High Deployability of IEEE 802.15.4k DSSS Systems in Interference Dominated Bands

Yasutaka Tada Yosuke Sato Shuzo Kato
Research Institute of Electrical Communications, Tohoku University
Sendai, Japan
yasutaka.tada@riec.tohoku.ac.jp

***Abstract*— This paper clarifies that 802.15.4k direct sequence spread spectrum (DSSS) systems are suitable for wide sensor networks with star topology. According to our evaluation, the robustness of 802.15.4k DSSS systems under the co-channel interference (CCI) is 60 dB stronger than that of 802.15.4g due to its DSSS (1023 spreading factor) and FEC. In addition, this paper clarifies the area where 802.15.4g cannot survive under 802.15.4k CCI and vice versa. The latter area is 50 times larger the former. Furthermore, we show that directive base station antennas can reduce the interference impacted area by 80% compared to omnidirectional base station antennas.**

Keywords—LECIM, IEEE802.15.4k, IEEE802.15.4g

I. INTRODUCTION

One of the latest standardization projects of 802.15 Working Group is P802.15.4k Low Energy Critical Infrastructure Monitoring (LECIM) Networks [1]. The standard is an amendment to the 802.15.4 standard to enable wide area sensor networks. Communication systems based the standard combine very low power consumption with long communication ranges with order of kilometers. There are two PHY layer options in the standard, the first one is based on direct sequence spread spectrum (DSSS PHY), the second one is based on frequency shift keying (FSK PHY). The focus of this paper is the DSSS PHY of 802.15.4k with following three reasons: (i) DSSS PHY deploys direct sequence spreading and this process gain is mandatory for longer transmission range – if 1023 spreading code length is used, the system can enjoy 30 dB processing gain. (ii) DSSS PHY standard mandates the use of strong FEC (rate 1/2 convolutional encoding with a constraint length of 7) while FSK PHY regulates it as an option and there has been none of FSK PHYs deploying FEC in market as of today. This may generate about 5 dB advantage of DSSS PHY against FSK PHY in AWGN channels and more than 8 dB difference in interference dominated environments, (iii) DSSS PHY regulate the use of PSK modulation which can be demodulated coherently while FSK PHY can't be demodulated coherently. This creates another 3 dB advantage to DSSS PHY. Thus, the total advantage of DSSS PHY against FSK PHY is more than 40 dB practically (with a spreading code length of 1023) and this is why this paper selected DSSS PHY as a targeted system

Although there will be a lot of different sources of interferences in 900 MHz bands, this paper focuses on how 802.15.4.k DSSS systems can survive against interference from another standard of the 802.15 family, namely 802.15.4g Smart Utility Networks (SUN). This is important assumption since we need to identify the interferer to analyze and in Japan, 802.15.4g is supposed to be a major interferer to IEEE802.15.4k systems. Both systems operate in unlicensed bands, between 920 and 928 MHz in Japan [2]. Our analyses assume 802.15.4k systems operating in the presence of IEEE 802.15.4g co-channel interference (CCI) as well as 802.15.4g systems experiencing 802.15.4k CCI.

For the interference analysis, we consider two parameters that affect the performance of both systems under CCI. The first is a relative location of an 802.15.4g sub-channel with respect to an 802.15.4k ~~channels~~. The second one is minimum desired signal to undesired signal ratios (D/U) of each system in AWGN environments. By using these two parameters, we will deduct "Installation inhibited area" in which the interferer destroys communications channels in each system. Further, the "installation inhibited area" is re-evaluated with a directive base station antenna for 802.15.4k DSSS systems showing how the "inhibited area" will be reduced by adopting high gain base station antennas instead of Omni antennas.

The outline of the paper is as follows. In the next section, we introduce 802.15.4k and 802.15.4g systems and illustrate their mutual interference. Section III provides the permissible D/U ratios of both systems under CCI. In Section IV, we show the Installation inhibited areas of 802.15.4k and 802.15.4g systems. Section V elucidates "installation inhibited areas" reduction by adoption of directional BS antennas. Conclusions are drawn in Section VI.

II. SYSTEM MODELS AND CO-CHANNEL INTERFERENCE

As mentioned in the introduction, we focus on the DSSS PHY of the 802.15.4k standard. It can operate in many unlicensed bands throughout the world including 920-928 MHz band in Japan with up to 1 MHz bandwidth as shown in Table I. Here, one sub-channel is defined as a channel with a bandwidth of 200 kHz and the maximum bandwidth is 1 MHz by bonding 5 sub-channels. The other system examined here, the 802.15.4g system, has a smaller bandwidth of 200 KHz or 400 KHz. Its details are shown in Table I as well.

