain and directivity of 2.38 dB and 7.09 dBi respectively. As a result, the antenna has higher directivity but lower gain when comparing with previous work due to the directivity of antenna is defined as the ratio of radiation intensity in each direction from the antenna to the radiation intensity averages over all directions. According to gain of antenna is related to the input or accepted power of the structure. In case of the proposed antenna that is not lossless antenna, the gain is not equal to the directivity. However, this result has not affected to the use for NB-IoT system.

B: NB-IoT System Architecture

The NB-IoT system includes the NB-IoT devices, NB-IoT base station, NB-IoT cloud, platforms and application server as shown in Figure 5. Before NB-IoT devices receive or transmit data, the devices must connect to base station, NB-IoT cloud and platform. In this paper, AIS NB-IoT devices are employed to analyze the system performance. The DEVIO NB-Shield I module is used with Quectel BC95 and LTE Cat.NB1 (NB-IoT) network technology operating at band 8 (900 MHz). The protocol stacks are UDP and CoAP which have eSIM on-board and Serial communication (UART). The devices can support over 100,000 IoT devices per base station as shown in Figure 6.

Experiment Setup

The aim of this paper is to enhance performance of NB-IoT system using automatic beam-steering antenna. The system performance is indicated by the received signal strength indicator (RSSI). The RSSI is a measurement that indicates the power level of received radio signal in dBm. In addition, the proposed microstrip patch antenna cooperating with a stepper motor used for steering the antenna is employed. In the experiments, the RSSI from the proposed antenna are compared with the RSSI from a conventional monopole antenna. The measurements are classified into 2 scenarios: static and dynamic. The static measurement is that the NB-IoT devices are not moving while dynamic measurement is that the devices are moving while

the devices and base station are connected all the time.

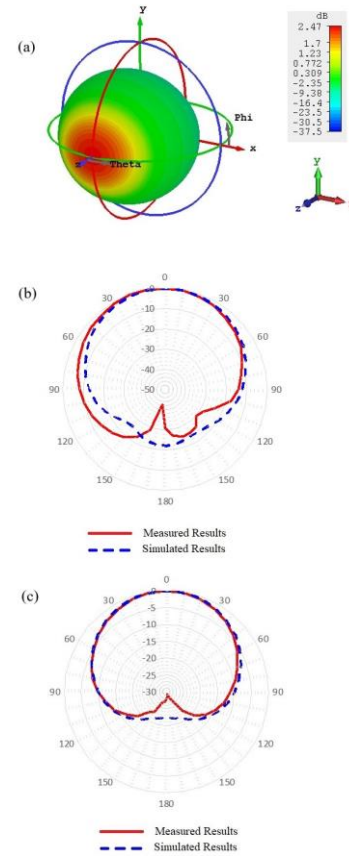


Figure 4 The radiation pattern of microstrip patch antenna under: (a) The simulate 3D radiation pattern. (b) E-plane pattern. (c) H-plane pattern

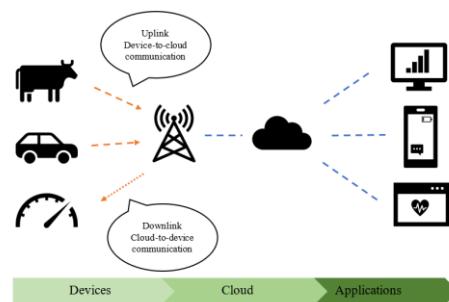


Figure 5 The NB-IoT system

Table 3. The summary of the simulated and measured results for the proposed antenna

The proposed antenna	Resonance frequency (MHz)	Return loss (S_{11}) (dB)	Bandwidth (MHz)
Simulated results	900	-24.67	23
Measured results	908	-17.76	16

1. In static measurement, the experiments are classified into two aspects including elevation distance and azimuth distance. For the first case, the experiment set is located in Sirindhorn Witsawaphat building, Suranaree university of technology (SUT), Thailand as shown in Figure 7(a). There are different five elevation levels. Figure 7(b) illustrates the layout of the indoor measurement points where NB-IoT devices are installed in the laboratory room where is 400 m apart from base station. The RSSI measured from each floor is compared with the others in off-line processing.

