Man-Made Noise Evaluation for Cryogenic Receiver Front-End

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Abstract—**This paper presents measured results of man-made noise impact on an cryogenic receiver front-end (CRFE) in urban and suburban areas in the 2-GHz band with amplitude probability distribution (APD). The CRFE comprises a high-temperature superconducting filter, cryogenically-cooled low-noise amplifier, and highly-reliable cryostat. The CRFE is expected to be an effective and practical approach to attain efficient frequency utilization and to improve the sensitivity of mobile base station receivers. It is important to measure the characteristics of man-made noise in typical cellular base station antenna environments and confirm their impact on the CRFE reception with APD because if man-made noise has a stronger effect than thermal noise, the CRFE would fail to offer any improvement in sensitivity. The measured results suggest that the contribution of man-made noise in the 2-GHz band can be ignored as far as Wideband Code Division Multiple Access (W-CDMA) system is concerned. The man-made noise is also measured in the VHF-band for comparison with the 2-GHz band environment.**

Index Terms—**cryogenic receiver front-end, man-made noise, amplitude probability distribution, wideband code division multiple access**

I. Introduction

Mobile phones are now coming into wide use as an important means of communications because of their outstanding portability and convenience. Mobile services provided through mobile phones have been enhanced and improved to cope with diversifying user needs. The frequency bands used in mobile phones have become increasingly higher with the growing demand for high-speed and high-capacity data transmission. In Japan, the wideband code division multiple access (W-CDMA) system has been in commercial service as one of the third generation mobile communication systems, IMT-2000, since 2001 using the 2-GHz band. It is important to improve the sensitivity of a base station receiver system since propagation and feeder losses in the 2-GHz band are greater than those in the 800- or 900-MHz band for the second generation mobile communication systems.

High-temperature superconducting filters (HTSFs) were proposed for use in mobile base station receivers from the standpoint of efficient frequency utilization and improving the receiver sensitivity. This is because HTSFs achieve low insertion loss and sharp skirt characteristics. High frequency selectivity characteristics can also reduce the saturation power level required for the low-noise amplifier used in the base stations since undesired interference signals in the adjacent passband can be thoroughly suppressed, which leads to the mitigation of the cryostat cooling capability.

A cryogenic receiver front-end (CRFE), comprising an HTSF, a cryogenically-cooled low-noise amplifier (CLNA), and a highly reliable cryostat, is anticipated to be an effective and practical way to achieve efficient frequency utilization and high sensitivity performance for mobile base station receivers [1]-[5].

Here, sensitivity represents the minimum received signal power level required to establish successfully a radio communication link between the mobile station and base station. Therefore, thermal noise must be evaluated because sensitivity increases as the thermal noise is reduced. Our previous investigations [4], [5] showed that sensitivity improvements of up to 3 dB can be attained by employing an antenna of small ohmic loss and a very low noise CRFE based on the equivalent noise temperature [6] which is an index for evaluating the thermal noise. The equivalent noise temperature represents the average power of the antenna noise at the input port of the base station receiver [4].

In addition to the thermal noise, it is important to measure the characteristics of man-made noise such as impulsive noise, lightning pulses, or interference on the received signals, in typical cellular base station antenna environments and confirm their impact on the CRFE reception because if man-made noise has a stronger effect than thermal noise, the CRFE would fail to offer any improvement in sensitivity. The amplitude probability distribution (APD) method [7], which provides amplitude distribution analysis data for the antenna noise envelope, is useful in estimating the impact of man-made noise.

