Propagation Comparisons at VHF and UHF Frequencies

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Abstract — **This paper presents and compares measured propagation data taken at four unlicensed-band frequencies including 151MHz, 433MHz, 902MHz and 2400MHz. A custom 10mW signal source was used as the transmitter, and a spectrum analyzer as the receiver to provide accuracy to within 1dB and sensitivity to better than -120 dBm. Both monopole and low-gain directional antennas were employed to represent expected use in an Energy Harvesting application. The measurement environment included both indoor and outdoor features. A range of up to 1.5km at the lower frequencies was achieved. The path-loss exponent was found to be approximately three to five and relatively independent of the operating band. Results confirm that lower frequencies are preferred for low-power applications when omni-directional and low gain antennas are used.**

Index Terms — **Radio, propagation, path loss, transmitter circuit, antenna, UHF, VHF.**

I. Introduction

The year 2009 marks the completion of the United States' changeover to digital television broadcasting. In the process, significant new spectrum resources will be freed-up in the UHF frequency range. Around the world, similar and even more dramatic changes are occurring [1]. In Japan, for example, frequencies formerly reserved for both VHF and UHF television will be made available to other users in 2011 [2]. In light of these changes, we have undertaken a fresh look at which frequencies are most appropriate for evolving radio spectrum assignments.

While much of the new spectrum resources will be exploited for ever-expanding cellular/PCS services, public safety and other applications also stand to benefit. In this paper, we look at finding the best frequencies to use for public safety radio systems which are highly energy constrained. For example, sensor networks could be setup on bridges and within buildings to collect structure-health information and periodically send it to monitoring sites. Ideally, these nodes would employ low-power Energy Harvesting technologies [3] so that no batteries or other maintenance would be required over periods of decades or centuries. In this application, the focus of the radio system design shifts from wideband, spectrally-efficient techniques, to those methods that optimize bits-per-joule measures.

In the sections to follow, we focus on determining the optimal frequencies of operation of such systems. While much is known about propagation at popular frequencies in the L-band and S-band spectrums, comparatively less work is available within the VHF and lower UHF frequency ranges [4-7]. These newly available frequencies theoretically exhibit lower path-loss in free-space if omni-directional or low-gain antennas are employed at either or both ends of the link. However, the path loss exponent must also be considered, as well as the ability of the waves to penetrate modern building structures. Measurements detailed below provide a preliminary verification of the advantages of using lower frequencies for energy–constrained radio systems when low-gain, low-directivity antennas are employed.

II. THEORETICAL BACKGROUND

In recent years, radio standards such as Bluetooth, 802.11, and Zigbee have focused on the relatively large, but crowded spectrum allocation from 2.40GHz to 2.48 GHz. The reasons for this have varied from common international spectrum allocations to marketing issues, and are not always technically optimum for system goals. This is easy to show using the well-known Friis Equation

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \quad (1)$$

relating received power P_r to transmit power P_t, the product of antenna directivity-gains $G_t G_r$, signal wavelength λ, and range R. For example, if both ends of the link employ simple dipole antennas with gains of 1.6 regardless of frequency, reducing the frequency of operation by a factor of 10 would result in 20dB larger received power due to the increase in wavelength. In an energy-constrained link, the somewhat larger antenna that this implies can be traded for a factor of 100 reductions in power or energy required to send a given data volume. Of course the assumption of maintaining gain and other variables constant must be carefully examined, and there is no guarantee that the equation applies for urban environments where the path loss exponent is not that of free-space.

While a theoretical treatment of all of these issues is outside the scope of this paper, we note that the assumption on antenna gain is valid if both ends of the link employ omni-directional patterns – since gain and directivity are fundamentally linked. Whether or not this is a valid operating case depends on system goals, and on physical size issues associated with antennas. For many applications, however, including that introduced in section I, one or both ends of the link should be relatively non-directional. Hence, in the study undertaken here, we examine only the cases of non-directional antennas at both ends, or use of a directional antenna at one end only. The final issue – whether the equation applies for non-free-space environments – will be answered in the measurement results discussion of section IV.