The channelization of these standards enables 802.15.4g with a bandwidth of 200 KHz to interfere with 802.15.4k systems in one of its 5 sub-channels. In Figure 1, we illustrate the spectra of 802.15.4g operating at 50 kbps (in 200 kHz) and 802.15.4k systems operating in 1 MHz bandwidth, where a D/U ratio is 0 dB. Here, D/U ratio is defined by (1), as a ratio of transmission powers of desired and undesired signals.

$$\mathrm{DUR} = \frac{\text{Transmit Power}_{\text{desired signal}}}{\text{Transmit Power}_{\text{undesired signal}}} \tag{1}$$

Sub-channel 3 of 802.15.4g is located at the exact center of the 802.15.4k signals with a bandwidth of 1 MHz.

In Figure 2, there are three channels of 802.15.4g systems with a bandwidth of 400 kHz, each interfering with 802.15.4k

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systems operating with 1MHz bandwidth. In this case, sub-channel 2 of 802.15.4g systems is located at the exact center of the 802.15.4k signals.

Fig. 3 shows a block diagram of the interference simulation. "Gain" enables us to set the transmit power of 802.15.4k and set expected D/U ratios. "Freq. offset" is used to set the location of 802.15.4g channels relative to the 802.15.4k bandwidth. Using this system, we evaluate BER performance of each system, and derive the minimum D/U ratios to meet the target PER (Packet error rate).

Fig. 4 compares simulated and theoretical BER performance of 802.15.4k and 802.15.4g systems. The theoretical performance is evaluated by (2) and (3) as follows [7].

Equation (2) provides bit error probability of BPSK modulation with FEC (R=1/2, k=7, Soft decision), and equation (3) yields that of Gaussian filtered FSK (GFSK) modulation. As indicated by the simulated and theoretical performance, the 802.15.4k and 802.15.4g simulation systems work correctly. In next section, we use the simulation system to evaluate the interference of both systems.

$$P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{R \cdot k \cdot \frac{E_b}{N_0}}\right)$$

$$= \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{7}{2} \cdot \frac{E_b}{N_0}}\right) \qquad (2)$$

$$P_b = \frac{1}{2}\exp\left(-\frac{E_b}{2N_0}\right) \qquad (3)$$

TABLE I. MAJOR SYSTEM PARAMETERS FOR 802.15.4K AND 802.15.4G

Parameter	***802.15.4k***	***802.15.4g***
Bandwidth	200 kHz to 1 MHz	200 / 400 kHz
Chip / Bit Rate	Up to 800 kcps	50/100 kbps
Modulation	BPSK, OQPSK	GFSK
Filter	Roll off factor = 0.2	Gaussian filter BT=0.5
FEC	Convolutional coding Rate=1/2, K=7	No *
Spreading factor	16-32,768	No
Information bits per packet	32 octets	32 octets
Target PER	0.01	0.01

* -Optional (Convolutional coding Rate=1/2, K=4)

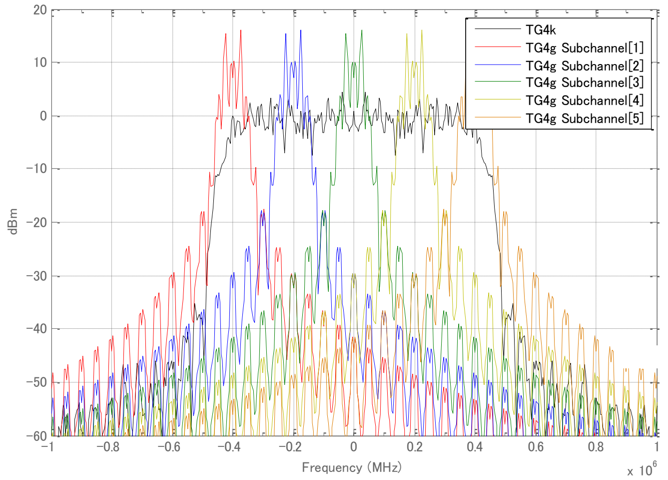

Fig. 1 Interference example of 802.15.4g signals with a bandwidth of 200 kHz and 802.15.4k signals with a bandwidth of 1 MHz