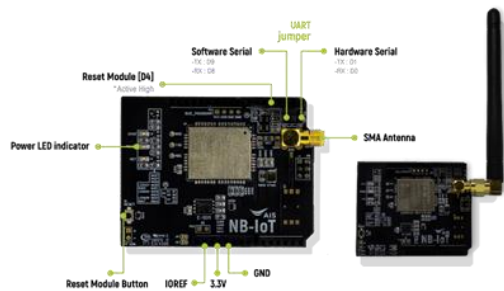


Figure 6 The DEVIO NB-Shield I and NB-IoT module with monopole antenna

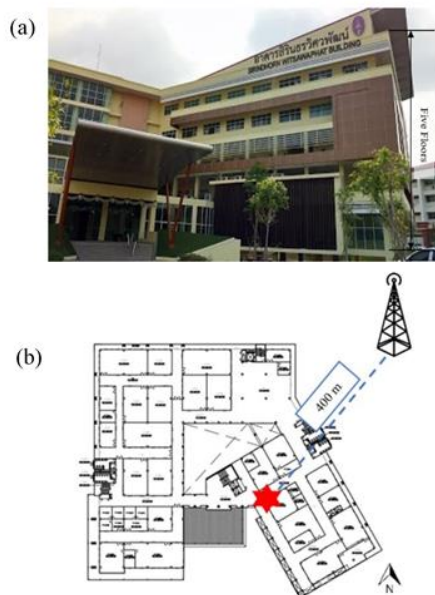


Figure 7 Location of Static measurement. under: (a) Sirindhorn Witsawaphat building, Suranaree university of technology (SUT), Thailand. (b) The layout of the indoor measurement points where NB-IoT devices was installed far away from base station about 400 m

For the second case, the measured RSSI depends on the distance between devices and base station. The measurement takes place at the road around the campus. There are five different distances between device and base station: 600, 1,000, 1,500, 2,000, and 2,500 m. The NB-IoT devices are installed in some utilized rooms such as common classroom, research building, sport center farm and dormitory, etc. The performance of two antennas is compared: conventional monopole antenna and proposed patch antenna as shown in Figure 8. For the first case, the experiment starts from using monopole antenna to measure RSSI. The measured RSSI is sent to cloud and shown in the platform all the time. In another case, the proposed antenna is employed to measure RSSI, starting to steer the proposed antenna in one cycle (from 0 to 360 degrees). In every 10 degrees, the RSSI values are stored including the steered angle and then sent to cloud. After all the records are done, all RSSI values are compared using algorithm as shown in Figure 9 which is the comparison of RSSI values. If the value is higher than the previous value, the value of interest will be recorded to the maximum signal strength and the degree of that value is stored to the direction of maximum signal strength. Then, both values are sent to the platform to present to users. After completely comparing all RSSI, the antenna is able to be steered to the best direction achieving maximum received signal strength. However, the environment might change affecting to the previous

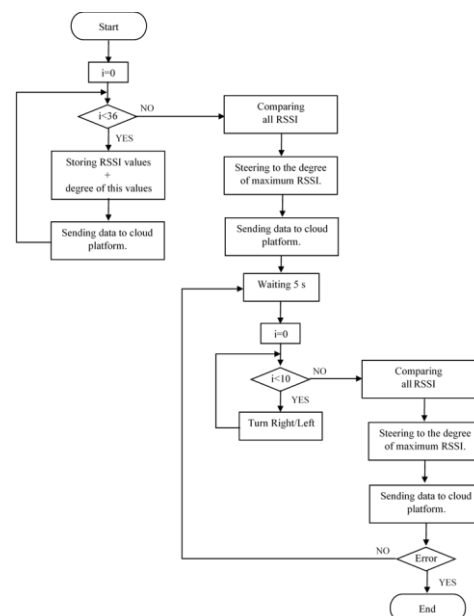


Figure 8 The flowchart of algorithm used to measure the best direction of maximum signal strength in static and dynamic measurements

measured maximum RSSI. Therefore, the proposed antenna must steer to find new best direction again and keep doing this measurement every hour.