III. EXPERIMENTAL SETUP

In this study, four unlicensed-band frequencies' propagation, including indoor and outdoor environment performance, were measured. The testing environment was selected in accordance with the construction monitor application and the highest received powers at various distances were measured and recorded.

A. Experiment environment

The testing locations were based at Kansas State University. The room, RA2097, on the 2nd floor (Figure I) of the engineering building, Rathbone Hall (yellow

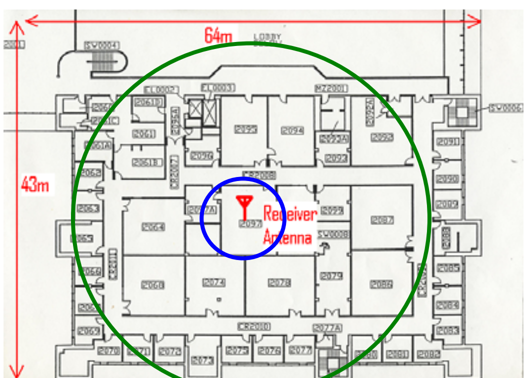

Figure I. Indoor propagation testing environment.

highlight in Figure II), was selected as the receiver's location. This building contains four floors (with basement) consisting of a concrete foundation, concrete wall supports, concrete slab floors with metal supports, and dry wall. The spaces between floors and walls contain power and cable lines, air conditioning ducts, fire protection sprinklers, and steel piping. Due to its structural makeup, this building serves as a good representative testing environment for construction monitoring applications. Indoor signal strength measurements were recorded at points of varying transmission radii away from the receiver location as indicated in Figure I.

The outdoor measurement paths were located northwest and northeast of the Rathbone Hall due to the fairly open terrain, but included several obstructions including buildings and trees. The longer northeastern blue path in Figure II was chosen due to its elevation of 50 meters above the receive site to add an assessment of a less obstructed path within the dataset.

Figure II. Outdoor propagation testing environment.

Two similar sized buildings are located north at distances of 0.16km and 0.27km while a taller building is located 0.21km northeast. These are the main objects causing signal diffraction. Located east of the engineering building is the main campus whose buildings are far more congested. This area will serve as a future measurement objective with more complex propagation environments.

B. Antennas

Figure III on the next page displays all the antennas used in the measurements. For the omni-directional tests, monopole antennas were constructed. The antennas used as directional antennas were commercial panel and Yagis.

The lengths of the monopole antennas were determined from basic antenna theory, which says the antenna's length $\lambda/4$ is inversely proportional to its operating frequency f according to:

$$\lambda = \frac{c}{f} \tag{2}$$

where c is the speed of light and λ is wavelength. The resulting antenna sizes are large when compared with a small RF circuit board, but the antenna size can be reduced to 1/10th of a wavelength using coil or ceramic loading, without significantly impacting overall efficiency.

Another important concept is antenna effective aperture. An antenna's aperture indicates the effective size of the antenna which can collect energy from passing electromagnetic waves. For a half-wave length dipole antenna, the effective aperture of a dipole is calculated by

$$A_e = \frac{\lambda^2}{4\pi} G_A \tag{3}$$

which can be used as an estimate for the monopole antennas used here[8], since their ground planes are truncated.

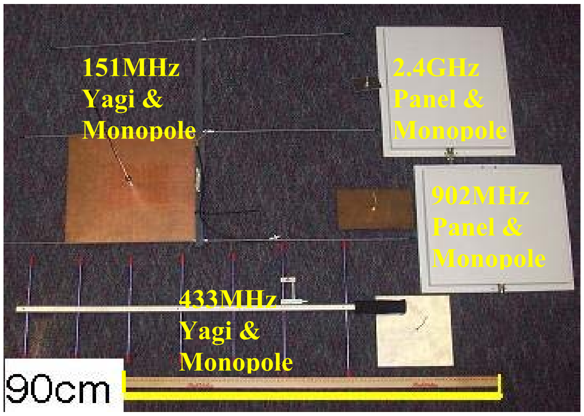

Figure III. Antennas used in testing.

