Electromagnetic Compatibility Issues in 400-MHz-Band Wireless Medical Telemetry Systems and Their Management Using Simplified Methods for Safe Operation

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Abstract

Wireless medical telemetry systems (WMTSs) are typical radio communication–based medical devices that monitor various biological parameters, such as electrocardiograms and respiration rates. In Japan, the assigned frequency band for WMTSs is 400 MHz. However, the issues accounting for poor reception in WMTS constitute major concerns. For example, the 400 MHz frequency band is also shared by other radio communication systems. Further, the intermodulation (IM) effect significantly reduces reception in WMTS. Additionally, the electromagnetic noises generated from electrical devices, such as light-emitting diode lamps and security cameras, can exceed the 400 MHz frequency band as these devices employ the switched-mode power supply and/or central processing unit and radiate wideband emissions. In this study, we analyzed the effects of the electromagnetic interferences caused by other radio communication systems, the IM effect, and the noises generated from electrical devices on WMTS and discussed their management. Moreover, we proposed and evaluated simplified and facile methods for evaluating the electromagnetic environment.

Introduction

A wireless medical telemetry system (WMTS) is a typical radio communication–based medical device that monitors the various biological parameters, such as electrocardiogram (ECG) and respiration rates, of patients. However, its safe introduction and operation is disputable because of several radio communications–related issues [1]. For example, the 400 MHz frequency band, which is the assigned band for WMTS in Japan, is shared by and used for other radio communication systems. For instance, hospitals are widely equipped with 400 MHz-operated fetal monitors and systems that detect wandering patients. However, some of these devices utilize the same frequency band as WMTS (400 MHz). Therefore, these communication devices may cause electromagnetic interference (EMI) [2]. The intermodulation (IM) effect generated by multiple transmitters generates undesired emissions, causing poor reception for WMTS channels. Another recent issue is the electromagnetic noise generated by electrical devices. Switched-mode power supplies are often installed in recent light-emitting diode (LED) lamps to facilitate low power consumption and save energy. Additionally, central processing units (CPUs), which are installed in most electrical devices, such as personal computers, security cameras, and nurse call systems, are widely used to control devices. These devices may radiate wideband emission and can exceed the 400 MHz frequency band in some instances [3]. LED lamps, which have become widespread, have been introduced in many modern hospitals, following the recently increasing interest in affordable and clean energy (a sustainable development goal (SDG)). The high-speed switching operation of the switched-mode power supply installed in LED lamps generates electromagnetic noise [4]. In actual settings, electromagnetic noise can cause EMI in various radio communications, including WMTS [5].

In this study, we analyzed the potential of EMI in WMTS caused by radio communication systems that share the 400 MHz frequency band. Moreover, we investigated the IM effect generated in WMTS receivers and discussed its potential EMI. Additionally, the electromagnetic noises generated by electrical devices, including LED lamps and security cameras, were investigated, after which we discussed the management of these severe issues using simple methods based on a simplified spectrum analysis function installed in the WMTS receiver and software-defined radio (SDR).

Electromagnetic interference issues caused by radio communication systems using the 400 MHz frequency band

Overview of the WMTSs and 400 MHz frequency band in Japan

In Japan, the specifications for radio communications for WMTS are regulated by ARIB STD-21 ed.3.0, “Medical telemeter radio equipment for specified low-power radio station,” published by the Association of Radio Industries and Businesses, Japan, with the following stipulations: aerial power, <1 mW; frequency bands, 420–430 and 440–450 MHz; bandwidth, 1 channel of 12.5 kHz; and modulation scheme, frequency shift keying [6]. The most popular biological-parameter transmitter in Japan is the type-A WMTS with an aerial power of <1 mW and a bandwidth of 12.5 kHz. Regarding frequency bands, Japanese WMTSs employ lower frequency bands than their European and American counterparts (also using 608–614 MHz) [7]. Fig. 1 depicts Japan’s frequency band usage in the 420–450 MHz range. WMTSs use lower and higher frequency bands of 420–430 and 440–450 MHz, respectively. Each frequency band is assigned to 40–120 channels. The six frequency bands (total bandwidth = 6 MHz) are assigned for such use. However, the 400 MHz frequency band is used by several radio communication systems. The 430–440 MHz frequency bands are generally used in amateur radio in Japan and other countries. Additionally, keyless entry systems for automobiles, wireless phones, capsule endoscopy, nurse call pagers, telecontrols for construction cranes, and real-time location-detection systems use the same or almost the same frequency as WMTSs (400 MHz). Particularly, the frequency band of 429 MHz (from 429.25 to 429.75 MHz) with a bandwidth of 500 kHz is called “Band 3.” It is assigned to 40 channels and shared by WMTS and other radio communications, i.e., a location-detection system for wandering patients and telecontrol services. In WMTS and other radio communications that use the same frequency band in the same environment, the overlap of frequency channels as well as the effects of spurious signals are well-known EMI issues. In the following section, we shall demonstrate the EMI potential using a location-detection system.

Possible electromagnetic interference due to the location-detection system for wandering patients

The location-detection system is among the introduced tools in hospitals for detecting wandering patients. These systems are introduced between sections, such as at the ward entrance. Fig. 2 depicts a schematic of a location-detection system for wandering patients. The system comprises a radio frequency (RF) tag for the patient, a detecting device, and a monitoring device. The RF-active tag is attached to a patient and generates a radio wave of 314 MHz. The detecting device emits a 429 MHz radio wave, including the detecting information, when the RF tag approaches it. The monitoring device sounds an alarm when it receives this signal. The 429 MHz band is a frequency channel that is also shared by WMTSs. Moreover, the limit of the aerial power of the location-detection system is 10 mW, although that of WMTS is 1 mW. The detection device can be installed on a wall near the ceiling. A previous study revealed that EMI was generated when the distance between the receiving antenna of WMTS and the detection device was 3 m [2].

Fig. 3 depicts the frequency spectrum of the location-detection system for wandering patients measured by a spectrum analyzer (SA) under the following conditions: measured frequency, 429–430 MHz; resolution bandwidth (RBW); and sweep time (SWT), 100 ms. The patient equipped with the RF tag waved his/her hand 2 m away from the detection device during the measurement as the detecting device does not emit a radio communication wave without detection. The red line indicates one measurement (a sample detector was used), and the blue line indicates a measurement using a positive peak detector with a maximum hold function of 30 min. A center frequency of 429.325 MHz (this frequency is shared with WMTS channel (ch) number 3007) of the peak signal was emitted by the detection device when the RF tag was detected. The thin blue lines that are excluded near the allocated carrier frequency indicate the intermittent wideband emission in a very short time. The light-green region indicates WMTS frequency Band 3. The instantaneous and impulsive voltage was observed in this frequency band. Our investigation revealed that the channels in Band 3 can be interfered with when the distance between the receiving antenna of WMTS and the radio communication system is short. Therefore, managing the frequency channels of hospital-deployed radio communication devices is key to promoting a safe electromagnetic environment.

Intermodulation effect caused by the two WMTSs transmitters

Overview of the intermodulation effect observed in WMTSs receiver

The IM effect is generated when two or more signals are input into the receiver; it represents a major issue for radio communications [8]. Figure 4 depicts the concept of the IM effect. If two signals with different frequencies (f_1 and f_2) are input into the receiver, two IM signals with frequencies f_1 − Δf and f_2 + Δf will appear on the receiver. These IM signals increase the noise floor of the relevant channels. Hence, hospitals operating WMTSs must conduct zone management to avoid the IM effect. Figure 5 depicts the schematic of zone management. The process involves the preliminary allocation of the WMTS channels in each ward to prevent the IM effect. Each zone is managed by color-coding rules. The same color transmitter is only used in one zone; therefore, using the same channel transmitter and another transmitter belonging to other zones is not allowed. In Japan, up to 10 zones are permitted. Despite these proposals, some hospitals do not conduct zone management. Additionally, the real-life effect of IM in the clinical setting is unclear. We demonstrate the experimental results of the IM effect in the following sections.

Experimental evaluation of the intermodulation effect

We investigated the dependence of the signal amplitude and frequency deviation on IM. Fig. 6 depicts the schematic of the experimental setup. The two signal generators (SG) generated different frequency signals in the 420 MHz band. The SG1 and SG2 signals were input into the patient monitor with an input impedance of 50 ohm through a hybrid coupler. The simplified spectrum analysis function was performed on the patient monitor. We shall carefully explain this function in a subsequent section. In this experiment, we measured the IM-affected amplitude of the IM channel. **Table 1** presents the scheme of the experiment. In condition No. 1, SG1 and SG2 generated 420.325 and 424.825 MHz, respectively, and the frequency deviation between them was 4.5 MHz. Hence, the IM channel was 429.325 MHz. In the actual setting, the IM effect will emerge at the lower frequency side of SG1 (415.825 MHz), although this frequency is outside of that allocated to WMTS. In this experiment, we adjusted the amplitudes of the SG 1 and SG 2 levels.

Table 1 Experimental conditions

	SG1	SG2	IM channel	Δf
No.1	420.325 MHz (ch1023, Zone 1)	424.825 MHz (ch2028, Zone 5)	429.325 MHz (ch3007, Zone 1)	4.5 MHz
No.2	420.2875 MHz (ch1020, Zone 9)	420.5625 MHz (ch1042, Zone 1)	420.8375 MHz (ch106, Zone 1)	0.275 MHz
No.3	424.525 MHz (ch2002, Zone 2)	425.2125 MHz (ch2059, Zone 9)	425.925 MHz (ch2116, Zone 2)	0.7125 MHz

Fig. 7(a) depicts the experimental results when the two input signal amplitudes were the same. The IM effect appeared strongly when the frequency deviation was narrow. Figs. 7(b) and (c) depict the experimental results when the two input signal amplitudes differed. Fig. 7(b) shows when SG2 (ch2028) was set to certain values, whereas SG1 (ch1023) was adjusted from low to high amplitude levels. Fig. 7(c) depicts when SG1 (ch1023) was set to certain values, whereas SG2 (ch2028) was adjusted. When the amplitude of SG1 was 1 dB higher, the IM amplitude increased by 1 dB. However, the IM amplitude increased by 2 dB when the amplitude of SG2 was 1 dB higher. Therefore, the amplitude of IM depends on the input signal near its frequency.

