Sensitivity and Bandwidth of Low-Gain Active Antennas Below 100 MHz

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Abstract

Below 100 MHz, external noise from natural and man-made origins is typically strong enough to be the limiting factor in the sensitivity of active antennas. As a result, even antennas with very narrow impedance bandwidth may have large effective bandwidth in a signal-to-noise ratio sense. Although this principle has been known and exploited for many years, the theoretical limits of performance are not well established. In this paper, this problem is studied in the context of a simple but realistic system model which is applicable to low-gain antennas and which yields deterministic predictions of sensitivity and effective bandwidth. This has implications for the design of elements for future low-frequency radio telescope arrays as well as frequency-agile and ultrawideband radios operating at these frequencies. The analysis is demonstrated using a simple dipole-like antenna.

I. Introduction

Usually, the bandwidth of an antenna is defined as the range of frequencies over which the quality of the impedance match to connected components is acceptable, and sensitivity is limited primarily by the noise generated by these components. Below 100 MHz, however, broadband external noise from natural and man-made sources typically dominates over this internal noise. In this case, even badly-matched antennas can yield acceptable performance. This concept has been known and exploited for many years. It is the basic principle of operation for electrically-short "active antennas," commonly used in HF (3-30 MHz) communications, which tend to be strongly limited by man-made noise [1]. Design principles are well known, but are somewhat heuristic in nature. In 2000, Tan and Rohner [2] showed that an active antenna approach was also applicable to low frequency radio astronomy, in which Galactic noise is ideally the limiting factor. However, their study did not quantify performance limits; for example, it was not clear to what extent the design of the antenna and associated electronics actually limits the degree to which the signal could be Galactic noise-limited, and over what range of frequencies. Recently, Stewart *et al.* [3] have reported achieving Galactic noise-limited performance in the range 10–50 MHz using a dipole-like antenna with a simple active balun. This confirms that the concept is valid, but design rules and performance bounds remain unclear. This paper addresses these issues using a simple but realistic system model which is applicable to low-gain antennas and which yields useful predictions of sensitivity and effective bandwidth.

II. System Model

In this analysis, the signal path is modeled as consisting of an antenna connected to a preamplifier located near the antenna. The preamplifier possibly also serves as a balun (sometimes referred to as an "active balun") if the antenna is a balanced type. The antenna transfers incident power, including external noise and signals of interest, to the antenna terminals. Let us first consider Galactic noise, since it is always present. The Galactic noise power can be described in terms of the intensity I_ν integrated over the antenna pattern, such that the power spectral density at the terminals of an antenna is given by

$$S_{sky} = \frac{1}{2} \int I_\nu A_e d\Omega \quad [\text{ W Hz}^{-1}] \tag{1}$$

where A_e is the effective aperture, the integration is over solid angle, and the factor of $\frac{1}{2}$ accounts for the fact that any single polarization captures about half of the available power since Galactic noise is unpolarized. If the antenna is non-directional (approximately constant A_e over the field of view), the intensity of Galactic noise can be modeled as being spatially uniform and filling the beam of the antenna. Thus, Equation 1 simplifies to

$$S_{sky} \sim \frac{1}{2} I_\nu A_e \Omega \tag{2}$$

where Ω is beam solid angle. Although this is only an approximation to Equation 1, it is difficult to improve accuracy by using the original equation. This is because the small diurnal variation in I_ν due to the movement of different regions of the Galaxy across the sky yields about the same uncertainty as the approximation used to obtain Equation 2.

Let $G = \eta D$ be the gain of the antenna, where D is directivity and η is efficiency. η may be significantly less than 1 if either (1) Loss due to the finite conductivity of the ground is significant (possible especially below 100 MHz); or (2) the antenna is sufficiently short that ohmic loss in conductors becomes significant compared to radiation resistance. Since

$$A_e = \frac{\lambda^2}{4\pi} G \text{ , and } \Omega = \frac{4\pi}{D} \text{ ,} \tag{3}$$

we have $A_e \Omega = \eta c^2/\nu^2$ where ν is frequency, and therefore

$$S_{sky} \sim \eta \frac{1}{2} I_\nu \frac{c^2}{\nu^2} \tag{4}$$

where c is the speed of light. It will be useful to express this power density in terms of an equivalent temperature. This is possible through the Rayleigh-Jeans Law:

$$I_\nu = \frac{2\nu^2}{c^2} k T_{sky} \tag{5}$$

where k is Boltzmann's constant (1.38×10^{-23} J/K), and T_{sky} is defined to be the antenna equivalent temperature corresponding to Galactic noise. Thus we have

$$S_{sky} \sim \eta k T_{sky} \text{ , where } T_{sky} = \frac{1}{2k} I_\nu \frac{c^2}{\nu^2} \text{ .} \tag{6}$$