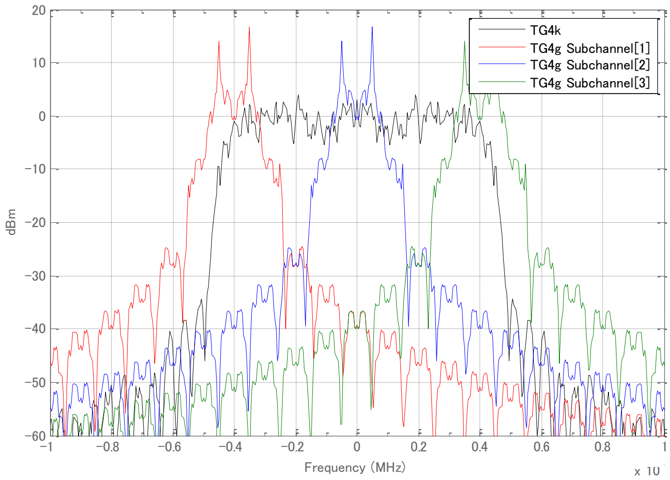

Fig. 2. Interference example of 802.15.4g signals with a bandwidth of 400 kHz and 802.15.4k signals with a bandwidth of 1 MHz

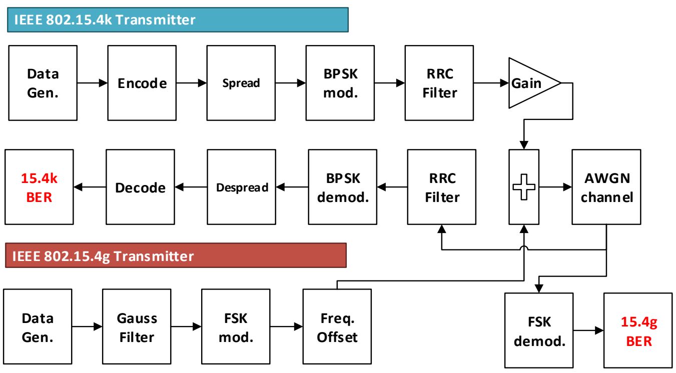

Fig. 3 A block diagram of the performance evaluation under CCI

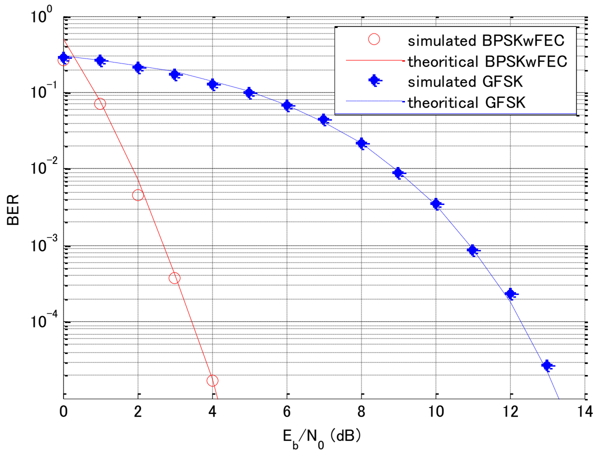

Fig. 4 BER performance comparison of 802.15.4k(BPSKwFEC) and 802.15.4g(GFSK) systems (theory and simulation)

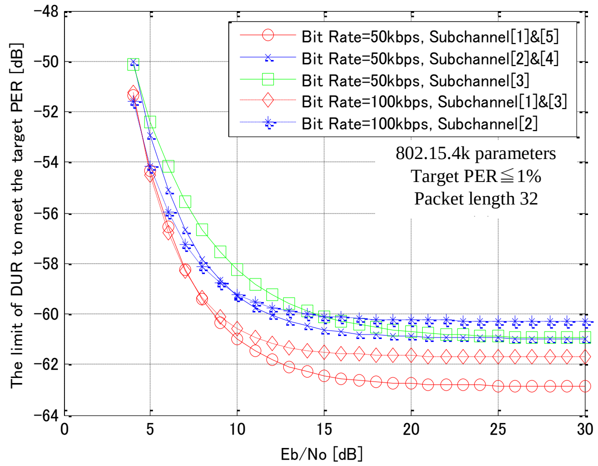

Fig. 5 Minimum D/U ratio vs. Eb/N0 of 802.15.4g under CCI from 802.15.4k with a 1023 spreading factor

III. The Minimum D/U Ratios of Both Systems

A. 802.15.4k DSSS system performance

We evaluate first the minimum D/U ratios of 802.15.4k systems with a spreading factor of 1023 to meet the target PER under CCI of 802.15.4g operating at different data rates (bandwidths). Fig. 5 plots the minimum D/U ratios versus Eb/N0 to meet the target PER with parameters of bandwidth and relative channel locations of 802.15.4g signals against 802.15.4k signals. For 802.15.4k systems, the target bit error rate (BER) is calculated as 3.9×10^{-5} to transmit 32-byte packets with less than 1 % packet error rate.

