16th European Signal Processing Conference (EUSIPCO 2008), Lausanne, Switzerland, August 25-29, 2008, copyright by EURASIP

EFFECT OF ANTENNA HEIGHT AND POLARISATION ON SHORT WIRELESS LINKS

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ABSTRACT

A characterization of the short range (< 100 cm) narrow-band wireless channel is presented, appropriate to a dense network of wireless transceivers operating in the 2.4 GHz ISM band. Transmission loss measurements have been made in vertical and horizontal polarisations using rectaxial antennas for a range of antenna heights and separation distances. A preliminary interpretation of the results suggests that surface wave propagation may be significant for short wireless links such as might be used in sensor network applications.

1. INTRODUCTION

Electromagnetic waves may be classified as sky waves, space waves and surface waves (e.g. [1], [2]). Surface waves are sometimes referred to as ground waves (although this term has also been used to describe the combination of direct and surface-reflected space waves.) Sky waves are reflected from the ionosphere (at HF frequencies and below) and can be used for long range communication. Here we are concerned with very short range communication, such as may be encountered in sensor networks, at microwave frequencies where only space and surface-waves are plausible.

Space waves travel, essentially unbound, via the direct line-of-sight path, reflected paths and (sometimes) refracted paths. Surface waves are (at least loosely) bound to the surface over which they propagate. There are various stages of transition between space and surface waves, and in practical wireless communication problems a clear division between the two is often difficult to draw [3].

The presence of a surface in close proximity to the communicating devices potentially modifies both wave generation and propagation mechanisms. It has been suggested [3] that in most situations surface-wave effects can be neglected if both transmitting and receiving antennas are elevated more than one wavelength above the surface. Conversely, and again in [3], it has been shown that surface waves can be significant if VHF antennas are located within less than one wavelength of the surface. Much existing work on surface wave propagation (e.g. [3], [4]) relates to long-range and relatively low-frequency communications. It is asserted in [1], for example, that surface wave effects are negligible for frequencies above 100 MHz and can be ignored for horizontal and vertical polarisations provided accuracies of the order of 1 dB are acceptable.

Transceiver nodes in future, densely-packed, wireless sensor networks (e.g. specknets [5]) will be small and are expected to be deployed close to (effectively on) the ground or other surface (e.g. walls, floors, ceilings etc.). With node elevation above the surface measured in centimetres, or even millimetres, it is possible that surface-wave propagation will be significant. In addition to link geometry (antenna heights and link length) and surface character (permittivity, conductivity and roughness). Polarisation might also affect the proportion of power carried by a surface-wave.

This paper reports transmission loss measurements made at 2.45 GHz over centimetric range paths between a pair of antennas with millimetric clearance over a plane surface, and makes an initial assessment of the impact of surface waves.

2. PROPAGATION MODELS

Many models (e.g. Castlia [6], Avrora [7],) have been proposed to predict radio link transmission loss but these invariably have been developed for applications typified by macro-, micro-, and pico-cellular systems with path lengths greatly in excess of those being considered here.

The propagation models used to describe indoor wireless channels can be broadly divided into free-space (Friis), the two-ray (plane-Earth) and shadowing varieties, the latter two incorporating fading due to multipath propagation. The free-space model may be adequate if line-of-sight (LOS) propagation is dominant (i.e. if multipath from environment boundaries and clutter is weak.). The path loss then increases with range at a rate of 6 dB/octave. The two-ray model is a more realistic if a second ray (typically reflected from a single plane surface) is significant. For path length greater than the farthest range of constructive interference, the path loss then increases with distance at a rate of 12 dB/octave.

The shadowing model is more complicated and considers fading effects caused by multipaths mainly due to fast fading. Although with short ranges (as envisaged by specknet) flat fading is expected.

For a relatively simple indoor communication link it is common to assume free-space propagation for ranges less than d_c and two-ray propagation for ranges greater than d_c, e.g.

[8]. The break-point, (d_c,), often referred to as the crossover distance, is typically given by:

$$d_c = \frac{4\pi h_t h_r}{\lambda} \tag{1}$$

where h_t and h_r are transmit and receive antenna heights above the plane surface, respectively, and λ is wavelength.