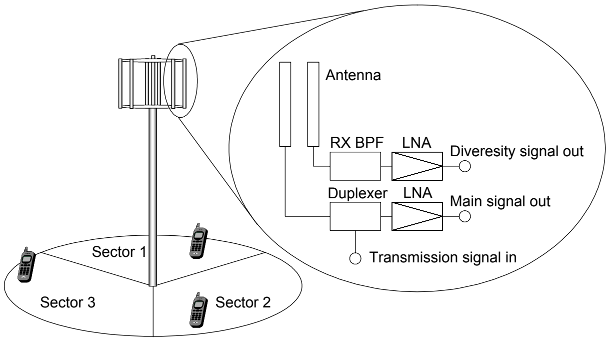
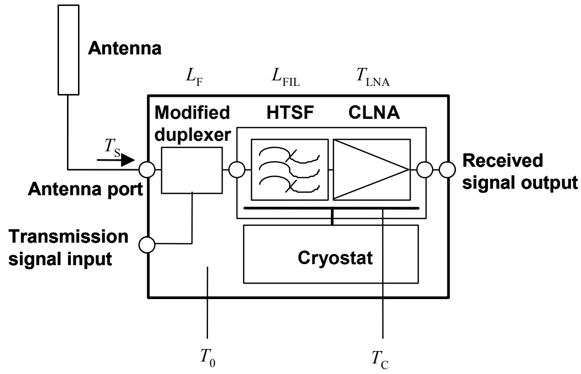
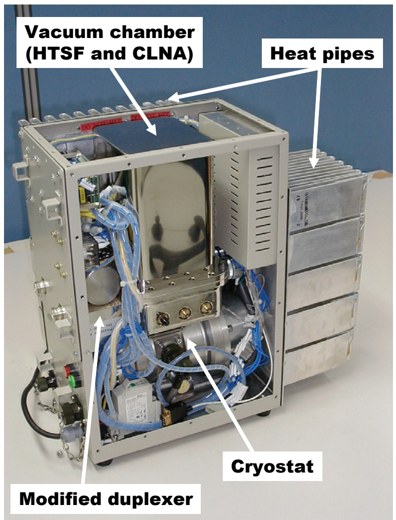


Figure 1. Basic configuration of a three-sector cellular base station.



(a)

Figure 2. An example of a tower mounted RFE.



(b)

Figure 3. Experimental CRFE. (a) Basic configuration. (b)Photograph.

There were reports on measurement results of impulsive noise pertaining to the electromagnetic environment for the universal mobile telecommunication system (UMTS) by using a receiver front-end (RFE) that comprised a normal temperature bandpass filter and normal temperature low-noise amplifier [8] or pertaining to the radio environment of mobile base stations [9].

This paper comprises as follows: Section II introduces the basic configuration and typical characteristics of the CRFE and shows the calculated improvement in sensitivity by applying the CRFE to the mobile base station receivers. Section III presents the measurement system of man-made noise using the APD approach. Section IV describes the measurement results of the man-made noise in 2-GHz and VHF bands, respectively. Finally, section V depicts the conclusions.

II. Cryogenic Receiver Front-End

A. Basic configuration

Fig. 1 shows the basic configuration of a three-sector cellular base station RFE including antennas. Each sector has two antennas (for main and diversity reception). Each antenna is followed by an RF front-end comprising a receiving bandpass filter (RX-BPF) and low noise amplifier (LNA). The diversity front-end has a simple RX-BPF, while the main front-end uses a duplexer in order to use the same antenna for simultaneous reception and transmission. This receiver front-end is located in the vicinity of the antenna (on top of the tower or tower-mounted), which yields highly-sensitive reception. Fig. 2 shows an example of existing tower-mounted RFE. In base station receiver systems, the CRFE mounted on top of the tower appears to be the most promising approach to maximize the sensitivity and efficient frequency utilization.

Fig. 3 shows the basic configuration and photograph of the experimental CRFE. The CRFE has a volume of 15 l (excluding heat pipes). The CRFE comprises an HTSF, CLNA, and cryostat. In this figure, a modified duplexer is inserted in front of the HTSF. The out-of-band attenuation of the receiving band of the modified duplexer is not as large as that of the conventional one shown in Fig. 1 since the following HTSF provides sufficient performance as RX-BPF. The CRFE should be lightweight, small, and highly reliable to offer easy installation and maintenance because it is to be installed on the tower-top similar to the conventional RFE. Table I summarizes principal characteristics for each component of the CRFE.