Intermodulation effect on the sensitivity of the WMTSs receiver

We disclosed the sensitivity of the WMTS receiver in our previous study. The required carrier-to-noise ratio (CNR) was ~15 dB when the electromagnetic noise, which can adopt a Gaussian approximation (GA) regardless of the amplitude of the noise power, was added [5]. However, CNR was 3–4 dB worse regarding the electromagnetic noise, which exhibited impulsive characteristics; hence, it could not adopt GA [9]. The IM effect on the sensitivity of the WMTS receiver remains unclear. Fig. 8 shows a schematic of the experimental setup. The type-A WMTS transmitter with a frequency of 429.325 MHz sends normal ECG signals. The transmitter and ECG simulator that generates normal ECG signals with 60 waves per minute were placed in a transverse electromagnetic (TEM) cell to extract the signal. Conversely, the 420.325 and 424.825 MHz continuous waves were generated by SG1 and SG2, respectively, and were input into a coupler, 1. The WMTS signal and coupled 420 MHz band continuous wave, including an IM frequency of 429.325 MHz, were input into the WMTS receiver through another oupler, 2. We evaluated the degradation of the wireless reception due to electromagnetic noise by visually examining the ECG waveforms on the display of the receiver. The critical WMTS signal level for normal reception was determined by decreasing the signal level with an attenuator (ATT). The decision criterion for defining a normal reception was if no abnormality was observed in the ECG waves during 100 wave periods. We varied the amplitude of IM by adjusting the SG power from high to low signal levels. The IM noise power, N, and WMTS signal power, C, were measured at the input port of the receiver at an RBW of 10 kHz using a SA.

Fig. 9 depicts the experimental results. The vertical and horizontal axes correspond to the WMTS signal power, and average IM noise power, respectively. The required CNR, which was obtained by subtracting the IM noise power, N, from the required signal power, C, was 17.7 ± 0.6 dB. The IM effect degrades the receiver sensitivity by several dB worse than the Gaussian Noise.

Measurement of the radio propagation of WMTS for evaluating the potential of the intermodulation effect

We measured the radio propagation of WMTS in the simulated environment to evaluate the actual potential of the IM-induced interference. Fig. 10 depicts the ground plan of the simulated environment. In this measurement, the whip antenna of WMTS, which was connected to SA, was placed at Point, A, of the second floor. The WMTS transmitter was moved from Point B to H per second to the fifth floor. **Table 2** presents the measurement results of the WMTS signal level. When the transmitter was placed on the second floor, the received signal level was −40 dBm/10 kHz to −98 dBm/10 kHz. However, the signal levels coming from the fourth and fifth floors were approximately −100 dBm/10 kHz.

Table 2 Received signal level of WMTS

	2F	3F	4F	5F
B	−68.6	−83	−99.9	−100
C	−84.8	−99.6	NM	NM
D	−97	−83	−99.7	−100.2
E	−88.8	−103	−99.2	−102
F	−77.2	−97.5	NM	NM
G	−98	−100.3	−100.3	−100.1
H	−40.4	NM	NM	NM

NM: not measured, unit: dBm / 10 kHz

Electromagnetic interference caused by electrical devices installed in switched-mode power supplies and CPUs

As already described, many recent electrical devices employ switched-mode power supply to save energy and achieve low power consumption. Additionally, CPUs are typical components that control communication signals, although they may generate high-frequency emissions. These devices may generate wideband emissions and cause poor reception for radio communications. For instance, LED lamps and security cameras are installed in many hospitals, and these devices generally utilize switched-mode power supplies and/or CPUs.

Fig. 11 depicts the assumed EMI scenario, including WMTS and LED lamps. Generally, LED lamps, including their power-feeding lines, and the receiving antenna of WMTS are installed in the ceiling of hospital wards. Therefore, the reception signals of WMTS and the electromagnetic noise generated from the switched-mode power supply installed in LED lamps are readily received and transmitted to the patient monitor in the same transmitting line.

Fig. 12 depicts the frequency spectra of the electromagnetic noise generated by an LED lamp and security camera. These spectra were measured on SA using the whip antenna of WMTS at a distance of 10 cm away from the devices in a semi-anechoic chamber. The spectra were measured at a frequency of 30 MHz–1 GHz and an RBW of 100 kHz. The green line indicates the background noise of the measurement system that was measured using the maximum hold function, and the orange line indicates its 100 times average function. The electromagnetic noises generated from the LED lamp and security camera are represented by yellow and blue lines, respectively. Here, by assuming the worst case, we used extremely strong noise sources. The electromagnetic compatibility standard, CISPR 15 “Limits and methods of the measurement of the radio disturbance characteristics of electrical lighting and similar equipment,” for LED lamps has been established for the protection of radio communications [10]. However, this standard only targets bulb-shaped LED lamps; therefore, tubular lamps are not targeted. Additionally, as CISPR 15 only considers a measured distance of 3 or 10 m, it is not ideal for WMTS as LED lamps and their power lines may cause near-field EMI at much smaller distances.

As described above, considerable caution is required to ensure that electromagnetic noise is not generated by the main body of electrical devices. Electromagnetic noise is delivered via the connected cables, including the power-feeding line and communication cables, and it radiates wideband emissions. Unfortunately, the distance between the receiving antenna of WMTS and the power-feeding line, which is an EMI source, may be much lower than a few centimeters. Generally, good reception is ensured for WMTS at a distance of 7 m under a line-of-sight propagation condition and in the absence of a noise source. However, the electromagnetic noise generated by electrical devices may shorten this distance and cause poor reception. Thus, hospitals must investigate the presence or absence of electromagnetic noises generated by electrical devices before installing them. Additionally, it would be desirable to maintain a separation distance between the receiving antenna of WMTS and electromagnetic noise sources.

Managing the safe operation of WMTS

Simplified spectrum analysis function installed in the WMTSs receiver

In the above sections, we introduced recent EMI issues in WMTS. Notably, EMI sources may exist in some situations before they are noticed. Therefore, it is crucial to manage the electromagnetic environment around the WMTS frequency band, including the intentional emission of other types of radio communication systems and electromagnetic noise generated from electrical devices. Monitoring the frequency spectrum is key to visualizing the electromagnetic environment around the 400 MHz frequency band. However, most hospitals cannot perform such management operations because of the lack of staff members and cost.

Thus, we recommend a simplified measurement method using a WMTS receiver. Recently, WMTS receivers were installed with simplified spectrum analysis functions that measure the amplitude of received signals and/or electromagnetic noises in each WMTS frequency channel. This simple function can measure and display the received signal levels of every WMTS frequency channel. Fig. 13 depicts the screen of this function installed in a WMTS receiver. A channel 5021 WMTS signal is detected (Fig. 13(a)), and an increase in the noise floor owing to the electromagnetic noise generated from the LED lamp is shown (Fig. 13(b)) [11].

We investigated the accuracy of the signal amplitude of the receiver. Fig. 14 depicts the schematic of the experimental setup. The RF player that captured the WMTS signal replayed the recorded signal with a frequency of 429.25 MHz via the variable ATT and input it into the WMTS receiver and SA. We used two WMTS receivers with different input impedances of the input port: one was 50 ohm (Receiver A), and the other was 75 ohm (Receiver B). In this experiment, the simplified spectrum analysis function was run, and the received signal amplitude was measured.

Additionally, we measured the signal power at a bandwidth of 10 kHz using a real SA, and Fig. 15 depicts the evaluation results. The horizontal axis represents the received signal level of the real SA, the left side of the vertical axis represents the received signal level of Receiver A, which was displayed as RSSI [dB], and the right side corresponds to the signal received by Receiver B, which is displayed as voltage [dBμV]. Each result was displayed by 50 times the average with a standard deviation. The indicated values of the received signal levels of both simplified spectrum analysis functions correlated with that of a real one.

However, this function is highly limited—the measurable frequency band is only the Japanese WMTS band (400 MHz)—and cannot configure detailed parameters, such as RBW, SWT, and a detector. Nevertheless, this function can easily measure the received signal level in each WMTS frequency channel. The WMTS signal and electromagnetic noise generated by electrical devices or other radio communication signals can be confirmed in clinical settings. The simplified spectrum analysis function facilitates the management of the electromagnetic environment in hospitals, such as electromagnetic noise detection and the management of the WMTS frequency channel.

We propose another approach for spectrum management using SDR. SDR is a radio communication system in which the components that have been conventionally implemented in analog hardware (e.g. amplifiers, filters, mixers, modulators/demodulators, detectors, etc.) are implemented using software on a personal computer or embedded systems [12]. Similar to SA, SDR can be used as a radio communication receiver facilitated by signal processing, such as fast Fourier transform. The greatest advantage of SDR is its inexpensiveness. For instance, RTL–SDR (RTL-SDR.com) is an 8-bit SDR with a frequency range of 0.5–1766 MHz, and it costs approximately 30 US Dollars. ADALM-PLUTO (Analog Devices) is a 12-bit SDR with a frequency range of 325–3800 MHz, and it costs approximately 230 US Dollars. Moreover, the free software for SDR SA was recently released. We investigated the receiver sensitivities of RTL–SDR and ADALM-PLUTO. Fig. 16 depicts the schematics of the measurement setup. SG generated a continuous wave with a frequency of 429 MHz and was input into SDR and a real-time SA that were connected to a personal computer. The input signal level was adjusted between −10 and −130 dBm. We used two SDRs: RTL–SDR and ADALM-PLUTO, and Fig. 17 depicts the experimental results. The horizontal axis represents the output power of SG; the left side of the vertical axis represents the signal level that displays as [dB] received, measured by SDRs; and the right one represents the received signal that displays as the [dBm] level measured by SA. In this experiment, we adjusted the amplifier-gain built-in SDR. RTL–SDR and ADALM-PLUTO ranged from 0 to 20 and 0 to 50 dB, respectively. The signal level was correctly measured from −120 to 10 dB when no amplifier was used at both SDRs. When the amplifier gain was high, a lower-level signal of −140 dBm was measured, although the high-level signal was not measured correctly as the receiver circuit was saturated. Conversely, the real-time SA was measured at lower- to higher-level signals between −140 and 10 dB without an amplifier. Fortunately, the indicated values of the received signal levels of both SDRs correlated with those of real-time SA. Moreover, we can evaluate the electromagnetic environment by adjusting the amplifier gain.