I_ν is known from measurements to be well-approximated by:

$$I_\nu = I_g \nu_M^{-0.52} \ \frac{1 - e^{-\tau(\nu_M)}}{\tau(\nu_M)} + I_{eg} \nu_M^{-0.80} \ e^{-\tau(\nu_M)} \tag{7}$$

where $I_g = 2.48 \times 10^{-20}$, $I_{eg} = 1.06 \times 10^{-20}$, $\tau(\nu_M) = 5.0 \nu_M^{-2.1}$, ν_M is frequency in MHz, and I_ν has units of W m^{-2} Hz^{-1} sr^{-1} [4]. T_{sky} is plotted in Figure 1(a); note that this value ranges from ~200,000 K at 10 MHz to ~ 800 K at 100 MHz.

The other possible source of external noise is the aggregate din associated with human activity. This noise is characterized in [5] in terms of four categories pertaining to human use. In each case, the associated noise power spectral density follows very nearly the same power law as the Galactic noise, but with a different intercept point. The power spectral density relative to Galactic noise ranges from about 0.3 to about 100, corresponding the "quiet rural" and "business" categories, respectively, in [5]. Thus Equation 6 can be generalized as follows:

$$S_{ext} = S_{sky} + S_{man} = S_{sky} + m S_{sky} \sim (1 + m) \eta k T_{sky} \tag{8}$$

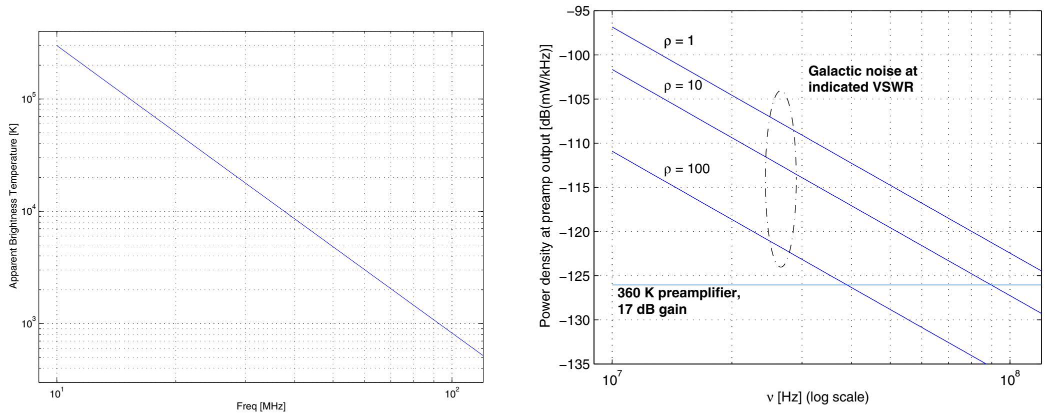
where the factor m takes on values ranging from 0.3 to 100.

The power spectral density due to external noise at the output of the preamplifier is therefore

$$S = (1 + m) \eta k T_{sky} \left[1 - |\Gamma|^2\right] G_p \tag{9}$$

where G_p is the gain of the preamplifier and Γ is the voltage reflection coefficient at the antenna terminals looking into the preamplifier and is given by

$$\Gamma = \frac{Z_p - Z_A}{Z_p + Z_A} \tag{10}$$



(a) (b)

Fig. 1. (a) Antenna temperature due to Galactic noise for a low-gain antenna; (b) Contributions to the power spectral density at the preamplifier output for constant values of VSWR, for $m = 0$ and $\eta = 1$.

where Z_p is the impedance of the preamplifier and Z_A is the impedance of the antenna. Thus, $1 - |\Gamma|^2$ is the fraction of power available at the antenna which is successfully transferred to the preamplifier. This fraction is nominally 1 but may be much less than 1 due to the impedance mismatch between antenna and amplifier.

Internal noise is due to a combination of ground noise and preamplifier noise. Ground noise is the excess antenna temperature due to the radiometric brightness of the Earth. A worst-case scenario is that of an isotropic antenna over a blackbody ground at a physical temperature of about ~ 290 K, adding ~ 145 K to the antenna temperature. For this hypothetical antenna, the antenna temperature due to Galactic noise is only $T_{sky}/2$, which at 100 MHz is about 3 times greater than the ground noise and increases dramatically with decreasing frequency. In practice, the significant conductivity of the ground results in behavior that is more like a reflector than a blackbody, so the actual ground noise is usually much less. Thus, it is reasonable to neglect the contribution of ground noise in this analysis.

