RF link considerations for digitizing the battlespace

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ABSTRACT

The warrior to warrior communication system is a key element for digitizing the battlespace. Power efficiency, wideband operation for security, and specified bit error rate and availability are the principal requirements. The RF carrier frequencies being considered for this application range from 2 MHz to 2 GHz. This paper presents the results of a study, whose objective was to evaluate the RF link over the frequency range of interest, as an aid in the selection of a carrier frequency for achieving the largest possible coverage for the warrior to warrior communication system. The main components of the RF link are the power radiated by the transmit antenna, the propagation loss, and the background noise level at the receive antenna.

Unique to this study is the quantification of the power radiated by the transmit antenna that is consistent with the safety standard for human exposure to RF electromagnetic fields. Over the frequency range of interest the radiated power is limited by the safety standard, in addition, at the lower frequencies, the available antenna volume limits the power that is radiated. The propagation loss consists of four factors, (1) free space and ground factor, (2) slow fade factor (attenuation, diffraction and scattering in the vertical plane), (3) fast fade factor (reflection and scattering in the horizontal plane) and (4) building penetration factor. Each of these factors is evaluated separately over the entire frequency range. The background noise at the receive antenna port is found in the literature. The measure of performance is the signal-to-noise ratio at the receive antenna port for a specified signal-information bandwidth.

The results of the study indicate that, for a new type of efficient antenna, operation at frequencies below 20 MHz has the potential for communications over a set of environments ranging from a benign flat rural terrain to a severe urban environment. Without this new antenna, no one frequency band provides good performance for all environments. This new "Merenda" antenna is discussed briefly in an appendix. The benefits associated with the use of this antenna are included in the body of the paper.

Keywords: propagation, warrior-to-warrior communication, RF link analysis, radiation safety

1. INTRODUCTION

The Small Unit Operations (SUO) Situation Awareness System (SAS) System Capabilities Document has defined a performance goal to achieve specified bit error rate and service availability for the warrior to warrior communication system. The objective of this paper is to evaluate the RF link performance for frequencies between 2 MHz to 2 GHz. Of interest is determining a frequency band for adequate signal-to-noise ratio over a range of environments.

Much work has been done and published regarding cellular wireless communications [1,2,3] where the operation is from base station to user and the operating frequency is allocated by national or international authorities. Several propagation models have been developed, based on theoretical and experimental data, that are useful for predicting system coverage at the allocated frequencies and are also of some help in comparing operation at frequencies from 2 MHz to 2 GHz. The approach taken in this paper is to reduce the propagation model to component parts that can be evaluated individually over the wide frequency range and then combined to estimate the overall performance.

The signal-to-noise is computed at specified distances between the warriors. The three key elements of the computation are:

- Effective isotropic radiated power (EIRP) (0 dBi gain is assumed for the transmit antenna)
- Propagation Path Loss

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- Receive antenna noise-power (0 dBi gain is assumed for the receive antenna and the signal information bandwidth is 2 KHz)

Each of these elements is discussed below individually. They are then combined to obtain estimates of signal-to-noise versus frequency for five scenarios: (1) rural, flat terrain, 5 Km distance; (2) rural, shadowing by hill, 5 Km distance; (3) jungle, foliage canopy, 5 Km distance; (4) suburban, building-foliage canopy, 1.5 Km distance; and (5) urban, building canopy and building penetration, 0.5 Km distance.

2. EFFECTIVE ISOTROPIC RADIATED POWER

For the warrior to warrior communication system the EIRP is limited by the safety levels for human exposure to radio frequency electromagnetic fields, the available primary power, and the transmit antenna efficiency. For the purpose of this paper the IEEE Standard C98.1-1991 (controlled environment) [4] is used to determine the maximum permissible EIRP. The antenna gain is taken to be 0 dBi such that the EIRP is equal to the transmitter radiated power.

2.1. Limitations Imposed By Safety Standard

At the low end of the frequency range the safety standard and the available antenna size (volume) limit the radiated power. The available volume is assumed to be a cube that has a side of ½ meter. The antenna is essentially an electric dipole (capacitor) or a magnetic dipole (inductive loop) [5]. The radiated power for each antenna type is given below.