We introduced an applicative trial using SDR with machine learning (ML). We developed a novel ML model to estimate the CNR of WMTS using the time-domain waveform data measured by RTL–SDR [13]. In this model, the lower to higher levels that ranged from 1 to 58 dB of CNR were correctly estimated, with a 99.5% R-square and 0.844 dB mean absolute error, using a gradient-boosting regression tree. RTL–SDR performed satisfactorily in estimating CNR despite using only an 8-bit resolution and inexpensive SDR. We implanted our model onto a single-board computer that is equipped with a graphic processing unit, such as the NVIDIA Jetson series. A novel inexpensive electromagnetic environment evaluation system that can be easily measured using SDR can be realized soon.

Discussion and conclusions

The Food and Drug Administration has stated considerable concerns about the EMI issues of WMTS [16]. For instance, the United States WMTS may cause poor reception by digital television transmissions in neighboring channels [17]. The EMI issues of WMTS are classic, yet new challenges. The recent accelerations of switching and operating frequencies cause wideband intentional emission. In this study, we describe the EMI issues in Japanese WMTS. These issues apply to Japanese, as well as EU or U.S. WMTS, as the IM effect will cause poor reception for any communication system, not just 400-MHz-band WMTS. Additionally, EMI caused by LED lamps could reach the 600 MHz band or higher [5]. Therefore, the EMI issues of WMTS are common worldwide.

Considering that the 400 MHz frequency band used in Japan is so crowded because of its easy applicability, the circuit boards of radio communications for this frequency band are inexpensive. In this study, the overlapping effect of the frequency channel of WMTS by intentional emissions generated from a location-detection system was demonstrated. These systems exhibit higher aerial power than WMTS; hence, spurious emissions may appear strongly. Therefore, hospitals must manage WMTS and other radio communication devices that share the 400 MHz frequency band before installing them.

As shown in Fig. 8, the IM effect was observed when both input signal levels were over −53 dBm. When the different signal levels, e.g., one signal level, was −100 dBm/10 kHz, another signal level was over −29 dBm/10 kHz to generate IM. In zone management, the same floor serves as the same zone. According to the measurement results, the maximum amplitude of the WMTS signal generated by another floor was −83 dBm/10 kHz. At this signal level, other signal levels must exceed −40 dBm/10 kHz to generate IM. Therefore, the signal level of WMTS generated by another floor cannot exert the IM effect when proper zone management is conducted. However, as earlier described, radio communication devices that use the same frequency as WMTS, such as telecontrol devices, generally exhibit output powers that are >10 mW. When introducing these devices, hospitals must conduct proper zone management to avoid the IM effect.

As described above, energy-saving devices and computed electrical control devices that employ CPUs have been rapidly introduced in hospitals. These devices are advantageous because of their inexpensiveness, SDG compliance, patient safety, and labor reduction; however, their rapid introduction may increase EMI potential and cause fatal accidents. We recommend that hospitals confirm the presence or absence and degree of electromagnetic noise radiated from electrical devices.

The manufacturers announced that the normal reception of WMTS is generally ensured at a distance of 7 m between the transmitter and receiving antenna. In extremely rare cases, it can receive signals from WMTSs of other hospitals, which are far away, from a few 100 m to over 1 km. Therefore, the management of frequency channels is required for the target hospital and neighboring ones. However, most hospitals are not interested in the electromagnetic environment for WMTSs.

According to the report presented by the Electromagnetic Compatibility Conference Japan in 2023, approximately 90% of Japanese hospitals have introduced WMTS, of which >70% use 400 MHz WMTS [14]. Approximately 20% of hospitals use >100 transmitters. Conversely, 56.6% have experienced issues with radio communications, such as poor reception, EMI, and degradation of the antenna system. Despite these issues, over 20% of the hospitals do not manage the frequency channel of WMTS. Moreover, only 30% of the hospitals conduct periodic inspections of radio communications, indicating low interest in the management of WMTS. In clinical settings, poor reception may cause fatal accidents, such as a missed alarm for ventricular fibrillations, and the following reasons may account for these situations. First, the lack of staff members with adequate skills or experience in electromagnetic compatibility. Generally, WMTS is managed by clinical engineers, although Japanese clinical engineers manage and operate such medical devices. According to a previous study, the number of staff and budgets for the management of medical devices are dissatisfactory in 30% of Japanese hospitals [15]. Particularly, introducing specific measuring devices, such as SAs, is challenging for most hospitals because of their expensiveness. We proposed two different approaches for measuring the electromagnetic environment of WMTS, beginning with the adequate performances of evaluation and inexpensiveness. These techniques can aid medical staff and accelerate medical safety management.

Declarations

Author contributions

Conceptualization: K.I.; Methodology: K.I. and E.H.; Validation: K.I. and K.F.; Formal analysis and investigation: K.I., K.H. and E.H.; Writing - original draft preparation: K.I.; Writing - review and editing: E.H.; visualization: K.I.; Supervision: E.H.; Project aministration: K.I.; Funding acquisition: K.I.; All authors read and approved the final manuscript.

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Data Availability

Data is available upon reasonable request.

Competing Interests

The authors declare no competing interests.