The minimum D/U ratio of 802.15.4k (with 1023 spreading factor) under CCI from 802.15.4g tends to be less than -60 dB for Eb/N0 values higher than 15 dB, regardless of 802.15.4g bandwidths and sub-channels. In the case of narrower bandwidth interference, 200 kHz bandwidth 802.15.4g interference, the inteference on the center of the 802.15.4k channel generates the largest degradation in the low Eb/N0 region. In the case of 400 kHz bandwidth interference, both non-centered 802.15.4g signals (sub-channels 1 and 3) give less degradation due to the drop in interference power created by passage through a 802.15.4k receiver filter.

B. 802.15.4g GFSK system performance

Fig. 6 plots Eb/N0 versus minimum D/U ratio of 802.15.4g under CCI from 802.15.4k with spreading factor of 1023. The target BER is the same value as the previous one. The minimum D/U ratios of 802.15.4g show up to 4 dB difference depending on the bandwidths and relative interfering channels (sub-channels) in the high Eb/N0 region.

From these two figures, 802.15.4k DSSS systems show much stronger interference-resistant performance than 802.15.4g FSK systems such as a -60 dB D/U ratio requirement for DSSS systems and 2-4 dB D/U ratio requirement for 802.15.4g FSK systems to realize a PER of 1%. This huge difference is due to the DSSS processing gain & de-spreading of the interference and FEC coding gain.

Using the performance results obtained above, the next section we will estimate the range / area in which 802.15.4g systems can disturb 802.15.4k communications and vice versa.

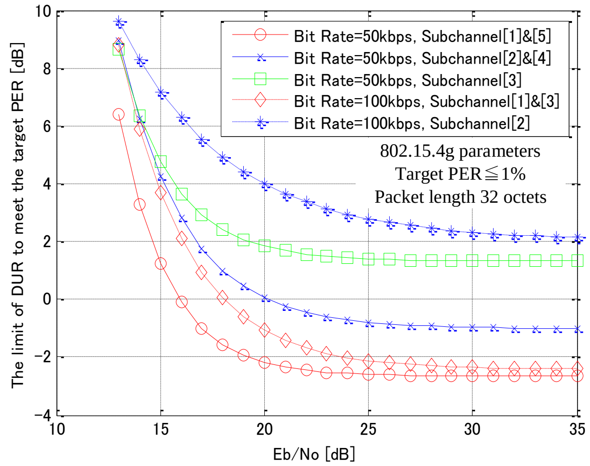

Fig. 6 Minimum D/U ratio vs. Eb/N0 of 802.15.4k (with spreading factor of 1023) under CCI from 802.15.4g operating with different bandwidths and sub-channels

IV. Instalaltion Inhibited Areas of 802.15.4k and 802.15.4g Systems

In this section, we evaluate "installation inhibited area" of 802.15.4g and 802.15.4k systems. We assume two things. First is that both systems operate as one-to-one communications. Second is that the 802.15.4k system uses a spreading factor of 1023. Simulation parameters are shown in Table II. Fig. 7 shows the "installation inhibited area" from the Sensor Node of 802.15.4g to the BS or Sensor Node (SN) of 802.15.4k as an interferer. Fig. 8 shows the "installation inhibited area" from the SN of 802.15.4k to the BS or SN of 802.15.4g as an interferer.

In this simulation environment, the receiver location is shown by (x, y) = (0, 0) meters. The transmitter is located at (x, y) = (0, d) meters. "d" means the communication range in Table II. We assume that if the D/U ratio is less than the permissible D/U ratios (defined in section III), communication is successful.

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Areas inside the contours in each figure indicate locations where the interferer transmitter can disturb communication, namely, "installation inhibited area".