$P_E = V^2 G$

$P_M = I^2 R$

Where

V = Drive voltage for electric dipole (rms volts)

G = Radiation conductance for electric dipole (mhos)

I = Drive current for magnetic dipole (rms amps)

R = Radiation resistance for magnetic dipole (ohms)

Both G and R are directly related to antenna volume. It can be shown that the maximum permissible radiated power is related to the maximum permissible human exposure to electric and magnetic fields and the antenna volume as given below.

$$P_E = \frac{E^2}{\eta}\frac{8}{3}\pi^3 K \frac{vol^2}{\lambda^4}$$

$$P_H = H^2 \eta \frac{8}{3}\pi^3 K \frac{vol^2}{\lambda^4} \qquad (1)$$

Where

E = Maximum permissible human exposure to electric field (rms V/m)

H = Maximum permissible human exposure to magnetic field (rms A/m)

η = Free space impedance = 120π ohms

vol = antenna physical volume

K = factor near unity

At the higher frequencies the maximum permissible radiated power is not limited by the available antenna size, but rather, by the nearness of the warrior to the radiation source. For this situation it is assumed that the radiation emanates from a point source and that the warrior can be as close as 1/6 of a meter from the point source. For this case the permissible radiated power is given by:

$$P = P_D 4\pi \left(\frac{1}{6}\right)^2 \qquad (2)$$

where

P_D = Maximum permissible human exposure to power density (W/m^2)

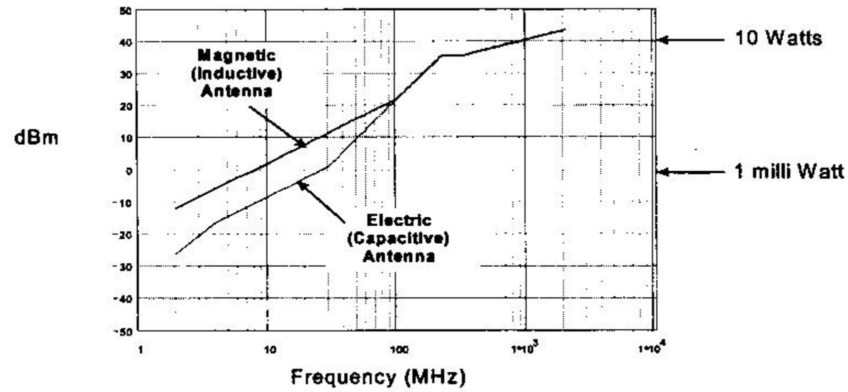

Figure 1. Permissible radiated power versus frequency.

The permissible radiated power versus frequency over the 2 MHz to 2 GHz frequency range is presented in Figure 1. The values for intermediary frequencies are determined by selecting the lesser value of Equations (1) and (2). In the discussion that follows the permissible radiated power for the magnetic antenna is used. It is noted that at the lower frequencies the safety standard permits about 10 dB greater radiated power for the magnetic antenna as compared with that of the electric antenna.

2.2. Limitations Imposed By Available Primary Power

For SUO SAS primary power is a critical system parameter. For the purposes of this paper it is assumed that 5 W of primary power is available. At low frequencies the realized radiation efficiency for a conventional wideband antenna system is given approximately by :

$$e = 7\frac{vol}{\lambda^3} \tag{3}$$

At high frequencies the realized radiation efficiency is assumed to be:

$$e = \frac{1}{3} \tag{4}$$

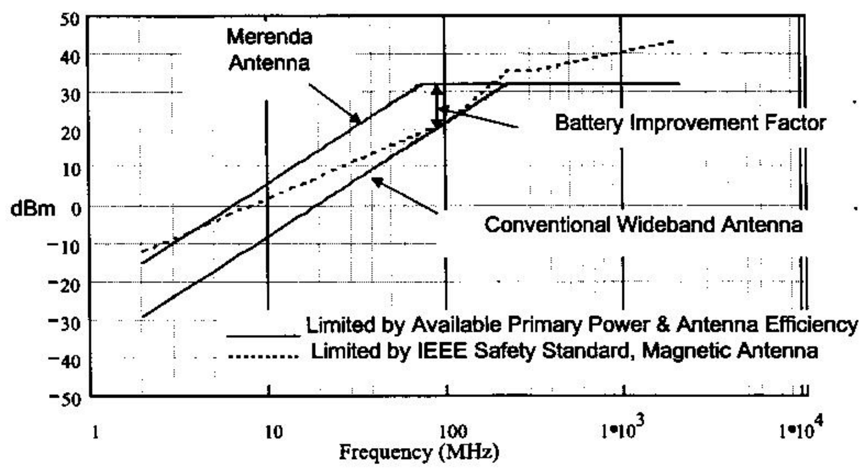

Figure 2. Radiated power limited by 5 W primary power, and antenna realized radiation efficiency.