Table I shows the relationship between the frequency, quarter-wave length and the effective aperture of dipole antennas when G_A equal to one. Note that the effective area of the 151MHz case is over two orders of magnitude larger than that at 2400MHz, providing the benefits previously discussed for operation at lower frequencies.

TABLE I THE QUARTER-WAVE ANTENNA SIZE AND EFFECTIVE APERTURE OF DIPOLE ANTENNA

Frequency (MHz)	Quarter-wave Length $\lambda/4$ (cm)	Effective Aperture of Dipole Antenna (cm^2)
151.94	49.36	3102
433.92	17.28	380
902	8.31	97.92
2400	3.12	12.39

To validate the antenna constructions, reflection coefficients of all antennas were measured prior to use. S11 of the quarter-wave length antennas ranged from -12dB to -30dB. The reflection coefficient S11 of the directional antennas ranged from -15dB to -35dB.

C. Transmitter and Receiver

The transmitters were designed to output constant 10mW un-modulated signals and were placed in metal boxes to make them more portable. The transmitter circuit includes a power supply, frequency synthesizer, amplifier, and an output harmonic filter.

An Agilent N9320A spectrum analyzer was used as the receiver. The minimum receive power of this equipment, with the preamp enabled, is lower than -130dBm. Since a common receiver with bandwidths on the order of 10kHz can receive a -120dBm signal, this spectrum analyzer was considered adequate.

IV. EXPERIMENT RESULTS

The experiment covered indoor and outdoor environments up to a range of 1.5km. Using room RA2097 as the center location, four circles were scribed with two indoor (7m and 30m) and two outdoor (40m and 90m) radii. Each circle contains four measurement locations. Beyond 90 meters, the points were not fixed.

Figure IV shows the comparison of using directional antennas at the transmitter. From the figure, on average, the 151MHz signal strength is 6dB better than 433MHz, 9dB better than 902MHz, and 19dB better than 2400MHz at same distance point. At the same receive power level, -120dBm, the 151MHz, 433MHz, 902MHz, and 2400MHz can achieve a distance of 1.46km, 0.672km, 0.537km and 0.198km, respectively. Finally, note that the received signal power experienced a step decrease around 50m because of an indoor/outdoor boundary. With this, the 151MHz, 433MHz, 902MHz, and 2400MHz experienced a 12dB, 10dB, 20dB and 29dB of excess path loss, respectively.

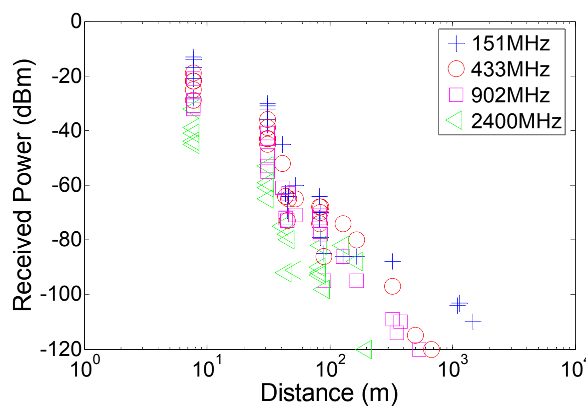

Figure IV. Four frequencies measured received powers versus distance with omni-directional antenna at one end and directional antenna at the other end of the link.