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Figures

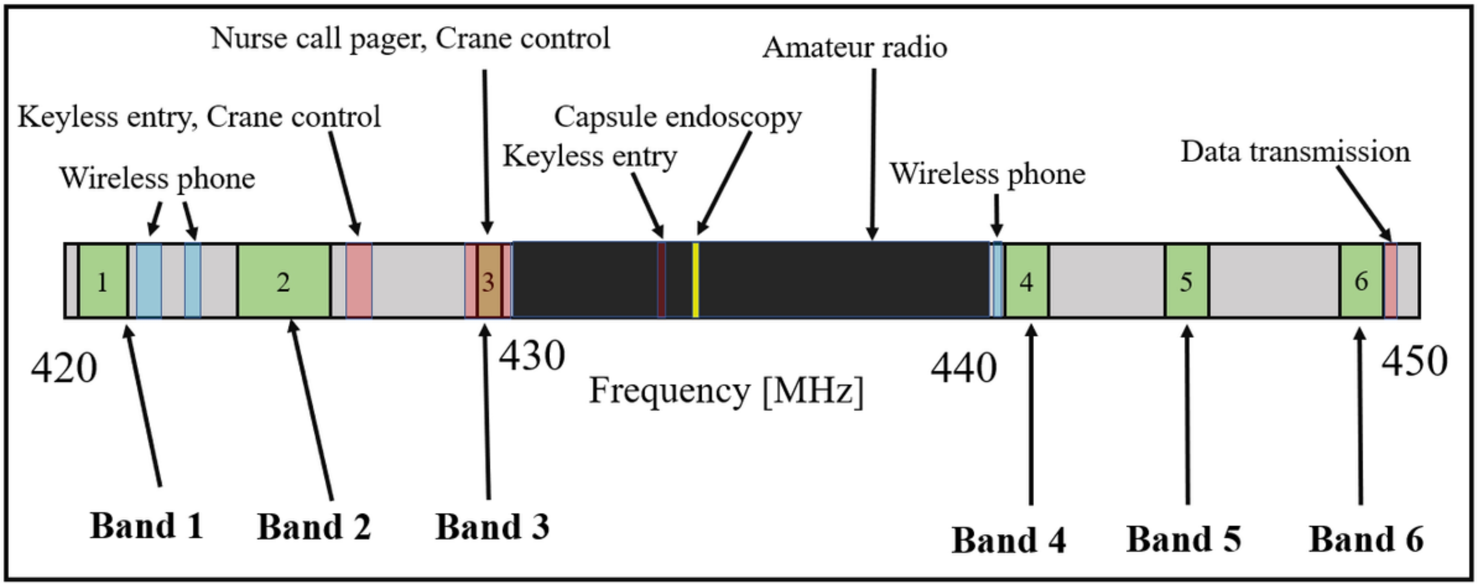


Figure 1

Japan’s 420−450 MHz frequency band usage

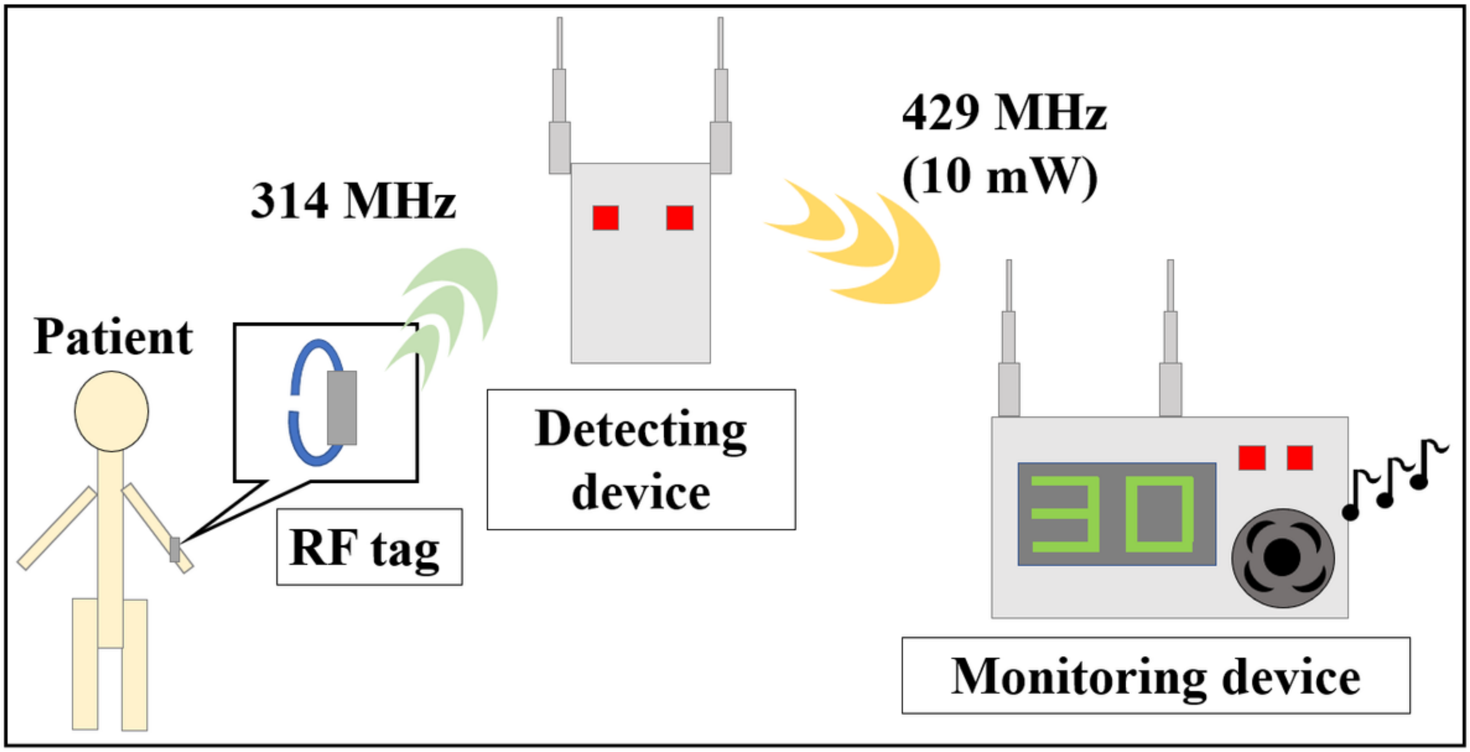


Figure 2

Schematics of the location-detection system for wandering patient

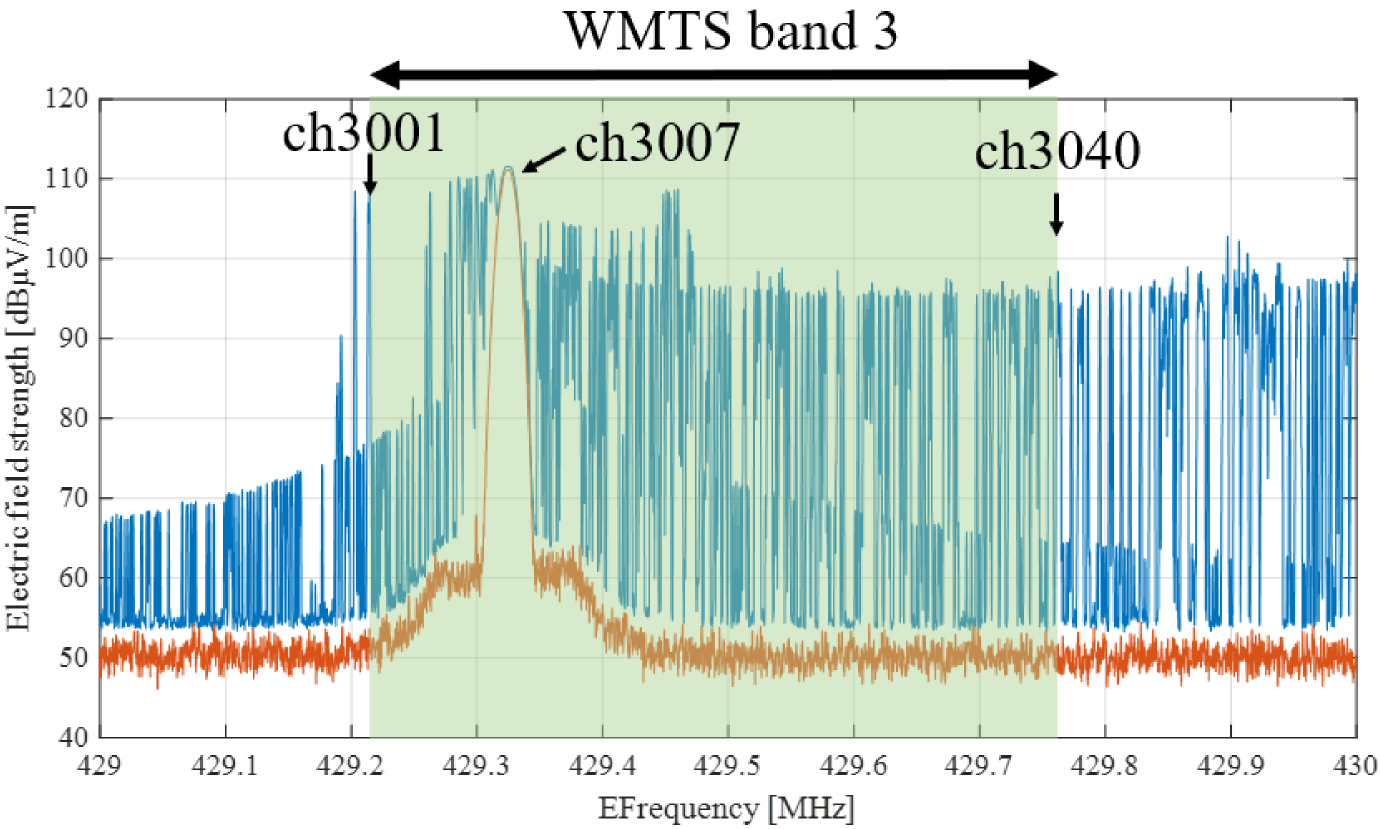


Figure 3

Frequency spectrum of the location-detection system for wandering patient

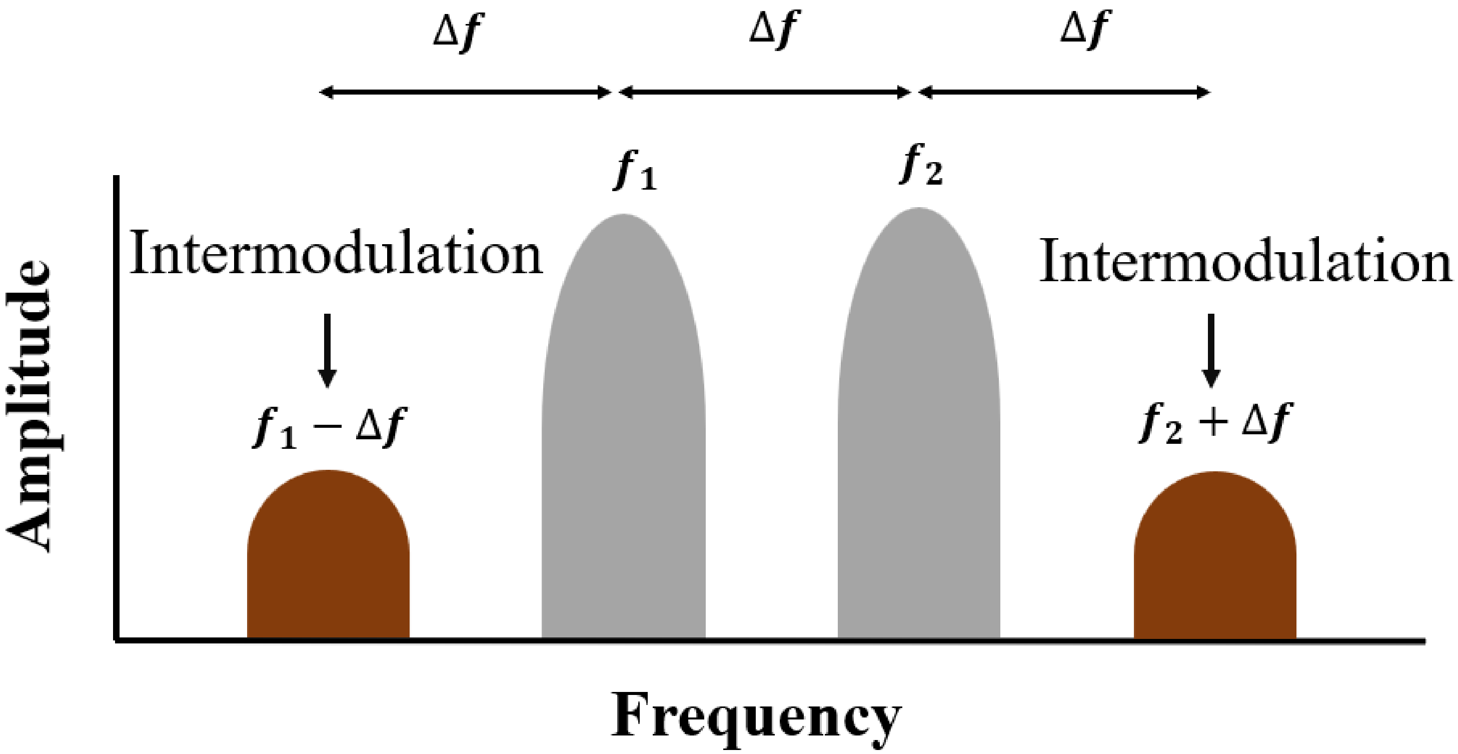


Figure 4

Schematic of intermodulation

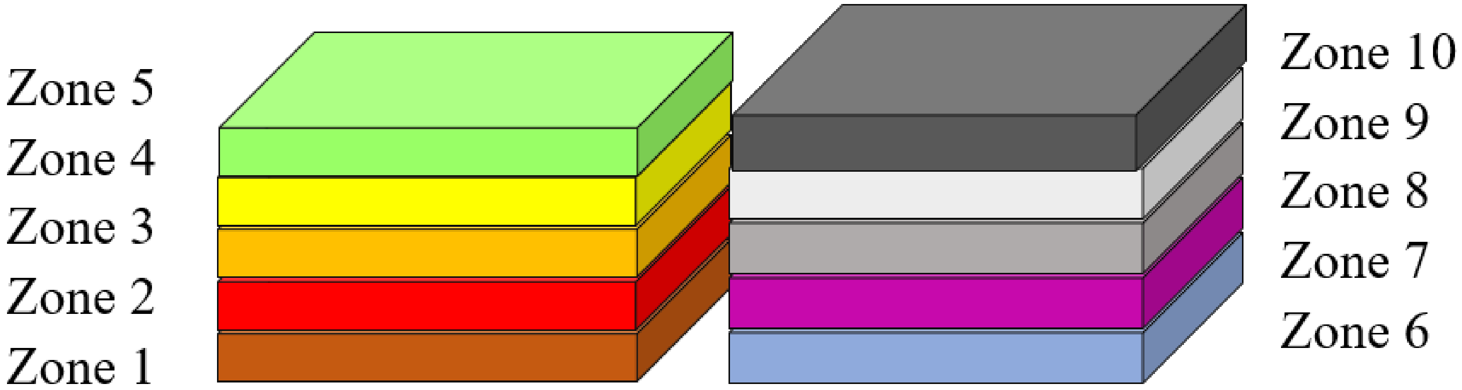