Fig. 4 presents an RF performance example of the CRFE. All characteristics were measured at 70 K. The

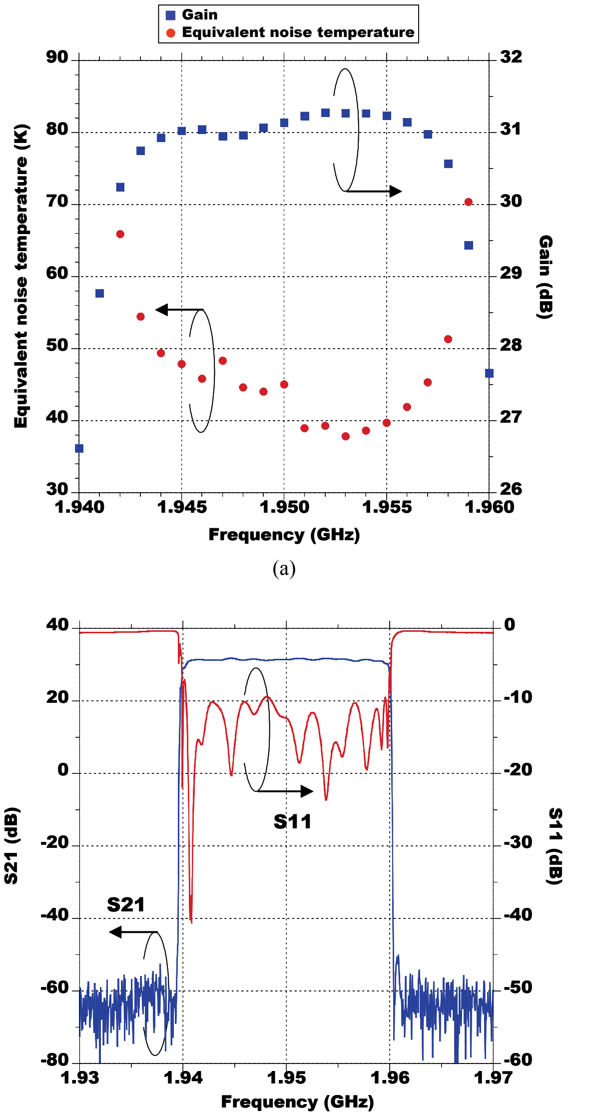


Figure 4. RF performance example of experimental CRFE measured at 70 K. (a) Equivalent noise temperature and gain. (b) Frequency characteristics.

CRFE has a center frequency of 1.95 GHz, a passband width of 20 MHz, and a sharp skirt characteristic of 20 dB/100 kHz. The average passband gain and average equivalent noise temperature are 31.3 dB and 47.9 K, respectively.

B. Improvement in sensitivity

As described in the previous section, sensitivity stands for the minimum receiving signal power level required to successfully establish a radio communication link between mobile and base stations. Thermal noise evaluation is indispensable in estimating sensitivity because sensitivity increases as the thermal noise is reduced. The equivalent noise temperature [6] is introduced as an index for evaluating the thermal noise instead of the noise figure. In Fig. 3(a), total loss from the antenna port to HTSF input is defined as L_F. From [1], the equivalent noise temperature of the CRFE, T_R, is given by

TABLE I.
PRINCIPAL CHARACTERISTICS FOR EACH COMPONENT OF CRFE

Component	Specification	Remark
HTSF	Center frequency: 1.95 GHz Passband width: 20 MHz Insertion loss: <0.5 dB	at 70 K
CLNA	Passband width: 1.9 – 2.0 GHz Gain: >30 dB Equivalent noise temperature: <25 K	at 70 K
Cryostat	Cooling capability: 2 W (77 K) Durability: five-year maintenance free (estimated)	–