The realized radiation efficiency includes the loss associated with the impedance mismatch at the antenna-generator interface and the power amplification efficiency.

The possible radiated power over the 2-2000 MHz band is equal to 5 W multiplied by the lesser of Equations (3) and (4). Figure 2 shows the possible radiated power versus frequency for a conventional antenna with a volume that does not exceed (1/2 meter)[3]. Shown in the figure, for comparison purposes, is the safety-standard-limited radiated power for a magnetic antenna. For the conventional wideband antenna the radiated power is limited by the primary power and antenna efficiency at all frequencies. The conventional wideband antenna is defined for electrically small antennas as the configuration where a linear amplifier is directly driving the antenna reactance.

Also shown in the figure is the radiated power for a primary-power-limited Merenda antenna system [13]. For the Merenda antenna system approach (see Appendix A) a higher efficiency transmit antenna is used for the low frequencies, and the conventional antenna approach is used for the transmit antenna at the high frequencies. The conventional receive antenna approach is used for the complete frequency band. From 2 to 3.5 MHz the radiated power is limited by available power and antenna efficiency, from 3.5 to 200 MHz it is limited by the safety standard, and from 200 MHz to 2 GHz it is limited by the available power. It is assumed that all battery power is used for the transmitter.

It is noted that the Merenda antenna can radiate higher power at the low frequencies where the limitation is now imposed by the safety standard. It should be noted that although near 100 MHz both the conventional and Merenda systems are constrained to the same radiated power by the IEEE safety standard when allowing 5 W primary power, the Merenda antenna requires considerably less battery power to realize the radiated level. Its benefit is defined by the battery improvement factor as indicated in Figure 2.

3. PROPAGATION PATH LOSS

The propagation path loss includes four factors; (1) distance factor, (2) ground profile factor (attenuation, diffraction and scattering in the vertical plane), (3) local environment factor (reflection and scattering in the horizontal plane), and (4) building penetration factor. These four factors are discussed below.

3.1. Distance Factor

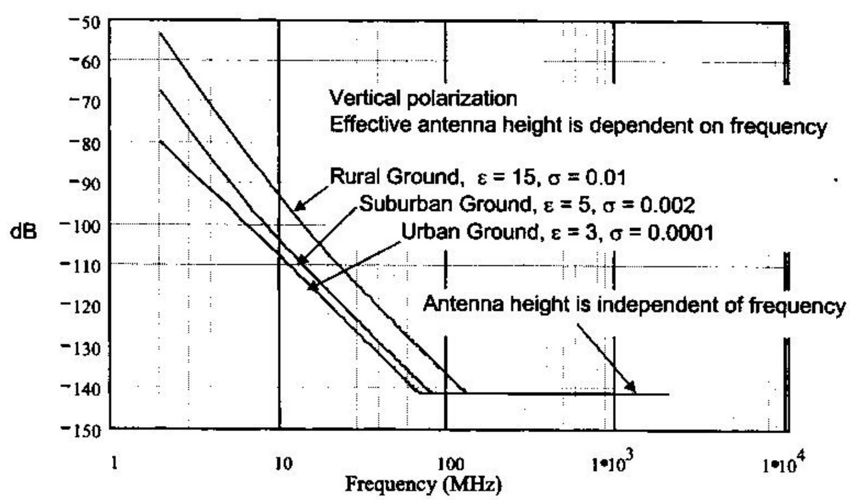

Figure 3. Flat ground distance factor, 1.5 m receive and transmit antenna height, 5 Km between transmit and receive antennas.

For the warrior to warrior communication system the required range of operation is at most 10 Km and, therefore, earth curvature effects need not be considered. A helpful model for estimating the propagation distance factor is defined below.

$$\text{if}\left(\frac{\lambda}{4\pi R}\right) < \left(\frac{H_T H_R}{R^2}\right), \text{then}, P_{DF} = \left(\frac{\lambda}{4\pi R}\right)^2, \text{else}, P_{DF} = \left(\frac{H_T H_R}{R^2}\right)^2 \quad (5)$$

Where

P_{DF} = Ratio of received power to transmitted power for isotropic receive and transmit antennas
H_T = Effective height of transmit antenna
H_R = Effective height of receive antenna
R = Distance from transmit to receive antenna
λ = Free-space wavelength

The model selects the lesser value of the free space factor $(\lambda/4\pi\pi R)^2$ or the near-ground factor $(H_T H_R/R^2)^2$.