Figure 5

Schematic of zone management

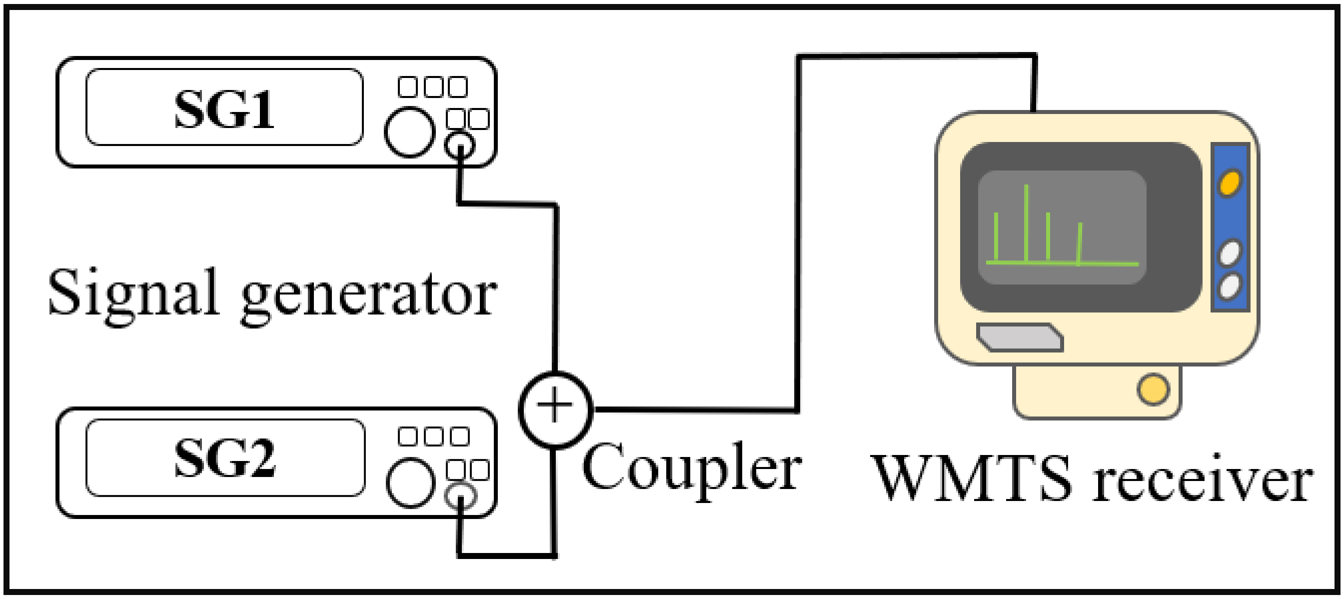
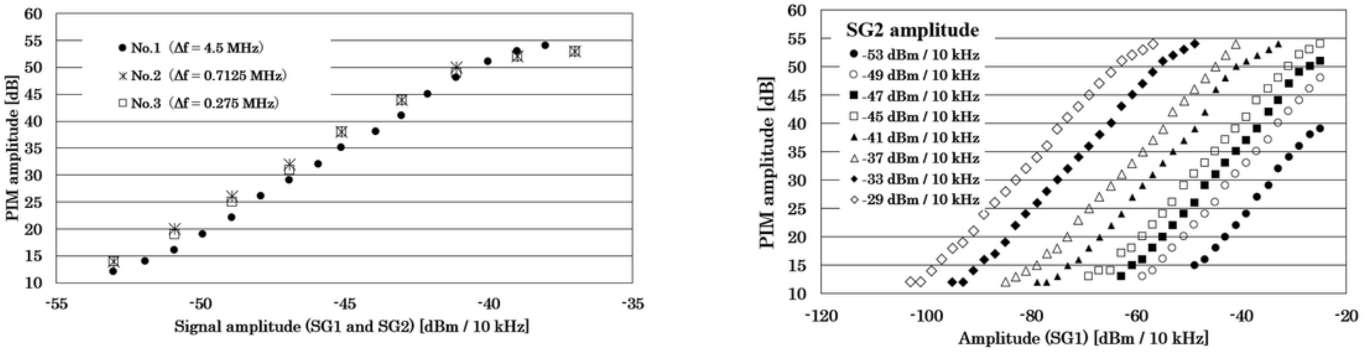


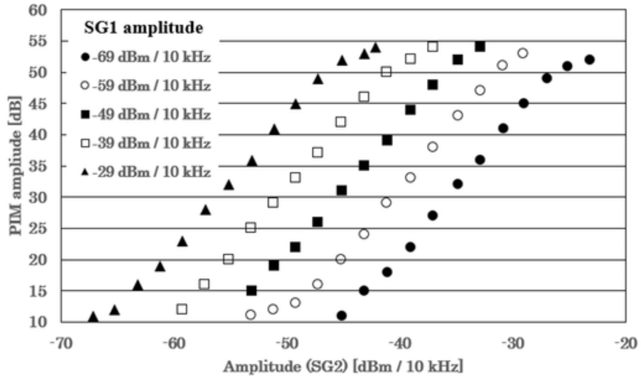
Figure 6

Schematics of the experimental setup for the appearance of the IM effect



(a) SG1 and SG2 with equal amplitudes

(b) SG1 amplitude was adjusted



(c) G2 amplitude was adjusted

Figure 7

IM amplitudes

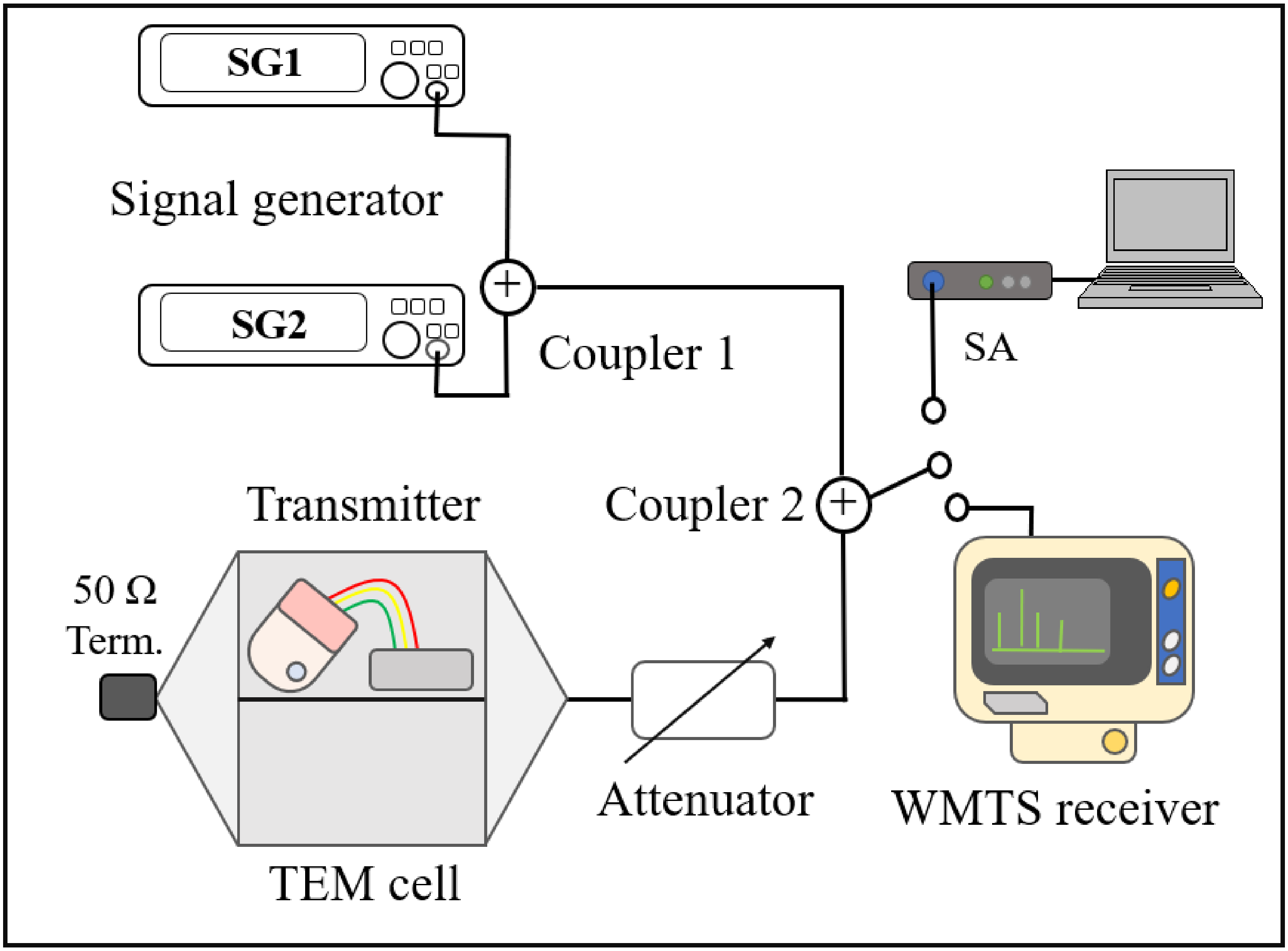


Figure 8

Schematic of the experimental setup of the sensitivity of the WMTS receiver affected by IM