The preamplifier is defined as the circuitry connected directly to the terminals of the antenna, whose purposes are typically to (1) constrain the noise temperature of the system and (2) buffer the impedance of subsequent components from that of the antenna. In this analysis, the preamplifier is described in terms Z_p, G_p, and noise temperature T_p. All three of these parameters typically exhibit some frequency dependence, but this variation is typically insignificant compared to the effect due to the variation in the antenna impedance. Also, T_p can be sensitive to the impedance match at the preamplifier input; however, this effect is technology-dependent and is difficult to model in a generic way. In this analysis, we will simply assume that this variation is insignificant compared to other effects, and note that this issue should be considered for future study. Under these assumptions, the preamplifier noise produced at the output is

$$N_p = kT_pG_p \ . \tag{11}$$

Given these findings, it is possible to determine the best possible performance that can be expected from any low-gain antenna. Figure 1(b) shows the contributions from external and internal noise at the preamplifier output in the best case scenario that $m = 0$ (no man-made noise) and $\eta = 1$ (lossless antenna above perfectly conducting ground). This plot also shows preamplifier noise for example values of $T_p = 360$ K and $G_p = +17$ dB. In this figure, S is shown for several fixed values of the voltage standing wave ratio (VSWR) ρ; for example, the $\rho = 1$ curve corresponds to a hypothetical antenna that is perfectly matched

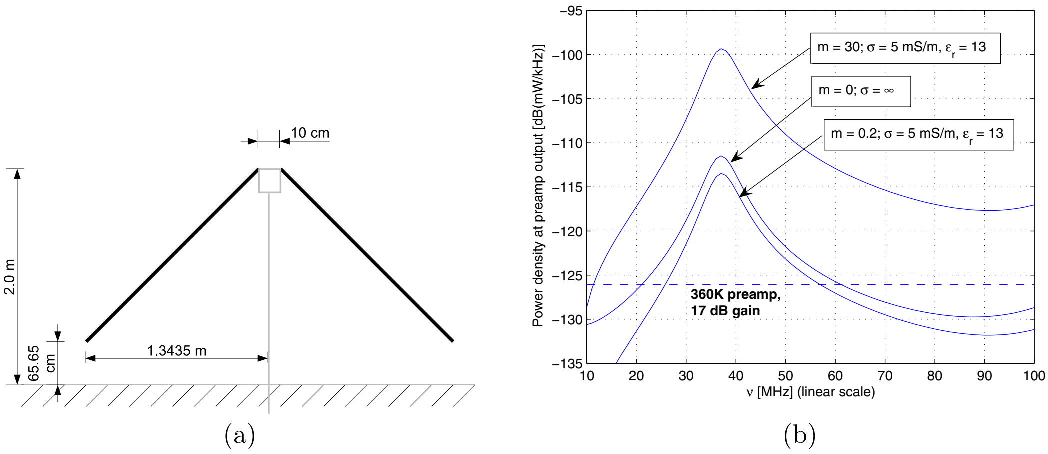


Fig. 2. (a) A simple dipole; (b) Contributions to the power spectral density at the preamplifier output.

to the preamplifier at all frequencies. Although practical antennas typically do not have constant ρ over bandwidth, this is useful for understanding how good ρ must be at any given frequency to obtain Galactic noise-limited operation. We note that a very modest T_p – on the order of a few hundred K – is sufficient to obtain very good external-to-internal noise ratio at low frequencies, even if the antenna is badly matched. This is due to the extreme brightness of the Galactic noise background.

III. Example: A 38 MHz-resonant Inverted V-Shaped Dipole

Figure 2(a) shows a simple inverted V-shaped dipole which is designed to be resonant at 38 MHz. Antennas of this general type are being designed for use in the future radio telescope LOFAR [6]. The specific design considered here is constructed from 1/2-in copper pipe, which has an outside diameter of 15.85 mm. Each arm of the dipole is 1.9 m long, resulting in resonance at $\sim$ 38 MHz. Bending the arms downward at a 45° angle improves the pattern characteristics while lowering the terminal impedance to $\sim 50\Omega$ at resonance. This antenna was analyzed using a NEC-2-based method-of-moments code, taking into account conductor losses (which turn out to be negligible in this case) and two types of ground: Ideal (perfectly conducting) and a realistic earth ground having conductivity $\sigma = 5 \times 10^{-3}$ S/m and relative permittivity $\epsilon_r = 13$. $Z_p = 50\ \Omega$ is assumed. Figure 2(b) shows that external noise-limited performance can be obtained over at a bandwidth of at least 10 MHz (26%) regardless of ground conditions and level of man-made noise. For a relatively severe $m = 30$ noise scenario, we see that the antenna is external noise-limited at all frequencies above 20 MHz or so.

Acknowledgments

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