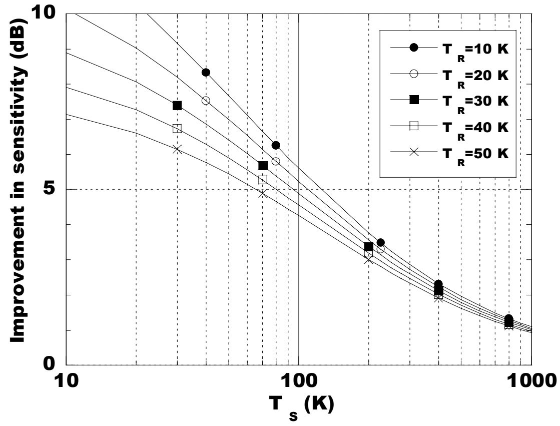


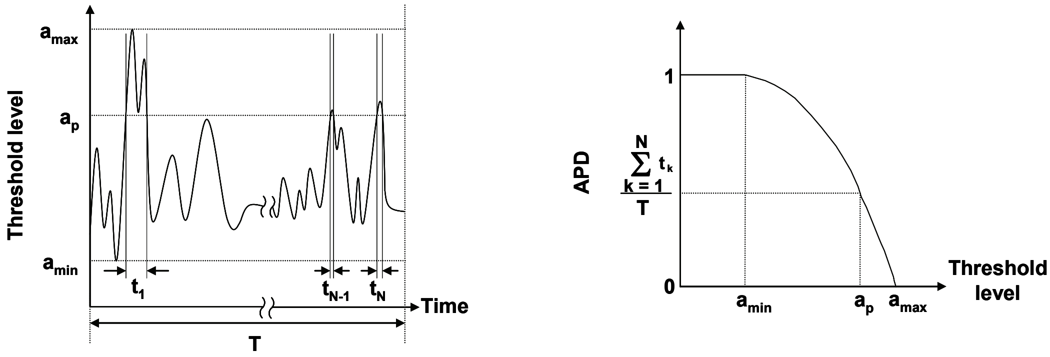
Figure 5. Improvement in sensitivity of CRFE.

$$T_R = (L_F - 1)T_0 + L_F(L_{FIL} - 1)T_C + L_F L_{FIL} T_{LNA}. \quad (1)$$

Here, L_{FIL} is HTSF loss; T_{LNA} is the equivalent noise temperature of LNA; T_0 is ambient normal temperature; T_C is cooled device temperature. L_F and L_{FIL} are antilogarithms. The contribution of the following equipment on T_R can be neglected if the CLNA has sufficient amplification gain (over 30 dB). Assuming that the equivalent noise temperature of antenna noise at the antenna port in Fig. 3(a) (hereinafter referred to as antenna noise temperature) is defined as T_S, the total equivalent noise temperature of the CRFE and antenna is given as $T_R + T_S$. When the CRFE is utilized in place of the normal temperature RFE, the improvement in sensitivity achieved can be estimated from the total equivalent noise temperature ratio given as

$$\frac{T_{R0} + T_S}{T_R + T_S}. \quad (2)$$

In this equation, T_{R0} is the equivalent noise temperature of the normal temperature RFE. The estimated T_{R0} in the 2 GHz band is typically 300 K [10]. Fig. 5 shows the calculated improvement in sensitivity. In traditional radio system design, T_S is usually set to 300 K for microwave bands. In this case, the improvement in sensitivity is estimated to exceed 2 dB if T_R is less than 50 K. In other words, it is expected from Fig. 5 to achieve the sensitivity improvement of over 2 dB by using the CRFE as the base



(a) Example of measured signal. (c) APD.

Figure 6. Definition of APD.

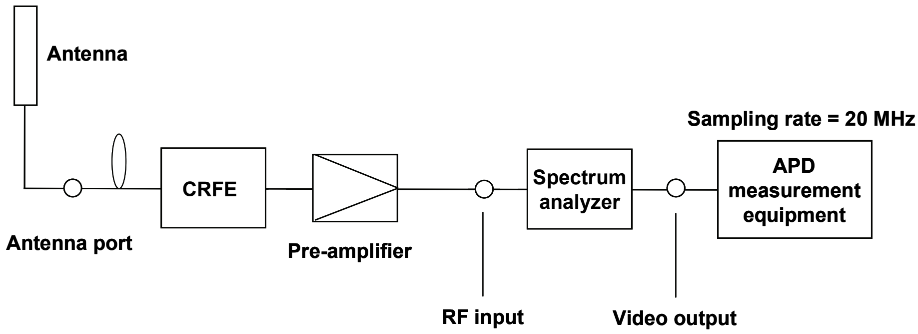


Figure 7. Configuration of APD measurement experiment.

station RFE since the CRFE attains the average equivalent noise temperature of 47.9 K.

Actual mobile base station antennas do not necessarily reach 300 K since the antenna covers some of the sky as well as the ground plane. This is because the equivalent noise temperature for the sky can be assumed to nearly equal 0 K. T_S can be regarded as 150 K for the co-linear array antennas used widely in current base stations if the antenna ohmic loss is negligibly small. Sensitivity improvements of up to 3 dB can be expected by employing an antenna with small ohmic loss and a very low noise CRFE since actual antenna noise temperatures measured in the field lie between 255 and 272 K [1].