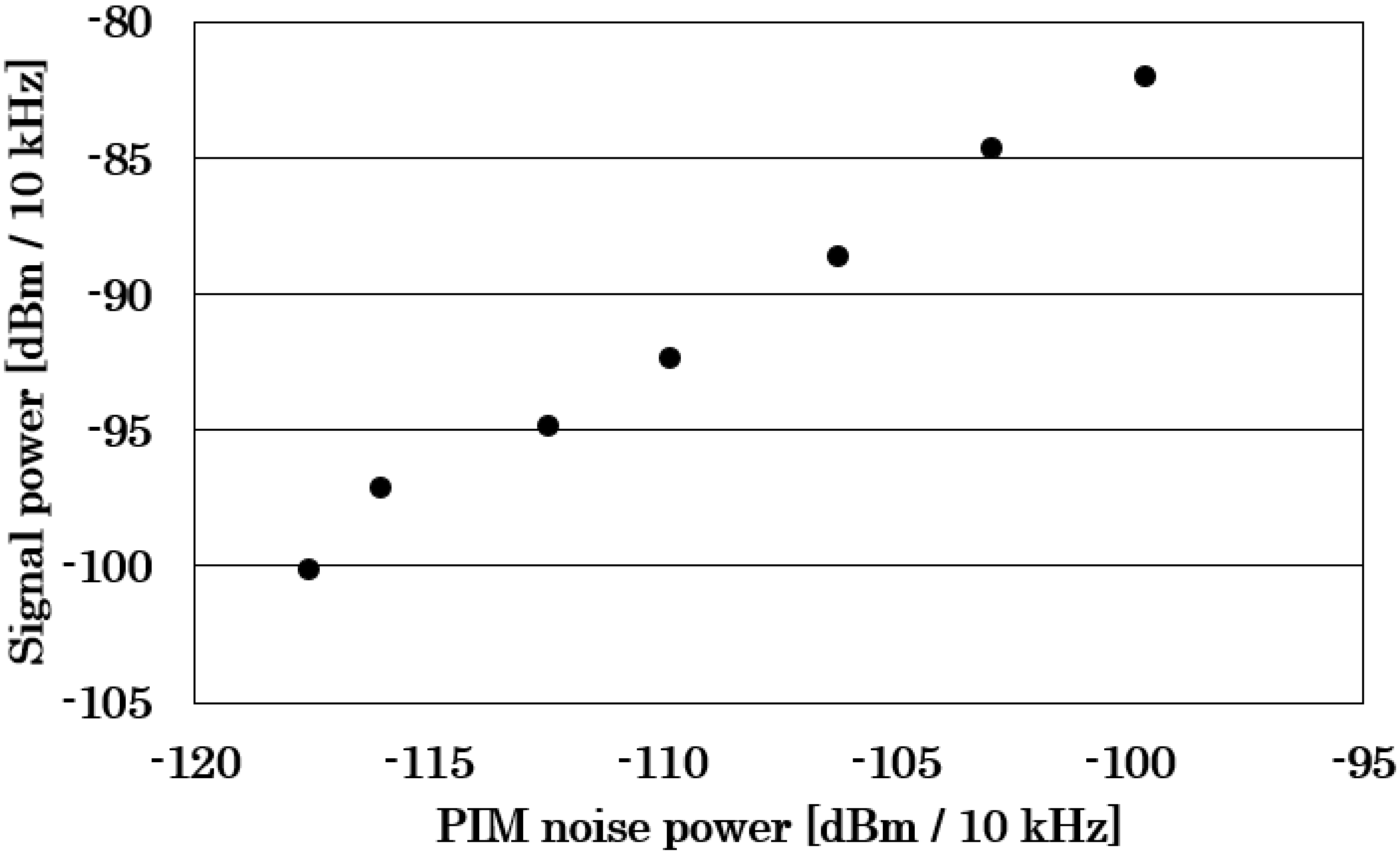


Figure 9

Degradation of the radio communication performance of WMTS under the IM effect

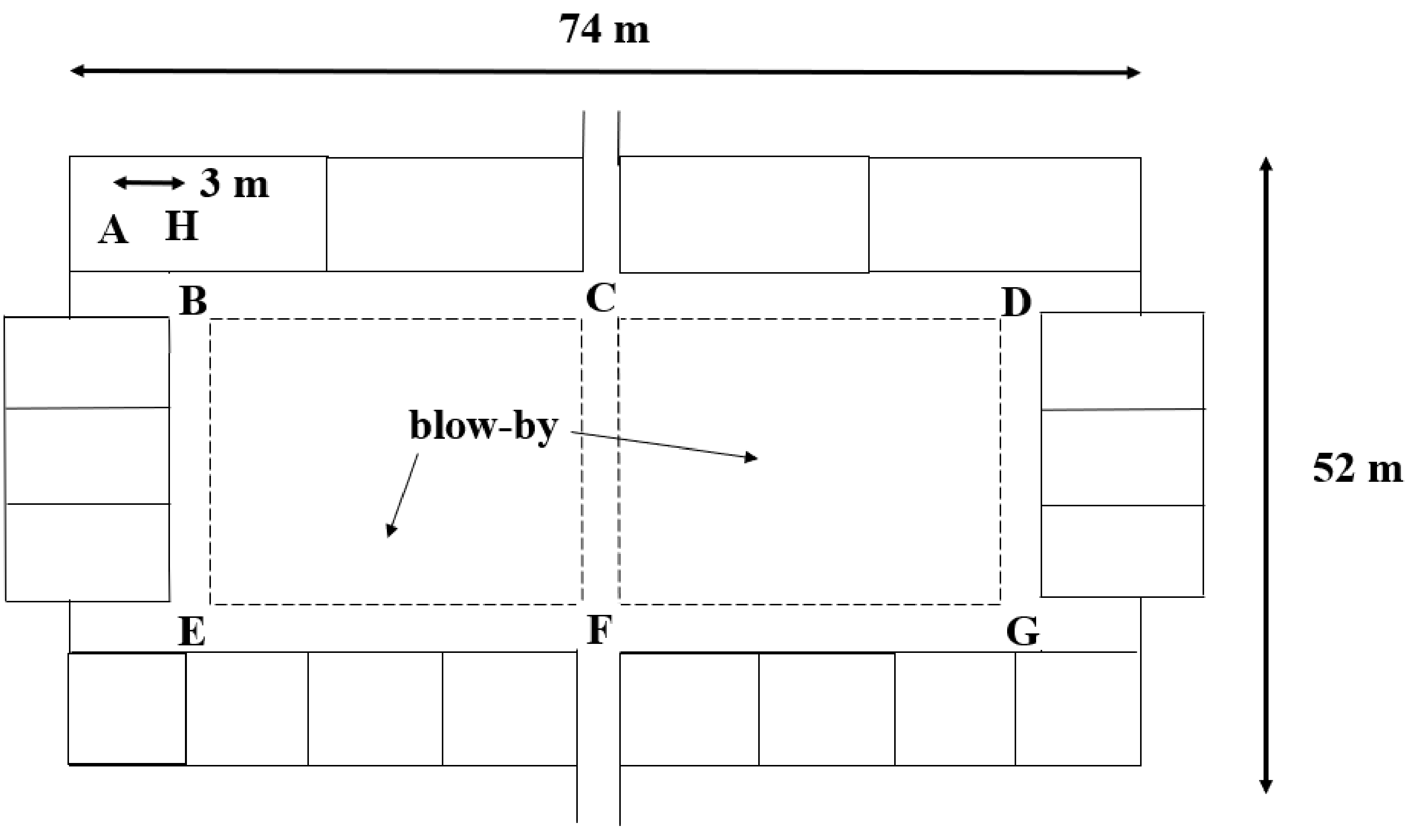


Figure 10

Ground plan for the simulated environment

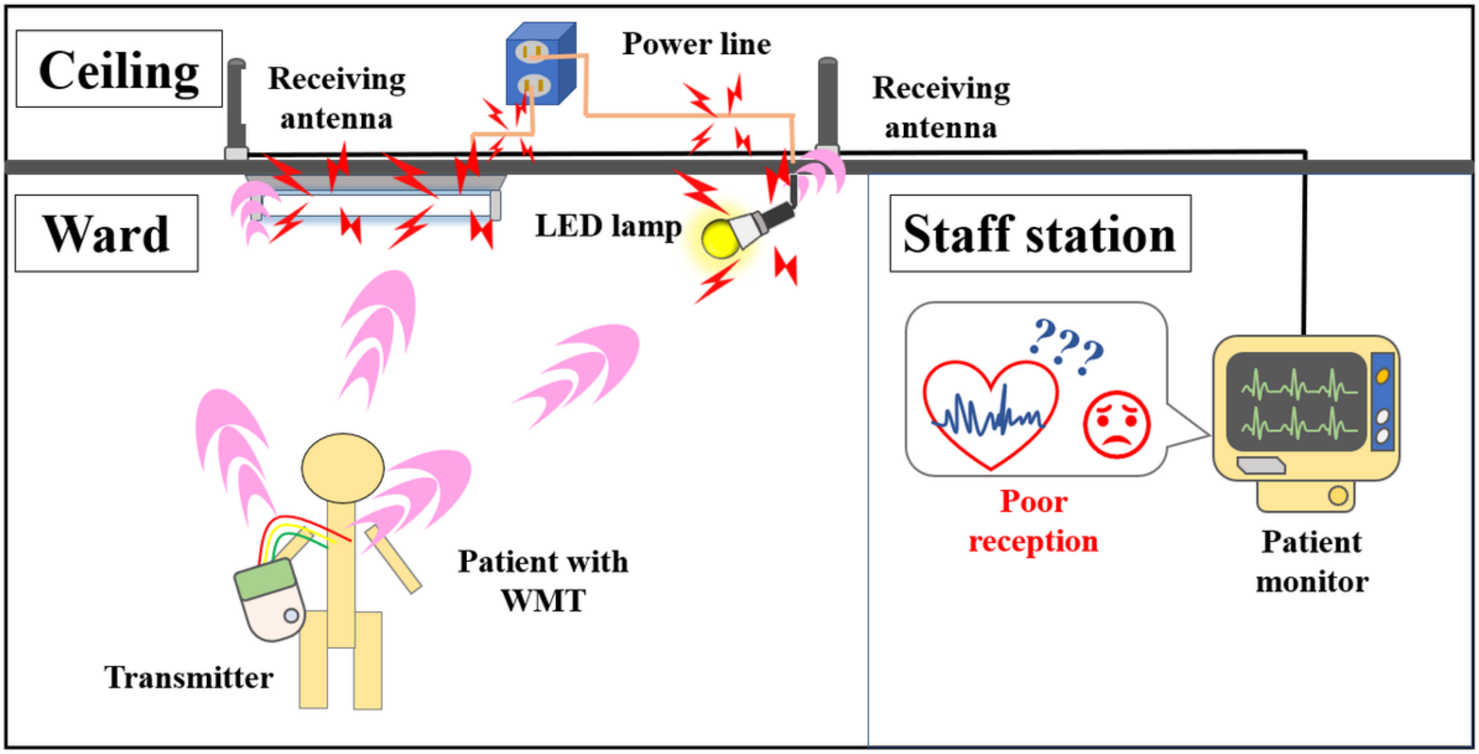


Figure 11

Assumed EMI scenario involving an LED lamp and WMTS