Figure V shows the comparison between using directional antennas and quarter-wave length monopole antennas at one end of the link for each frequency. For 151MHz, the directional antenna can improve reception by 6dB over using the monopole antenna on average. Using the same setup for 433MHz, 902MHz, and 2400MHz, the reception improved by 8dB, 12dB, and 12.5dB, respectively. These numbers are generally consistent with the gains of the antennas used, and partially, but not fully, offset the advantages of operating the link at lower frequencies. The green and magenta trend lines are used to show the indoor and outdoor path loss exponent N. For indoor, N is from 3

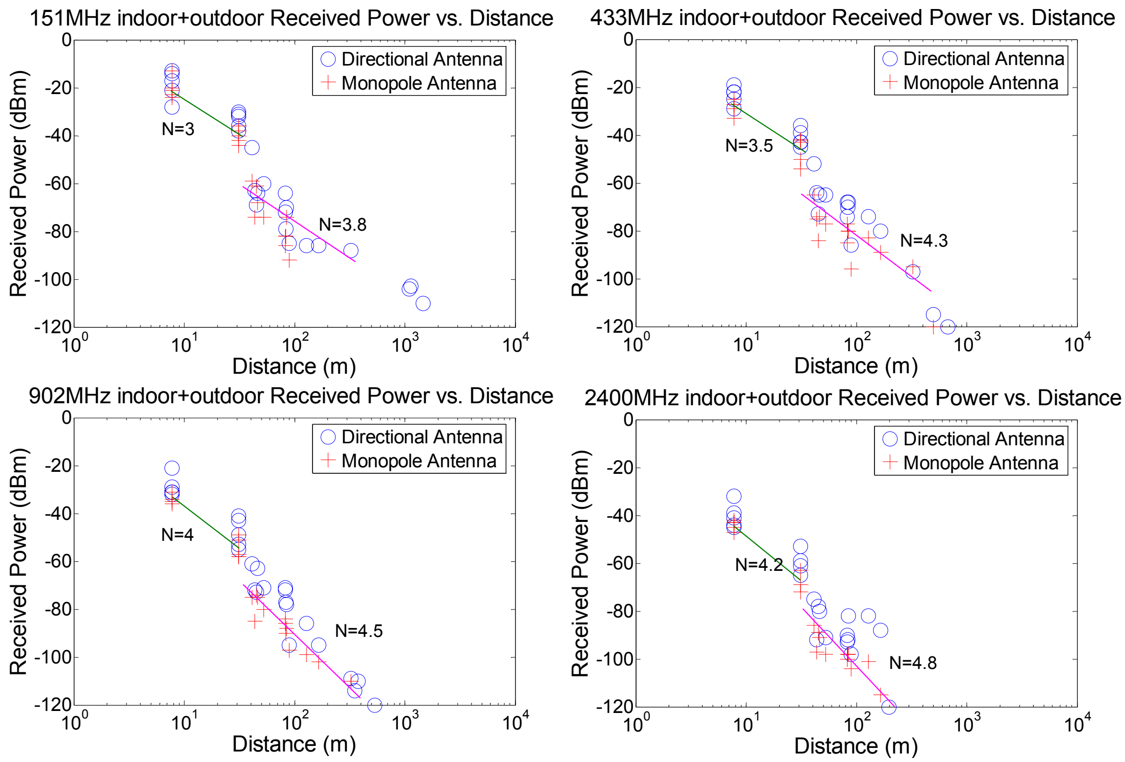

Figure V Four frequencies comparison with Path loss Exponent

to 4 and for outdoor, N is between 4 and 5. These results are consistent with results from [9] where path loss exponents vary between 2.8-5.3.

V. CONCLUSION

From the experimental results, it is easy to see that the propagation distance is inversely proportion to the operating frequency. This matches behavior predicted by the Friis equation when low-directivity antennas are used. Due to the varying wavelengths from 12 cm to 2 m, the influence of reflection, refraction, and diffraction are different for each frequency. In other words, small-scale propagation becomes more complex to model and compare. These measured results confirm that lower frequencies, such as 151MHz and 433MHz, are preferred for long-distance, power-constrained applications employing relatively omni-directional antennas.

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