III. Measurement System

A. Amplitude probability distribution

In this paper, the APD is defined as the percentage of time during which the impulsive signal envelope exceeds a certain threshold level. As shown in Fig. 6(a), if the measured signal envelope exceeds a certain threshold level, a_p at t_1, …, $t_{N\text{-}1}$, t_N during the time interval T, the APD is given as

$$APD = \sum_{k=1}^{N} t_k / T. \tag{3}$$

An example of the APD is shown in Fig. 6(b).

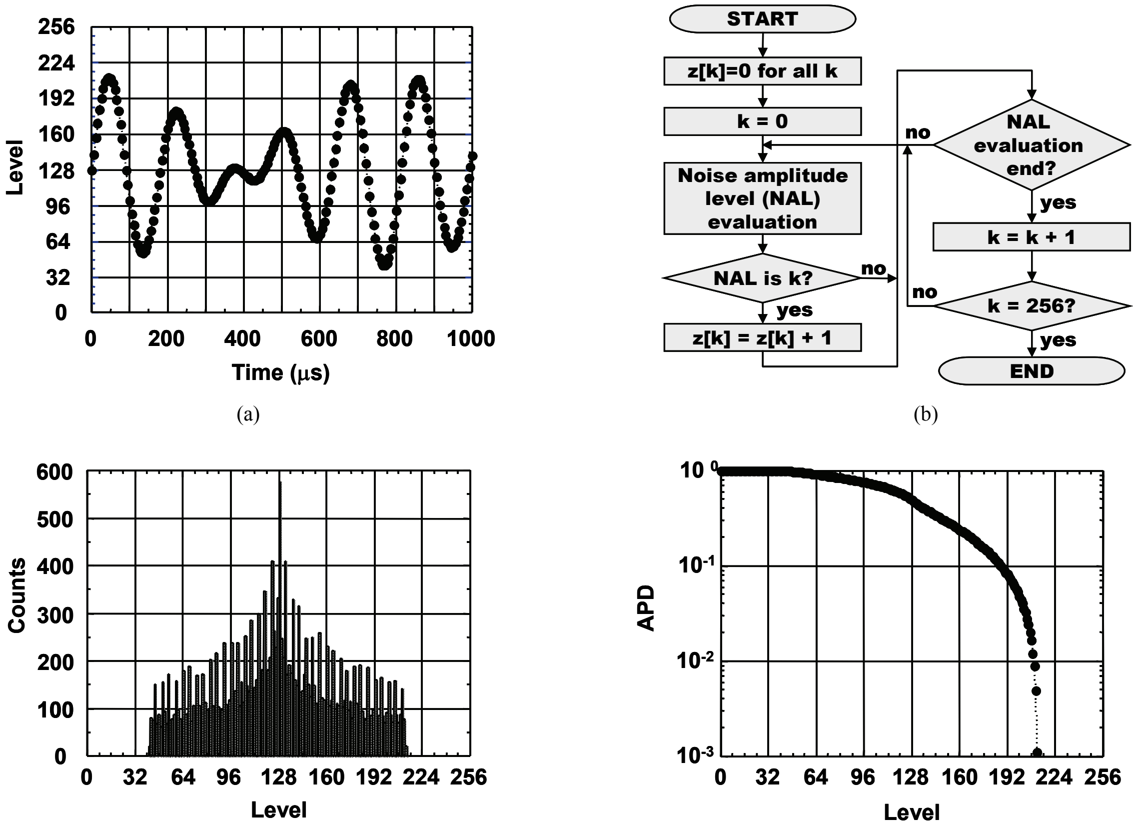
B. Measurement system

Fig. 7 shows the configuration of the APD measurement experiment. The target noise is measured at center frequency f_c of the spectrum analyzer in the zero-span mode. The intermediate frequency (IF) bandwidth, which corresponds to the resolution bandwidth (RBW) of the spectrum analyzer, must be set sufficiently wide when evaluating the instantaneous value of noise because it is difficult to observe the influence of the man-made noise if the IF bandwidth is too narrow. In other words, it is ideal to measure noise with the IF bandwidth of a specific signal when evaluating the influence of noise on that specific signal. Thus, the noise waveform observed for specific frequency f_c is derived from the video output port of the spectrum analyzer.