2. In dynamic measurement, the aim of this measurement is to investigate the mobility of NB-IoT devices that can connect base station all the time using the proposed antenna. The steering process to find maximum RSSI is automatic. This measurement takes place at the road around the campus. There are three routes: route 1 (distance of 3.9 Km), route 2 (distance of 3.7 Km), and route 3 (distance of 3.4 Km) as shown in Figure 10. Each route is situated in different environment e.g. outdoor, many buildings, dense forest, etc. In addition, there are three measured cases for each route. Firstly, the received signal strength is measured using monopole antenna. Secondly, the monopole antenna is replaced by the proposed antenna. For this case, the antenna is continually steered to find the maximum RSSI. Furthermore, there are three speed of vehicle built in NB-IoT

devices that are 60, 80, and 100 km/h to test the impact of vehicle speed on the RSSI.

In the dynamic experiment, there are three cases including three algorithms to analyze the performance of NB-IoT system. For the first case, the experiment starts from using monopole antenna to measure RSSI which is sent to cloud and platform all the time similar to the first case of static measurement. On the other hand, the proposed antenna used to measure the RSSI is steered in one cycle starting from 0 to 360 degrees and the RSSI is measured in every 10-degree. Then, all RSSI values are compared using comparing algorithm and steered to the best direction of received signal strength. After that, while the device is moving, the steering process stops but the RSSI is continually measured. In the last case of measurement, while the devices are moving, the antenna automatically finds the best direction for the maximum signal strength all the time. The RSSI is measured in every 10-degree and compared with others. Then, the antenna is steered to the best direction giving the maximum RSSI. Then, the system is idle for 5 sec to continue steering. Next, the antenna is rotated to the right side for 10 degrees and RSSI values are measured every 1-degree including the left side. These values are stored and compared to the others for finding the maximum RSSI. Then this value is sent to cloud and shown in platform for users. In addition, the system waits for 5 sec again and continues steering to the right and left. These algorithms are used to measure for three speed of the vehicle on three routes around the campus. According to this, the proposed antenna will be steered to the best direction of maximum signal strength in every 5 sec.

According to the survey, there are two eNBs that can support NB-IoT network nearby the SUT campus as shown in Figure 10, and these measurements does not consider the interference arising from non-NB-IoT cells in the network during the measurements.

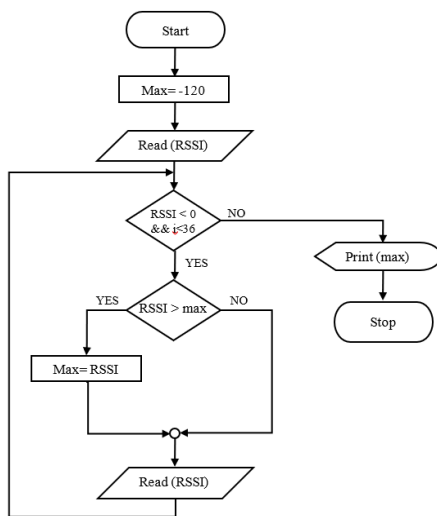


Figure 9 The flowchart of algorithm used to compare the received signal strength



Figure 10 The map of the campus

Results and Discussion

This section presents the result of signal strength analysis of NB-IoT in which the experiments are in static and dynamic scenarios.

A: Static Measurement

Firstly, static measurement evaluates the indoor coverage of NB-IoT system at the SUT campus, the observation point inside the building which is at 400 m apart from the base station is deployed at different elevation levels. In addition, the measurement evaluates the coverage performance

of NB-IoT system at different distances away from base station. The aim of both of experiments are to investigate the effect of height and distance between the devices and base station on the system sensitivity.

Table 4 presents the average RSSI measured at different elevation levels for a duration of 1 h at the observation point. The columns of Signal Strength in Table 4 are based on the NB-IoT received signal strength (RSSI) reference values as shown in Table 5 and presented in Teltonika (2019). In terms of elevation levels, the RSSI values using monopole antenna are about -60 to -67.76 dBm. These values show that NB-IoT system provides a good coverage in indoor environment for all elevation levels. On the other hand, the RSSI values using the proposed antenna are about -57.15 to -63.12 dBm in the direction of about 280 degree. When comparing the measured RSSI values from different five floors, the received RSSI employing the proposed antenna provides higher signal strength over the use of monopole antenna. Furthermore, NB-IoT devices located on the higher elevation levels receives higher RSSI over lower elevation levels. In conclusion, the average RSSI can be improved, approximately 3.8 dB, using the proposed antenna.