The effective height, H_T or H_R, is the larger of h, the physical height or h_0, the electrical height [6].

$$h_0 = \left|\frac{\lambda}{2\pi z}\right|$$

where, for vertical polarizati on

$$z = \frac{\sqrt{\varepsilon - j60\sigma\lambda - 1}}{\varepsilon - j60\sigma\lambda}$$

ε = Dielectric constant of ground relative to unity in free space
σ = Conductivity of ground, mhos / meter

Figure 3 presents the distance factor versus frequency for isotropic receive and transmit antennas, 1.5 m heights for receive and transmit antennas, a distance of 5 Km between the receive and transmit antennas, and ground constants for rural, suburban, and urban environments.

3.2. Ground Profile Factor

Certain ground profiles between the warriors can substantially increase the propagation path loss by shadowing and so called "canopy" effects. The variation of this path loss with motion is generally associated with slow fading phenomena. The shadowing and "canopy" effects are described below.

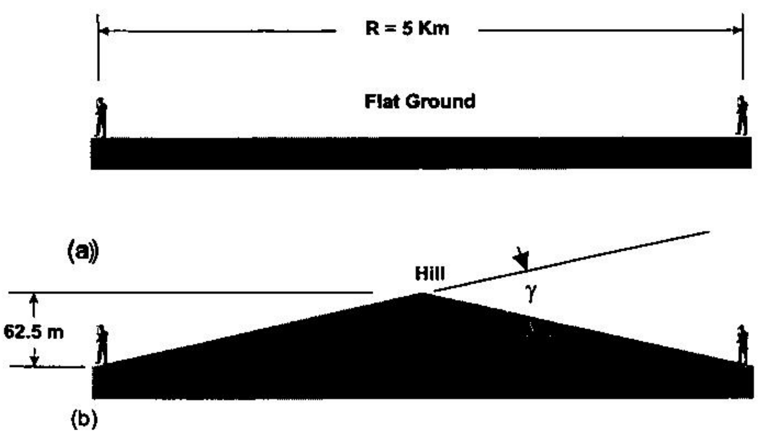

Figure 4. Ground profiles.

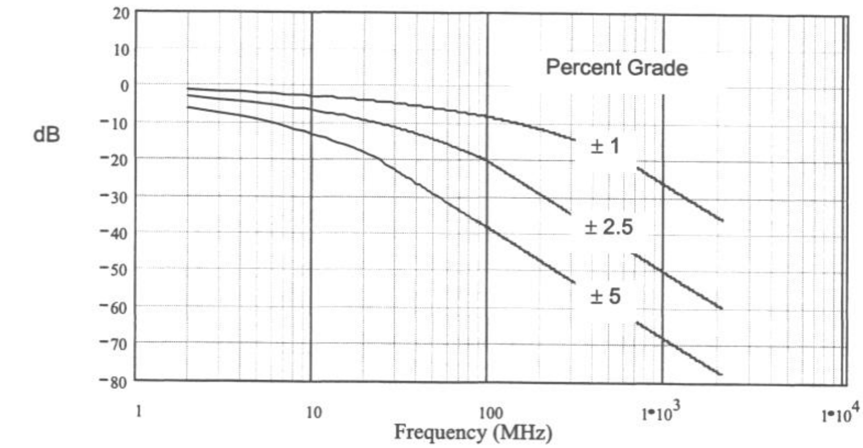

Figure 5. Hill shadowing factor versus frequency, relative to flat terrain, 5-Km distance.

3.2.1. Shadowing effects

The propagation path loss presented in Figure 3 is for a flat ground situation as shown in Figure 4a. Figure 4b shows a situation of shadowing caused by a hill with a crest height of 62.5 meters half way between two warriors (± 2.5 percent grade).

The shadowing factor, relative to the flat ground case, is given by the wedge-diffraction model [7,8]:

$$\xi = \gamma\sqrt{\frac{R}{4\lambda}} \qquad 0 \le \xi < \infty$$

$$\text{If } \xi < 1, \text{ then } dB(P_{SF}) = -20\xi, \text{ else } dB(P_{SF}) = -60\log\left(\pi^{2/3}\xi\right) \tag{6}$$