Figures 7 and 8 show that the 802.15.4g system is weaker against the interference. The "installation inhibited area" is 210 meters range, 105 percent of the communication distance. Fig. 8 indicates that spreading can greatly suppress 802.15.4g interference on 802.15.4k systems. As a result, "installation inhibited area" is a maximum of 100 meters, 2 percent of the communication distance. Finally, we conclude 802.15.4k systems have high tolerance to the interference due to spreading and FEC. The next section clarifies how the directive antenna reduces the interference compared with the omnidirectional one.

TABLE II. SIMULATION PARAMETERS

Parameter	***802.15.4k***		***802.15.4g***	
Center frequency	922.4 MHz		922.4 MHz	
802.15.4k Bandwidth	1 MHz		200 kHz	
EIRP	16dBm		16dBm	
Transmit power	13dBm		13dBm	
Base station antenna gain	3dBi		3dBi	
Base station antenna height	Urban	30m	Urban	30m
	Suburban	10m	Suburban	10m
	Rural	10m	Rural	10m
Sensor node antenna gain	3dBi		3dBi	
Sensor node antenna height	1m		1m	
Spreading factor	1023		No	
Communication range	5000m		200m	
Path loss model	Extended-Hata model[4]		Extended-Hata model[4]	

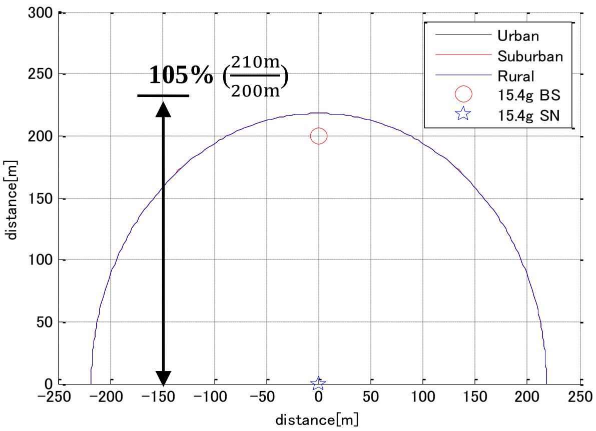

Fig. 7 "installation inhibited area" of 802.15.4g SN with interference from 802.15.4k SN or BS to victim 802.15.4g SN

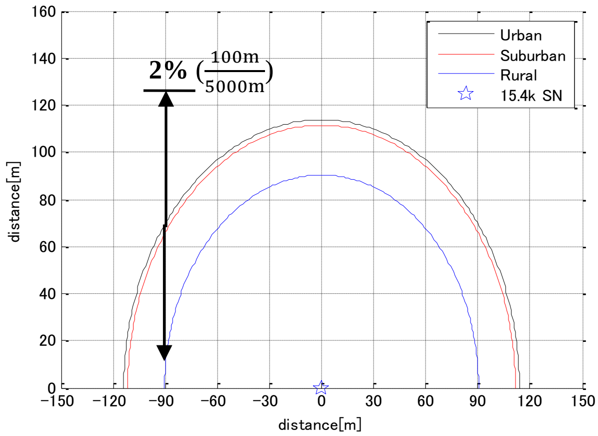

Fig. 8 "installation inhibited area" of 802.15.4k SN with interference from 802.15.4g BS or SN

V. INSTALALTION INHIBITED AREA REDUCTION BY DIRECTIONAL BS ANTENNA

In this section, we investigate the reduction of the interference from 802.15.4k to 802.15.4g and the one from 802.15.4g to 802.15.4k when 802.15.4k BS employs a directional antenna. The BS antenna gain pattern of the 802.15.4k system is based on a 4-element linear beam forming antenna as shown in Figure 9. We use this antenna with a gain of 10dBi and an omnidirectional antenna with a gain of 3dBi. Simulation parameters are the same as in Table II, except the transmit power for directive BS antenna is set the total transmit eirp does not exceed 16 dBm as regulated in Japan. Fig. 10 shows the "installation inhibited area"–of 802.15.4k under 802.15.4g interference for the two types of antennas. The "installation inhibited area" is evaluated by formulas (4) and (5) as follows. Formula (4) yields a continuous value, while the formula (5) yields a discrete value.

$$S = \frac{1}{2}\int_0^{2\pi} r^2 d\,\theta \qquad (4)$$

$$= \frac{\pi}{N}\sum_{k=0}^{N-1} {r_k}^2 \qquad (5)$$

With the omnidirectional antenna, the area is 0.04 km^2 but with the directive antenna it is 0.01 km^2. The directional antenna reduces the area by 75 percent relative to the omnidirectional antenna. Fig. 11 shows the "installation inhibited area" of 802.15.4g under 802.15.4k interference. The omnidirectional antenna offers an area of 0.15 km^2 while the directional antenna reduces this to 0.03 km^2. The directional antenna reduces the area by 80 percent relative to the omnidirectional antenna. Therefore, BS directional antenna can well suppress the interference and increase spectrum efficiency.