Table 6 presents the average received RSSI for different distances away from base station for a duration of an hour. In terms of different distance, the RSSI values using monopole antenna are about -51 to -78 dBm. On the other hand, the RSSI values, when the proposed antenna is employed, are about -51 to -75 dBm. These values present that the NB-IoT system provides an excellent and a good coverage performance for different distances. Furthermore, the directions of the proposed antenna are different in each location. This is because the system automatically turns to the best direction providing the maximum RSSI. When the proposed antenna is employed, the average RSSI values at distances of 600 and 1,000 m located at the academy building and sport center are -64.92 and -65.58 dBm corresponding to the direction of 190 and 10 degrees, respectively. These values provide a good coverage performance in the direction of base station. Moreover, the average RSSI values at distances of 1,500 and 2,000 m located at the research building and university hospital are both of -51 dBm in the direction of 10 degree providing an excellent coverage performance in the direction of base station. In addition, at distance of 2,500 m away from base station located at dormitory, the

Table 4. The results of RSSI for difference elevation levels

Elevation levels	Measurement points at 400 m from base station				
	Monopole Antenna		Proposed Antenna		
	Avg. RSSI (dBm)	Signal strength	Avg. RSSI (dBm)	Direction (degree)	Signal strength
1 st floor	-65.19	Good	-61.83	280	Good
2 nd floor	-67.76	Good	-63.05	290	Good
3 rd floor	-67.54	Good	-63.12	290	Good
4 th floor	-63.15	Good	-59.51	280	Excellent
5 th floor	-59.99	Excellent	-57.15	270	Excellent

Table 5. The NB-IoT received signal strength (RSSI) reference values (Teltonika, 2019)

LTE	NB-IoT	Signal Strength
> -65 dBm	> -60 dBm	Excellent
-65 to -75 dBm	-60 to -80 dBm	Good
-75 to -85 dBm	-80 to -95 dBm	Fair
-85 to -95 dBm	-95 to -110 dBm	Poor
< -95 dBm	< -110 dBm	Disconnect

Table 6. The results of RSSI for difference distance away from base station

Distance far away from base station	Measurement points at real environment				
	Monopole Antenna		Proposed Antenna		
	Avg. RSSI (dBm)	Signal strength	Avg. RSSI (dBm)	Direction (degree)	Signal strength
600 m	-69.32	Good	-64.92	190	Good
1,000 m	-70	Good	-65.58	10	Good
1,500 m	-51.59	Excellent	-51	10	Excellent
2,000 m	-51	Excellent	-51	10	Excellent
2,500 m	-78.13	Good	-75.24	190	Good

average RSSI values is about -75.24 dBm in the direction of 190 degree providing a good coverage performance.

Due to the building structure and dense forest, the signal strength is lower than other locations. When comparing RSSI values using monopole and the proposed antenna for each distance, the received RSSI employing the proposed antenna is higher than the use of monopole antenna for all cases.

From the above results, the device employing the proposed antenna can automatically steer its beam to find the best direction providing maximum signal strength. However, the different of signal strength is observed at different elevation levels and different distances due to lots of factors such as construction material, building structure, direction of antenna beam, distance between devices and base station, etc.

B: Dynamic Measurement

Dynamic measurement is the test that the NB-IoT device is moving while performing the measurement. This measurement is to evaluate the received signal strength at different three vehicle's speeds on three different routes around the campus with commercial base station and NB-IoT devices. The RSSI measurement is performed using monopole antenna comparing with the proposed antenna.

Figure 10 illustrates the measurement in terms of RSSI for three cases as follows:

- 1) using monopole antenna. There is no antenna steering for this case (solid line)
- 2) using proposed antenna when steering the antenna only one cycle to find maximum signal strength (dotted line)
- 3) using the proposed antenna when steering for one cycle to find the best direction of maximum signal strength and then continually steering to find the best new ones all the time while the device is moving (dash-dotted line).