As shown in Fig. 8(a), the noise waveform is sampled at a sampling frequency of 20 MHz and digitized by an 8-bit A/D converter. The waveform is measured for one second, and subsequently the number of times is summarized for each value from 0 to 255 of the noise amplitude. This is performed as shown in Fig. 8(b). First, array variable $z[k]$ ($0 \le k \le 255$) is prepared and $z[k]$ is set to 0 for all k. Next, the digitized noise amplitude level (NAL) is evaluated for each sample, and one is added to the array variable of the array number corresponding to the NAL, i.e. if the NAL is k for a certain sample, then

$$z[k_1] = z[k_1] + 1. \tag{4}$$

This one-second measurement yields a histogram where horizontal and vertical axes serve as level (array index k) and counts (array value $z[k]$), respectively, as shown in Fig. 8(c). After outputting these array values to a file, they are all reset to 0 and the next one-second measurement is performed. This process is repeated for a pre-determined time interval. Thus, as shown in Fig. 8(d), if $Z[i]$ represents the total number where the noise



(c) (d)

Figure 8. Statistical process using APD measurement equipment. (a) Sampled noise waveform. (b) Noise amplitude level (NAL) evaluation. (c) Histogram. (d) APD.

amplitude becomes *i*, the APD to the threshold level *a*, APD[*a*], is given as

$$APD[a] = \frac{\sum_{i=a}^{255} Z[i]}{\sum_{i=0}^{255} Z[i]}. \quad (5)$$

IV. Measurement Results

A. 2-GHz band experiment

In this experiment, center frequency f_c of the spectrum analyzer in Fig. 7 is set to 1.949 GHz after spectrum observation of the passband width of the CRFE to avoid specific frequencies that may be used by other communication systems. The antenna in Fig. 7 is a co-linear array antenna that has a 60-degree beamwidth in the horizontal plane and a 5-degree beamwidth in the vertical plane, as shown in Fig. 9.

Zero- and six-degree beam tilt angles are used for the measurement. The measuring time interval is 1 h in the evening for each beam tilt angle. The antenna height is approximately 70 m in the suburban area, and approximately 100 m in the urban area. The IF bandwidth is set to 1 MHz because the upper limit of the spectrum analyzer used in this experiment is 1 MHz, although the IF bandwidth of the W-CDMA system is 3.84 MHz [11]. Fig. 10 shows some typical APD data for the 2-GHz band in the urban and suburban areas. In the figure, the APD measured by connecting a 290 K terminator to the input port of the CRFE is also plotted in order to determine the thermal noise level. The reference point of the abscissa in Fig. 10 is the minimum value of the noise envelope derived by connecting the 290 K terminator. The APD data for the antenna noise almost coincide with those of the thermal noise at probabilities higher than 10^{-4}. Here, the following three assumptions are employed to conduct a rough but fundamental estimation of the influence of the received noise on the W-CDMA system: (1) Thermal noise is dominant above while man-made noise is dominant below the probability of 10^{-4}. (2) The APD value is an indicator of the bit error rate (BER) measured in front of the detector. This is because instantaneous bit error might be caused when the instantaneous noise power exceeds the threshold level signifying error. (3) Although the IF bandwidth for the W-CDMA system is 3.84 MHz, the difference between 3.84 MHz and 1 MHz (used in this experiment) is inconsequential with regard to the APD characteristics.

From Fig. 10, the major noise at the corresponding amplitude probability distribution of 10^{-3} is only thermal noise since the W-CDMA system employs very strong

Figure 9. Example of experimental environment in 2-GHz band.

Figure 11. APD of antenna noise measured in 2-GHz band.