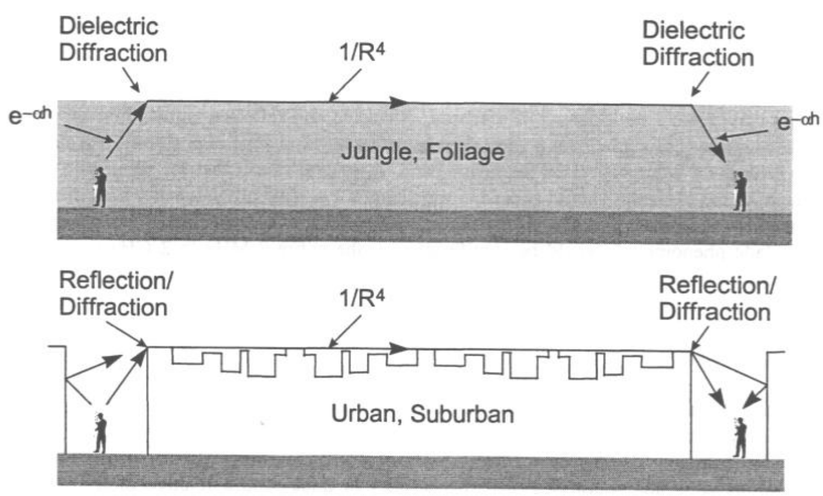

Figure 6. "Canopy" effects.

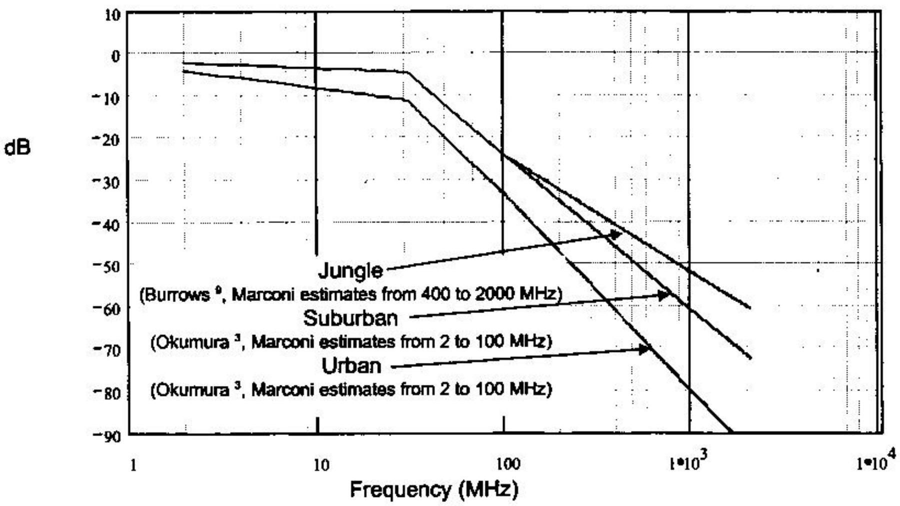

Figure 7. Canopy factor versus frequency relative to flat ground.

where

P_{SF} = Propagation shadowing factor relative to flat ground

$\gamma = \pi$ - Interior wedge angle (radians)

Figure 5 shows the shadowing factor versus frequency for the Figure 4(b) situation for grades of ± 1,± 2.5 and ± 5 percent.

3.2.2. Canopy effects

Propagation in a jungle or forest environment is described [9,10,11] in terms of a local attenuation factor through the foliage canopy and diffraction excitation at the top of the canopy of a ground (lateral) wave with a $1/R^4$ distance dependence as indicated in Figure 6. Urban and suburban environments have been found to exhibit similar characteristics. The local attenuation and diffraction is characteristic at both the transmitter and receiver sites. The propagation factor, relative to flat ground, for canopy environments is presented in Figure 7.

3.3 Local Environment Factor

The local environment can create a multiple set of scattered, diffracted and reflected signals that are associated with a fast fade phenomena (substantial loss of signal over a short time or with a small change in position). It is difficult to quantify the fast-fade phenomena over the 2 MHz to 2 GHz frequency band. A general rule is that for significant scattering, diffraction and reflection the height of the obstacles should exceed ¼ wavelength. For a suburban locality with obstacle heights of about 20 m, for frequencies below 4 MHz, the fast fade phenomena would not be significant. In an urban environment it is expected that the fast fade phenomenon would be significant over the entire 2 MHz to 2 GHz frequency band. The local environment fast-fade factor is not included in the estimates of signal-to-noise ratio for the set of environments presented in Section 5.