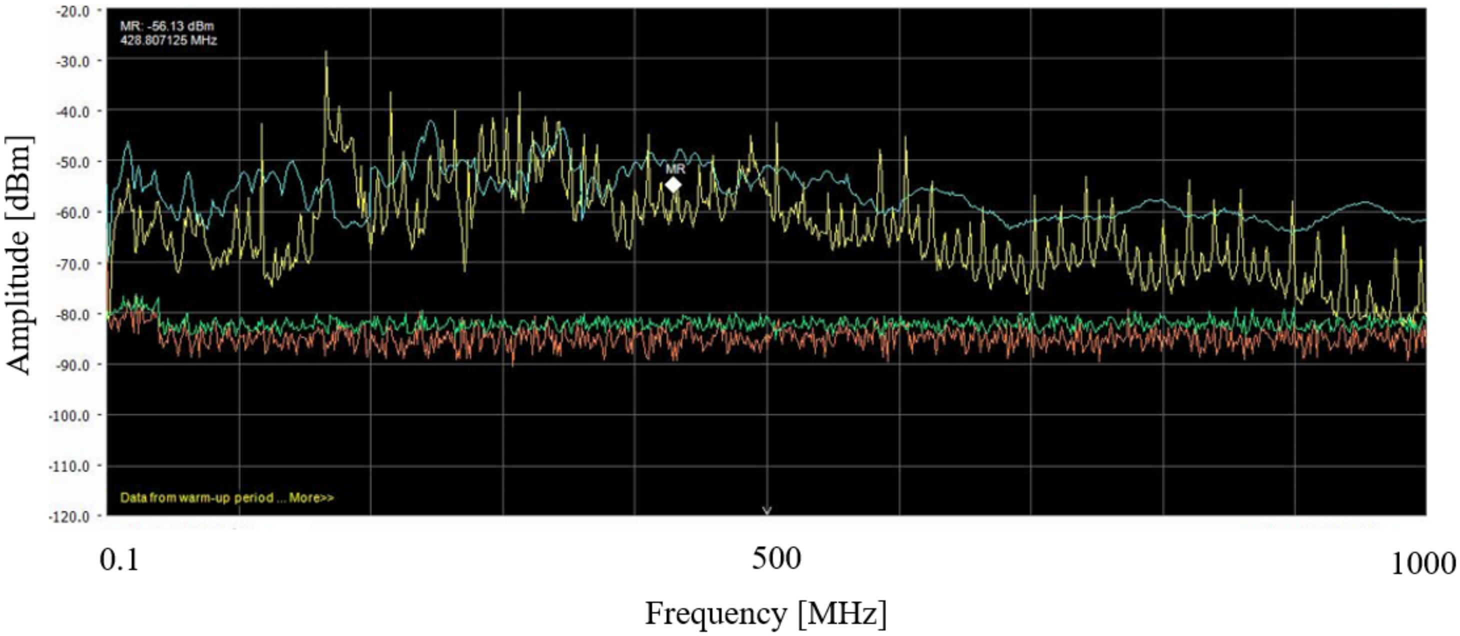


Figure 12

Frequency spectra of the electromagnetic noise generated by electrical devices

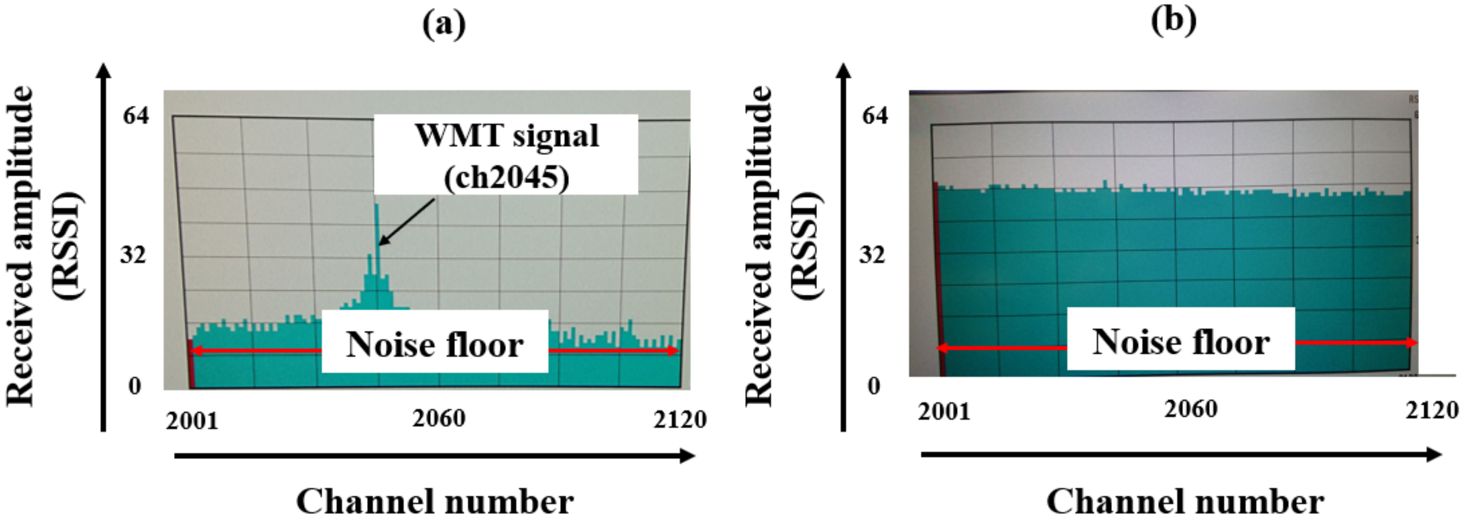


Figure 13

Simplified spectrum analysis function installed in the WMTS receiver: (a) detection of the WMTS signal and (b) detection of the electromagnetic noise generated from the LED lamp