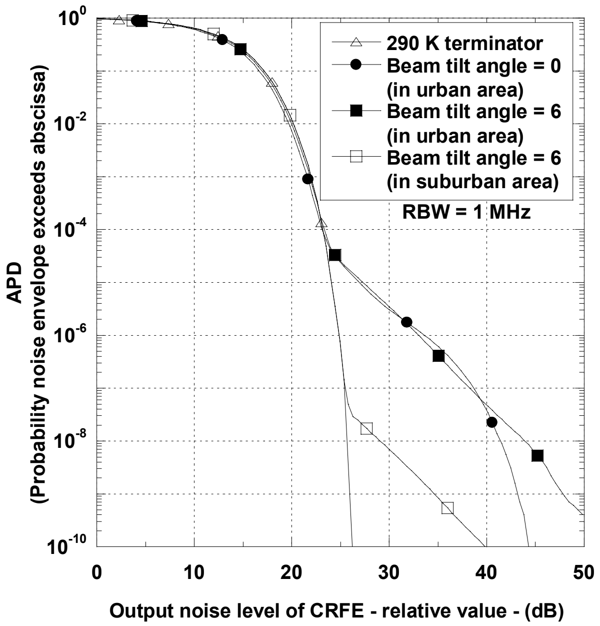


Figure 10. Example of experimental environment in VHF band.

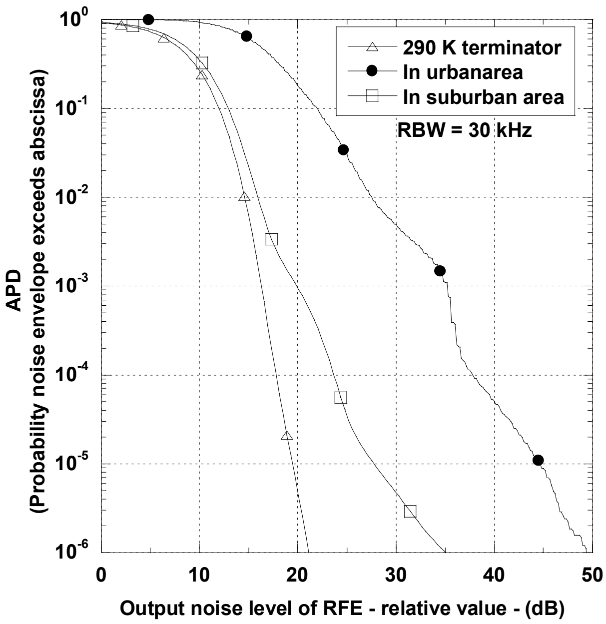


Figure 12. APD of antenna noise measured in VHF band.

error correction techniques and therefore requires a minimum BER of approximately 10^{-3} for both voice and data. This suggests that the contribution of man-made noise can be ignored as far as the W-CDMA system is concerned and sensitivity improvement offered by the CRFE will be attained.

B. VHF-band experiment

The man-made noise is also measured in the VHF-band for comparison with the 2-GHz band environment in a similar manner as the 2-GHz band experiment. However, there are some differences in the measuring configuration: (1) The RFE is used instead of the CRFE. (2) Center frequency f_c of the spectrum analyzer is set to 264 MHz. (3) The RBW of the spectrum analyzer (IF bandwidth) is set to 30 kHz. (4) A double ridged guide antenna is used, as shown in Fig. 11. (5) The antenna height is approximately 50 m in the suburban area, and approximately 95 m in the urban area.

Fig. 12 shows typical APD data for the VHF-band in the urban and suburban areas. The APD data exhibit a definite difference compared to those in the 2-GHz band. In the urban area, a 3-dB or higher noise level is observed below the probability of 0.1 compared to the case for the thermal noise. Impulsive noise can be observed around the probability of 10^{-2} and 10^{-4}, respectively. In the suburban area, the difference from the thermal noise is apparent below the probability of 10^{-2} and impulsive noise can be observed around 10^{-3} and 10^{-5}, respectively.

Experimental results suggest that the contribution of man-made noise seems to be considerable in the VHF-band, although a more detailed investigation is required to assess the sensitivity improvement based on the communication system requirements to which the CRFE is to be applied.

IV. Conclusion

This paper presented measured characteristics of man-made noise in urban and suburban areas for the 2-GHz band using the APD method in typical cellular base station antenna environments and confirmed their impact on the CRFE reception from the viewpoint of improving the sensitivity of the base station receivers. The man-made noise was also evaluated in the VHF-band for comparison with the 2-GHz band environment. Experimental results showed that the influence of man-made noise can be ignored as far as the W-CDMA system is concerned. They also implied that the influence of man-made noise seems to be considerable in the VHF-band, although there is still need for discussion on the applicability of the CRFE to the VHF-band in detail.

Measuring man-made noise in long time intervals is left as a future investigation for the purpose of seasonal factor analysis.

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