3.4 Building Penetration Factor

Building walls introduce additional signal loss by reflection and attenuation. Because of the great variability in the construction of building walls it is difficult to develop a theoretical model for estimating the building penetration loss factor. Some measurements [3] indicate that the penetration factor is about -15 dB for frequencies between 400 MHz and 2 GHz. A simple model that approximates this result is a wall that is 0.25 m thick with a relative dielectric constant of 4 and a

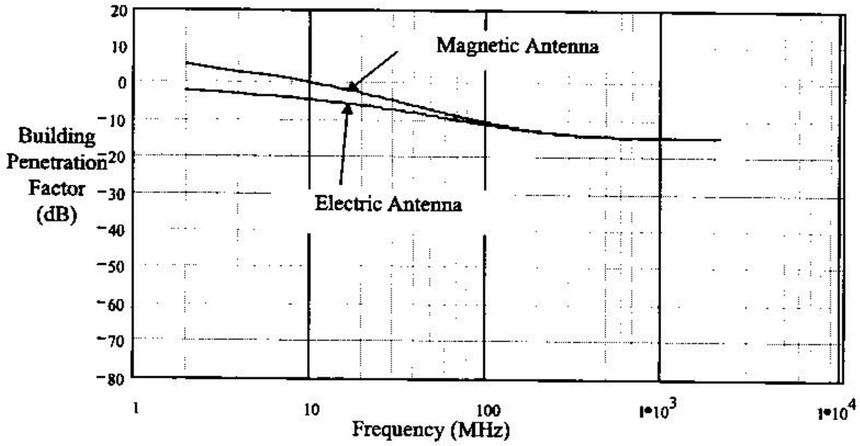

Figure 8. Building penetration factor.

conductivity of 0.025 mhos/m. The building penetration factor, P_{BP}, for this model is given by the equation below and is shown in Figure 8.

$$dB(P_{BP}) = -\frac{20}{\ln(10)} \frac{2\pi}{\lambda} \sqrt{\sqrt{\varepsilon^2 + (60\lambda\sigma)^2} - \varepsilon} \qquad (7)$$

where

ε = relative dielectric constant

σ = conductivity (mhos/m)

At very low frequencies, vertical metal columns in buildings tend to cancel the electric field and double the magnetic field [14]. This results in improved building penetration capability for the magnetic antenna at the low frequencies as shown in Figure 8.

4. ANTENNA NOISE LEVEL

Estimates of antenna noise power versus frequency are found in the literature [12]. Figure 9 shows the expected noise power for rural, suburban and urban environments. The noise power is at the receive antenna port for a 0 dBi gain antenna.

5. SIGNAL-TO-NOISE RATIO ESTIMATES VERSUS FREQUENCY

The signal-to-noise ratio is evaluated for five representative warrior-to-warrior environments. The parameters for these cases are presented in Table 1. The signal-to noise ratio versus frequency for each of these cases is presented in Figures 10. The curves presented in Figure 10 are an estimate of system performance and should be smoothed to obtain a trend over the 2 MHz to 2 GHz frequency band. The low EIRP and high noise level at 2 MHz relative to 2 GHz results in about a 20 dB advantage in the signal-to-noise ratio at the higher frequency in a benign environment, Figure 10(a). It is observed that for the first four cases presented in Figure 10, the signal-to-noise ratio for the Merenda antenna remains near or above 10 dB at frequencies below 30 MHz. For the most stringent case of the urban environment, the signal-to-noise ratio for the Merenda antenna remains near or above 10 dB at frequencies below 10 MHz. Of the three bands, HF, VHF and UHF, the HF band appears to have the best potential for operation over a wide range of environments.