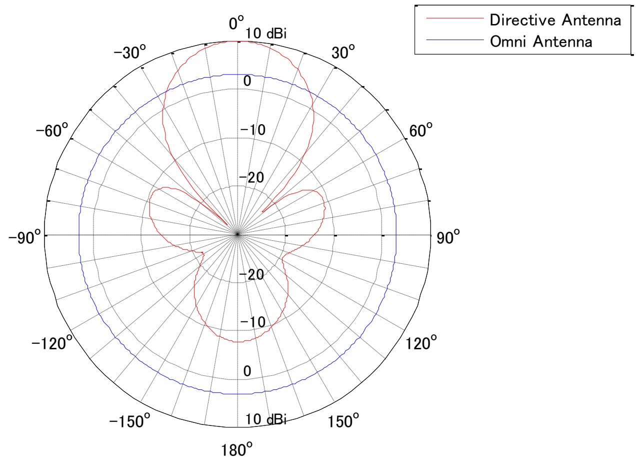

Fig. 9 802.15.4k BS antenna directivity pattern and omnidirectional antenna pattern

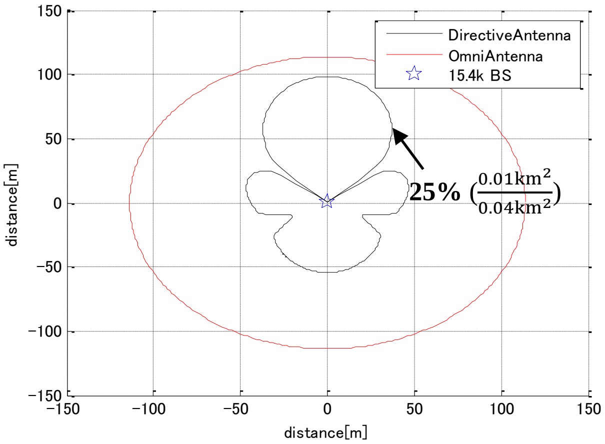

Fig. 10 The reduction of "installation inhibited area" by using directional antenna: interference from 802.15.4g

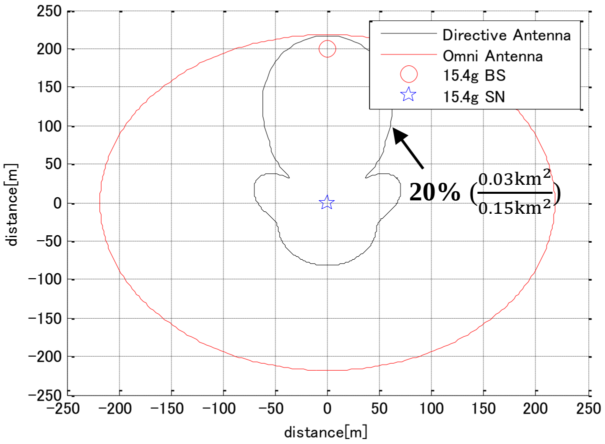

Fig. 11 802.15 4g "installation inhibited area" reduction by using directional BS antenna: interference from 802.15.4k BS

VI. CONCLUSIONS

In this work, we have investigated the performance of 802.15.4k and 802.15.4g systems under CCI. We confirmed that 802.15.4k DSSS Systems under CCI is 60 dB more robust than 802.15.4g. We have clarified "installation inhibited area" in which 802.15.4g or 802.15.4k cannot survive under CCI of the other system. The "installation inhibited area" of 802.15.4k turned out to be 50 times smaller than that of 802.15.4g. Furthermore, we have showed deployment of directional antennas can reduce the "installation inhibited area" (from other system) by 80 percent and by 75 percent (to other system). Therefore, 802.15.4k DSSS PHY and directional 802.15.4k BS antennas can reduce the interference much smaller and increase the spectrum efficiency a lot. 802.15.4k DSSS systems are suitable for wide area sensor networks with star topology and are much more widely deployable in interference dominated ISM bands than 802.15.4g systems with higher spectrum efficiency.

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