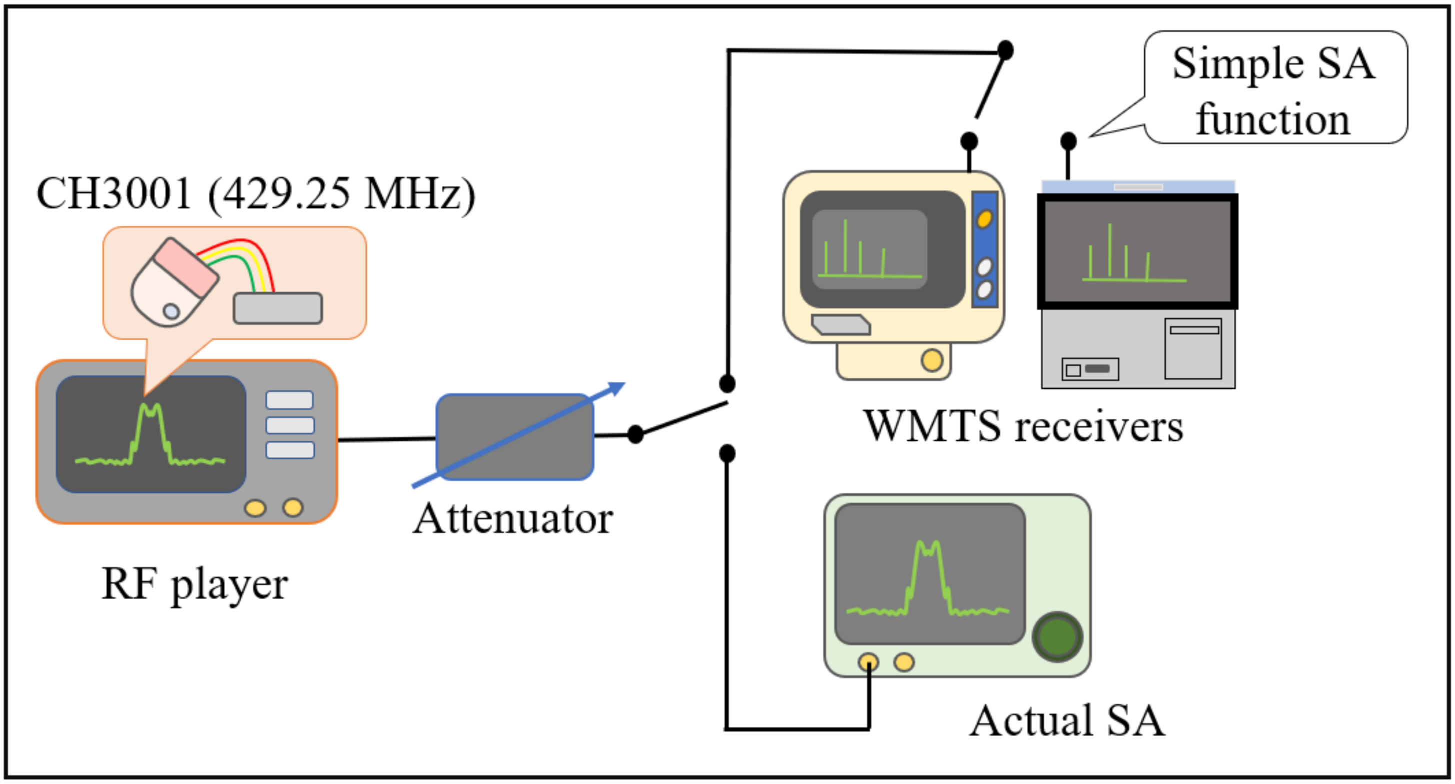


Figure 14

Schematics of the setup for the evaluation of the simple SA function

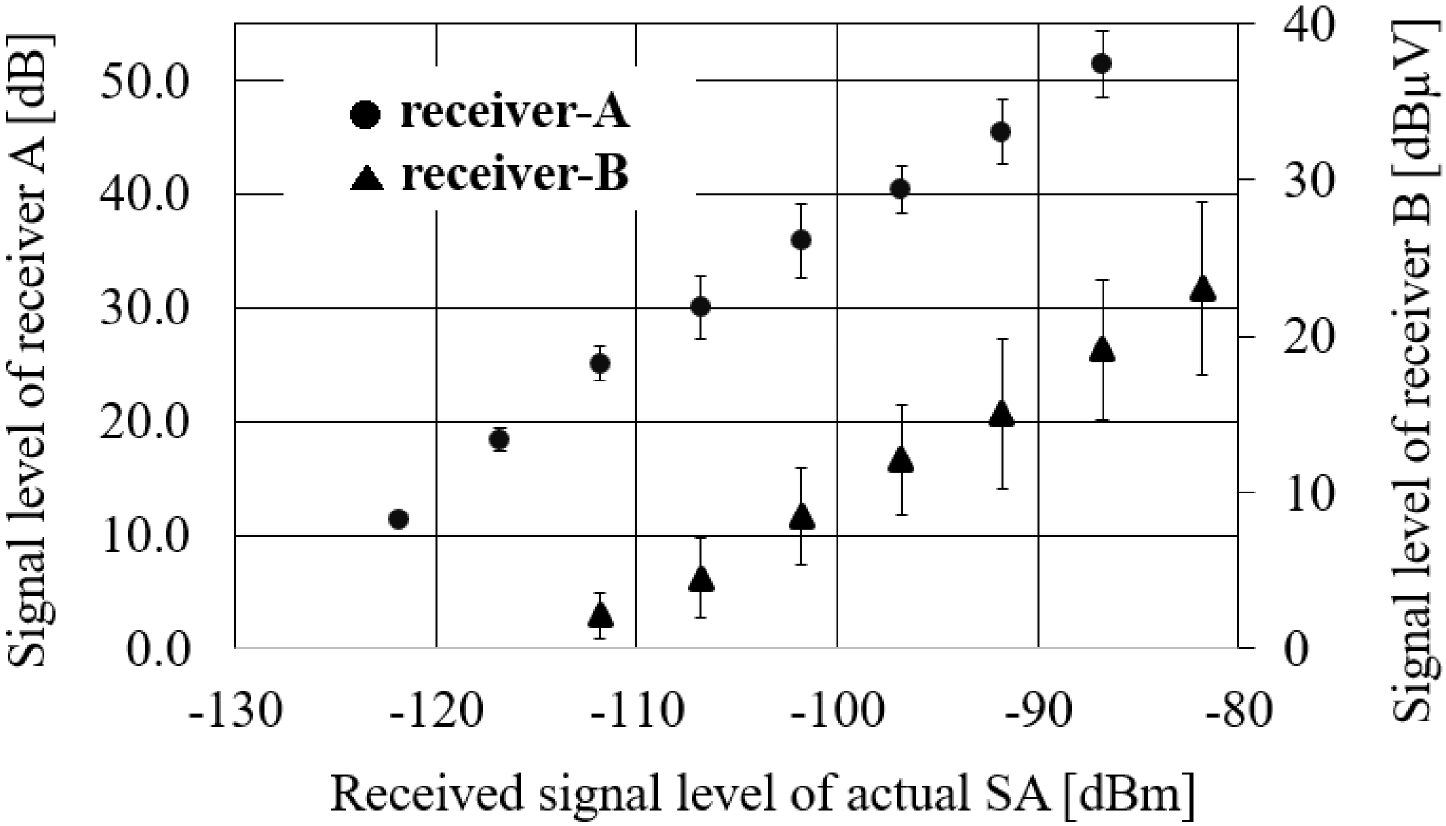


Figure 15

Comparison of the received signal levels of the simplified SA function

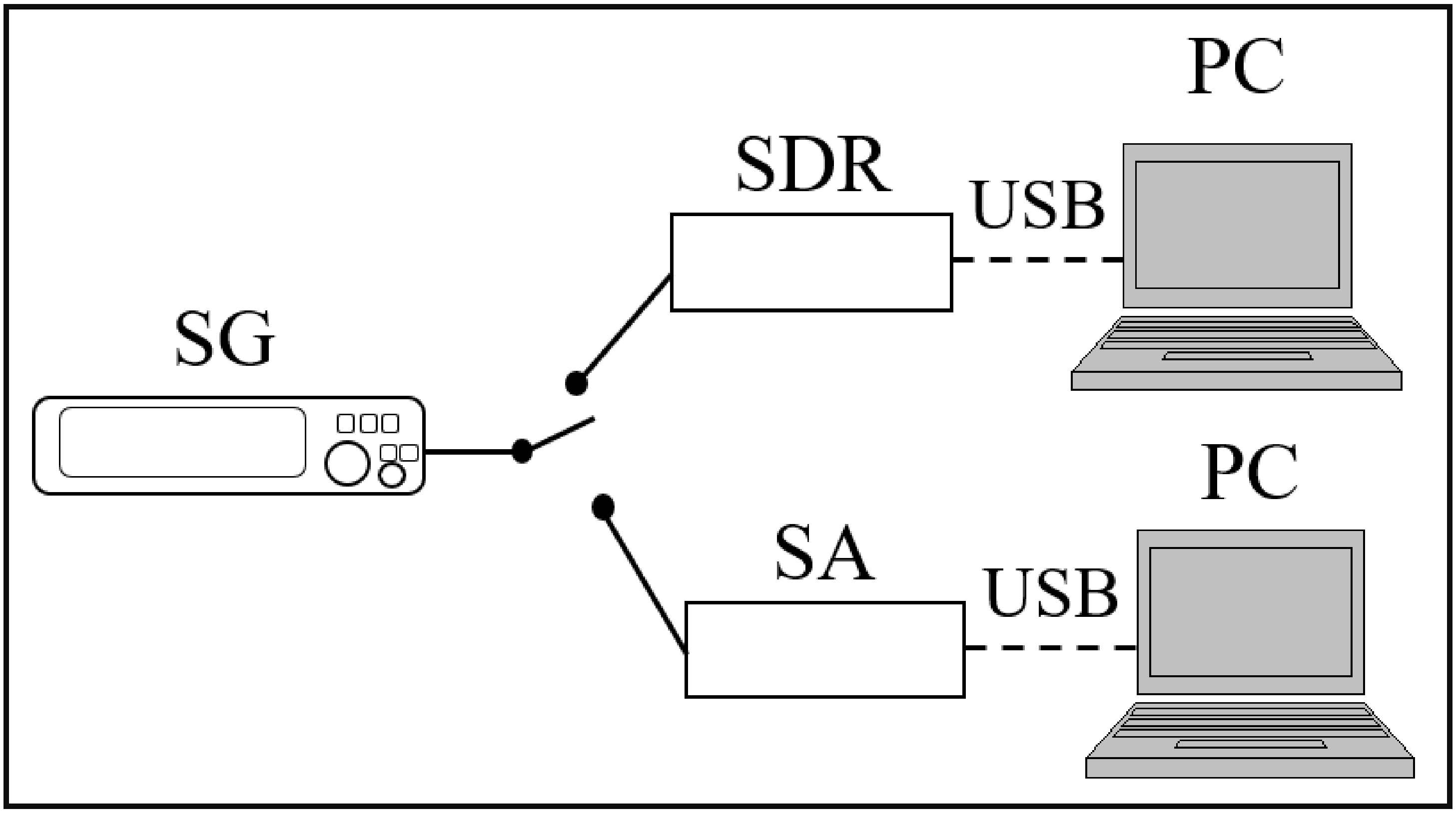


Figure 16

Schematic of the evaluation setup for receiver sensitivity of SDRs

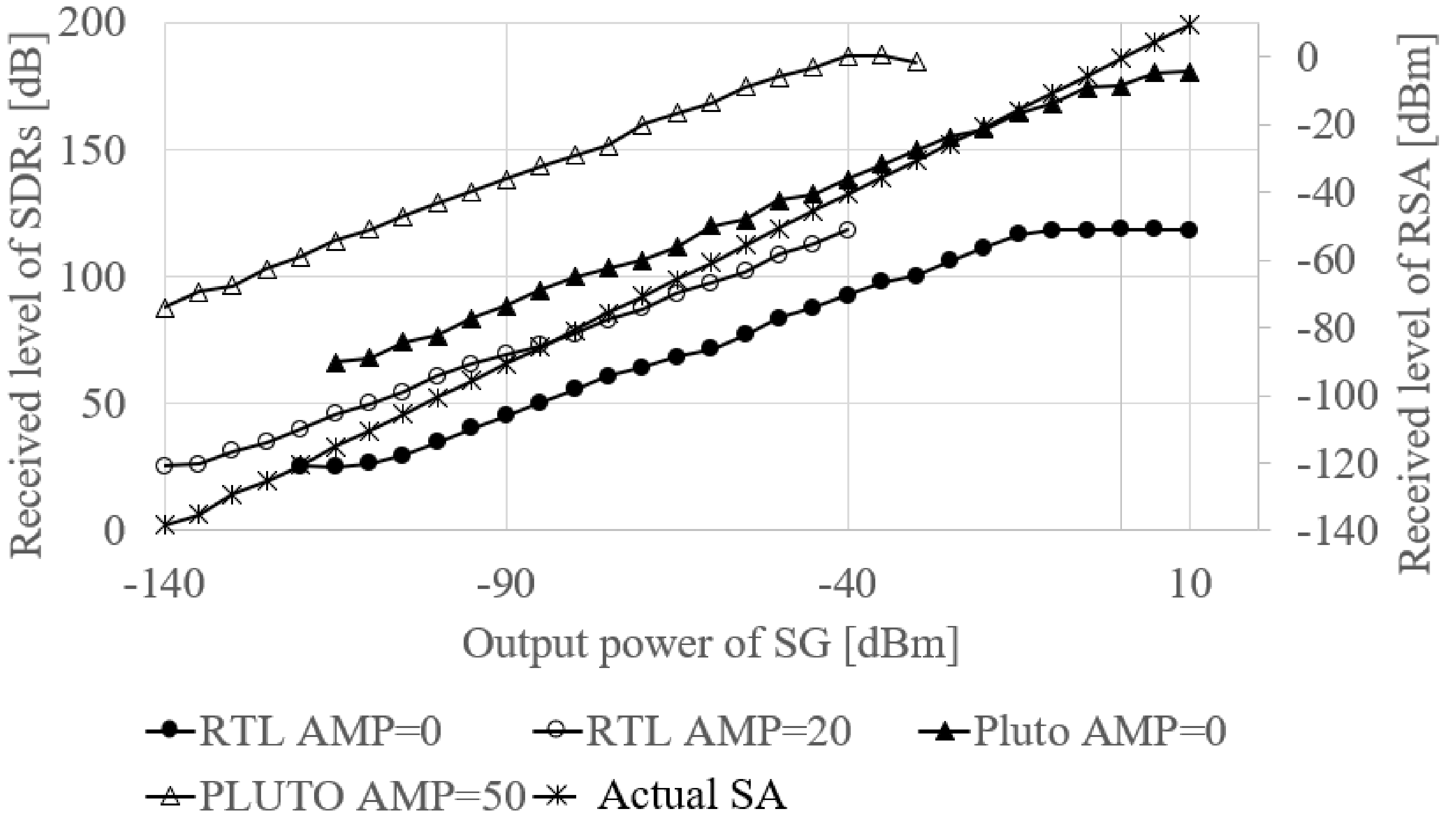


Figure 17

Comparison of the receiver sensitivities of SDRs and real-time SAs