Figure 11(a) presents the measurement on the three routes with the vehicle speed of 60 km/h. Firstly, the monopole antenna is used to measure the RSSI throughout the experiment. The average RSSI values for this case are -72.9, -68.88, and -77 dBm with respect to three routes. Afterwards, the monopole antenna is replaced by the proposed antenna. The received RSSI are about -57, -63, and -57 dBm before the device moves. Then, when the device starts moving, the device automatically find the best direction all the time along the route. Therefore, the graph of three routes with respect to the speed of 60 km/h shows that using proposed antenna provides a higher RSSI comparing to the use of monopole antenna.

The results of measurement on the three routes when the vehicle is moving with the speed of 80 km/h are shown in Figure 11(b). This measurement takes approximately 120 sec. The average RSSI values employing monopole antenna throughout experiment for three routes are -65.66, -77.46, and -67.76 dBm. When using the proposed antenna before the device moves, the maximum signal strength values are about -57, -69, and -57 dBm, respectively. After moving the vehicle, the device automatically finds the best direction of maximum signal strength all the time along the route. As a result, the performance of employing the proposed antenna overcomes the use of conventional monopole antenna.

The measurements of speed of 100 km/h that take 100 sec to measure are shown in Figure 11(c) for the three routes. The average RSSI values of measurement using monopole antenna throughout experiment for three routes are -73, -73, and -67.1 dBm. The maximum signal strength values are

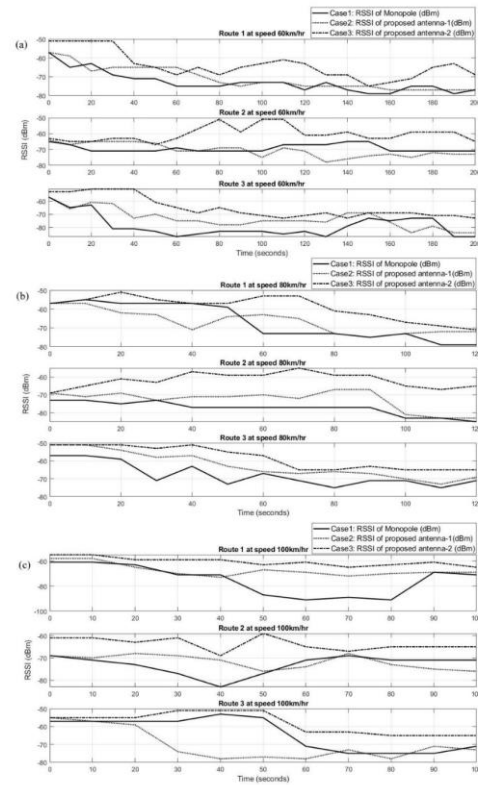


Figure 11. The result of dynamic measurement in terms of received signal strength under:
(a) The measurement on the three routes of 60 km/h in term of RSSI. (b) The measurement on the three routes of 80 km/h in term of RSSI. (c) The measurement on the three routes of 100 km/h in term of RSSI

about -61, -69, and -57 dBm, respectively when the device using the proposed antenna is not moving. Then, the vehicle starts to move, the device automatically finds the best direction of maximum signal strength. Therefore, the graph of three routes with the speed of 100 km/h shows that the average RSSI of using proposed antenna are higher than the average RSSI when using monopole antenna.

Moreover, comparing the results obtained from the three speed of vehicle reveals that the mobility of NB-IoT system is suitable for low speed communication such as 80 km/h or lower. From the overall results, the NB-IoT devices employing the proposed antenna can automatically steer its beam to find the best direction providing maximum signal strength while the device is moving. In addition, the NB-IoT system supports mobility condition.

Conclusions

This paper has presented the analysis of NB-IoT system performances which are the coverage and mobility performances. The patch antenna has been designed having low back lobe to achieve directive gain at the front. Also, the designed NB-IoT has been designed to automatically find the best direction for the case that the system is employed in the low speed vehicle. From the simulation and measurement results, all cases have confirmed that the proposed system overcomes the use of monopole antenna as the proposed one can automatically adapt its beam to the best direction having the maximum signal strength all the time.

Acknowledgements

This work was supported by Suranaree University of Technology, Thailand.

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