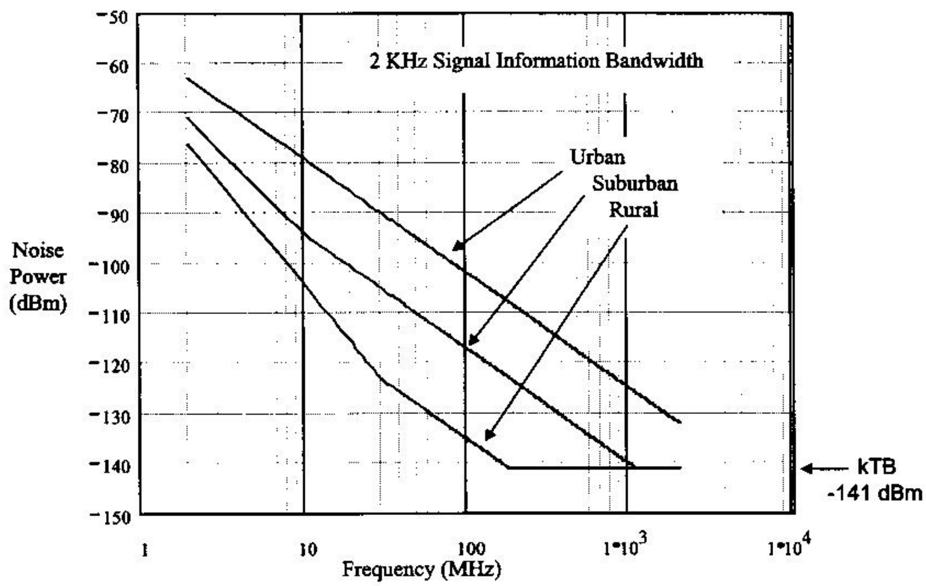

Figure 9. Receive antenna noise power

Table 1. Parameters for five representative warrior-to-warrior environments

No.	Propagation Model	Distance (Km)	Ground Parameters ε	σ	Noise Model
1	Rural, flat terrain	5	15	0.01	Rural
2	Rural, shadowing caused by rising and falling terrain, ± 2.5 percent grade	5	15	0.01	Rural
3	Jungle, foliage canopy	5	15	0.01	Rural
4	Suburban, building-foliage canopy	1.5	5	0.002	Suburban
5	Urban, building canopy and building penetration	0.5	3	0.0001	Urban

Notes:
1. ε = Relative dielectric constant
2. σ = Conductivity of ground (mhos/m)
3. Transmit and receive antenna height = 1.5 m
4. Transmit and receive antenna gain = 0 dBi
5. Signal bandwidth = 2 KHz
6. Primary power = 5 W

6. SUMMARY

This paper, perhaps for the first time, presents the conversion of a standard for safety levels with respect to human exposure to electromagnetic fields to permissible radiated power over the frequency range of 2 to 2000 MHz. Limitations imposed by the system primary power source were combined with the safety related limitations to estimate the transmit power consistent with both the safety and primary power requirements.

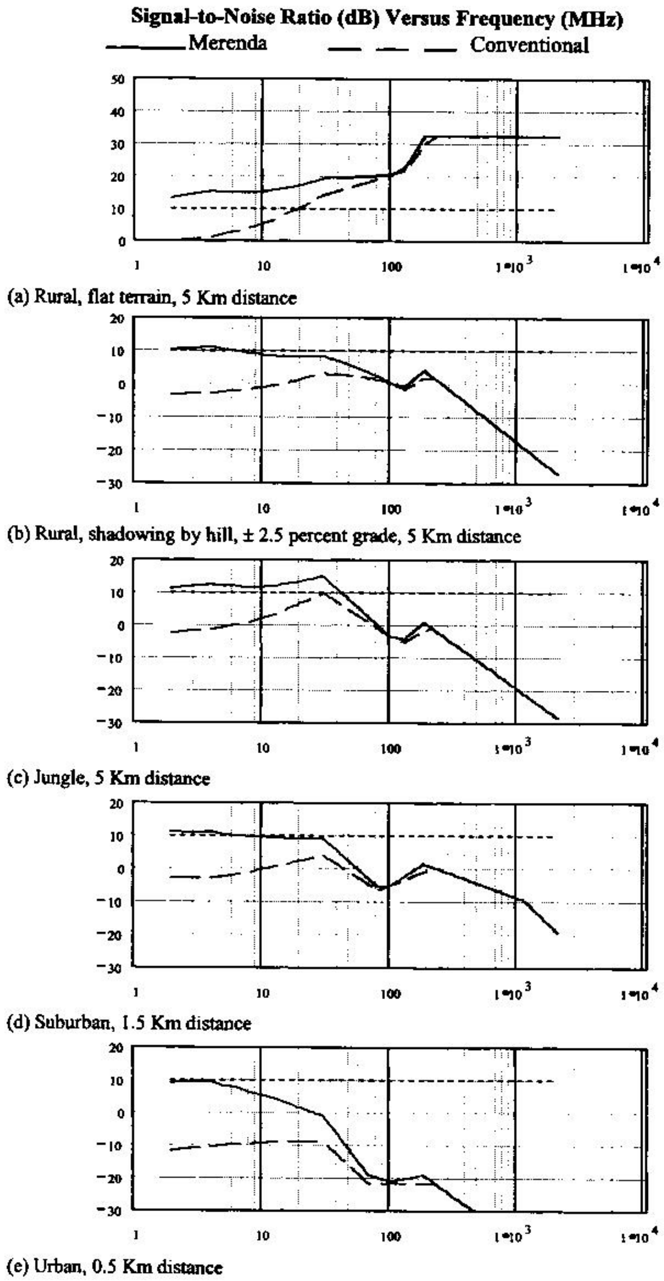

Figure 10. Signal-to-noise ratio (dB) versus frequency (MHz).

Although better SNR is realized at the higher frequencies, HF performance is more than adequate.

Adequate performance is not achieved at frequencies above about 100 MHz.

Adequate performance is not achieved at frequencies above about 60 MHz.

Adequate performance is not achieved at frequencies above about 40 MHz.

Adequate performance is not achieved at frequencies above about 10 MHz.

Only HF provides adequate performance over all environments.
With a 5 W source, UHF is limited by shadowing and building penetration.

The propagation loss factor was reduced to constituent factors that were evaluated separately and then combined to provide estimates of the overall propagation loss. The propagation loss was combined with the transmit power and noise characteristics to obtain estimates of the signal-to-noise ratio performance over the frequency band of 2 to 2000 MHz.

The results of the study indicate that, for a new type of efficient antenna, operation at frequencies below 20 MHz has the potential for communications over a set of environments ranging from a benign flat rural terrain to a severe urban environment. Without this new antenna, no one frequency band provides good performance for all environments.

APPENDIX A – THE MERENDA ANTENNA CONCEPT

The Merenda transmit antenna concept is described with reference to four components, (1) a DC primary power source, (2) an energy storage device, (capacitor), (3) an electronic switching device; and (4) a highly reactive antenna (electrically small loop antenna). The electronic switching device is used to control the transient response of the loop inductance such that the desired RF carrier frequency is generated with the desired wideband information modulation. The capacitor stores the reactive energy during the transition periods when the current in the loop antenna is changing direction. After the initial start up, the DC power supply maintains the stored energy in the capacitor at a minimum level and inhibits energy from flowing backwards. If the switching device and the loop conductor losses are zero then, in principle, a 100 percent realized radiation efficiency can be achieved. In practice, with current state-of-the-art components, about a 15 dB improvement in realized radiation efficiency can be achieved with respect to the conventional wideband antenna. The highest frequency of operation is limited by the speed of the switching device. Devices are currently available which allow operation up to about 100 MHz.

REFERENCES

1. Jakes, W. C., *Microwave Mobile Communications*, Wiley-Interscience, 1974.
2. Lee, W. C. Y., *Mobile Communications Design Fundamentals*, Wiley Interscience, 1993
3. Rappaport, T. S., *Wireless Communications*, Prentice Hall, Chap. 3, 1996
4. "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 KHz to 300 GHz.," IEEE C95.1-1991, 1992.
5. Wheeler, H. A., *Antenna Engineering Handbook*, Chap. 6, 2nd Edition, Johnson & Jasik, Editors, McGraw-Hill, 1961.
6. Bullington, K., "Radio Propagation Fundamentals," Chap. 33, *Antenna Engineering Handbook*, 1st Edition, H. Jasik Editor, McGraw-Hill, 1961.
7. Lopez, A. R., "Application of Wedge Diffraction Theory to Estimating Power Density at Airport Humped Runways," IEEE Transactions on Antennas & Propagation, pp. 708-714, June, 1987
8. Lopez, A. R., "Cellular Telecommunications: Estimating Shadowing Effects Using Wedge Diffraction," IEEE Antennas & Propagation Magazine, Feb., 1998.
9. Burrows, C. R., "Ultra-Short-Wave Propagation in the Jungle," IEEE Trans. Antennas & Propagation, vol. AP-14, No. 3, May, 1966.
10. Wait, J. R., "Asymptotic Theory for Dipole Radiation in the Presence of a Lossy Slab Lying on a Conducting Half-Space," IEEE Trans. On Antennas & Propagation, vol. AP-15, No. 5, pp. 645-648, Sept., 1967.
11. Tamir, T., "On Radio-Wave Propagation in Forest Environments," IEEE Trans. Antennas & Propagation, vol. AP-15, No. 6, pp. 806-817, Nov. 1967.
12. Jordan, E. C. (Editor), *Reference Data for Engineers: Radio, Electronics, Computer, and Communications*, 7th Edition, Howard W. Sams, Chap. 34, p. 34-9, 1985.
13. Merenda, J. T., "Synthesizer Radiating Systems and Methods," U. S. Patent 5,402,133; Mar. 28, 1995.
14. Lopez, A. R., "Loop Antenna - Enhanced Building Penetration at HF," GEC-Marconi Hazeltine Internal Memorandum, 98071401.aoi, July 14, 1998.