3. SURFACE WAVES

A simple, but fundamental, model [1] of propagation that accounts for LOS space-wave, surface reflected space-wave and surface-wave is given by Equation (2).

$$P = \left| \frac{e^{-jKd}}{2Kd} \left[F_d + F_r[\Gamma + (1-\Gamma)A] \right] e^{-j\phi} + \ldots \right|^2 \tag{2}$$

Here F_d represents the direct (LOS) wave and F_r represents the reflected wave which includes amplitude correction for added distance travelled. Γ is the (frequency-dependent) surface reflection coefficient which depends on incident wave polarisation and surface permittivity and conductivity. ϕ is the additional phase delay for the reflected ray. The remaining component represents the surface wave. A is the (complex) surface-wave factor with a magnitude less than one given by [1]:

$$A = \frac{-1}{1 + jkd\left(jkd\left(\Gamma + sin(\theta) \right) \right)^2} \tag{3}$$

where d is the path length from transmitter to receiver, k is wave number, θ is incidence angle at the surface which depends on the node height and separation distance, and Γ is the ground reflection coefficient for vertical and horizontal polarisation. The surface-wave factor depends on incident wave polarisation, frequency and surface properties. Figure 1 illustrates its dependence on several of these parameters.

Surface-waves are significant for devices operating close to a surface. For small grazing angles the reflection coefficient Γ is approximately -1 and the line of sight and surface reflected waves approximately cancel leaving the surface-wave to dominate. A decreases with increasing node separation and antenna height (the incidence angle θ and the reflection coefficient Γ changes with antenna height). The following observations are made with respect to Figures 1(a) – (d).

- $|A|$ decreases with increasing frequency (Figure 1a).
- $|A|$ is larger for vertical polarisation than for horizontal polarisation (Figure 1a)
- $|A|$ decreases with antenna height for vertical polarisation and is small and approximately constant for horizontal polarisation (Figure 1b).
- $|A|$ increases with increasing surface permittivity for vertical polarisation and is small and approximately constant for horizontal polarisation (Figure 1c).
- $|A|$ increases with increasing surface conductivity for vertical polarisation and is small and approximately constant for horizontal polarisation (Figure 1d).

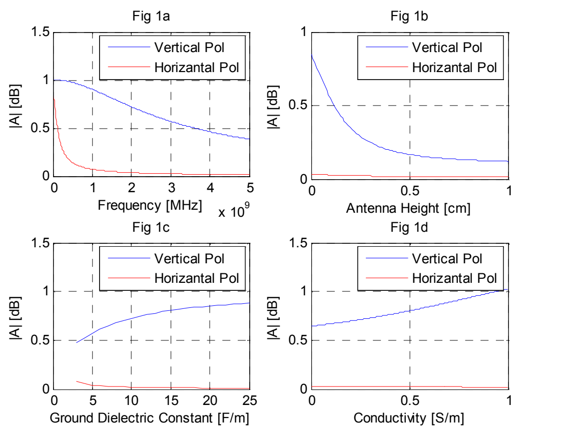

Figure 1 - Variation of surface-wave factor magnitude (εr = 7, σ = 0.005 S/m and f = 2.45 GHz unless implied otherwise)

4. METHODOLOGY

The effect of antenna height has been investigated using a pair of identical rectaxial antennas [9]. An Agilent E4438C ESG vector signal generator was used as a source to generate a 2.45 GHz unmodulated carrier with a power of 0 dBm. Received power was measured using an Agilent E4440A spectrum analyzer. The measurements were carried on a plane, horizontal, surface (Figure 2(a)) of laminated chipboard (thickness, length and width 2.5 cm, 180 cm and 160 cm respectively).

The linearly polarised antennas were oriented to radiate vertically (± 2^o), Figure 3(a). The largest dimension of the radiating element is 13 mm (see [9] for antenna description) and the antenna's nominal phase-centre is assumed to be located at this element's mid point. The height (h) of the antenna above the surface is defined as that of the nominal phase centre, Figure 2(b). The distance between transmit and receive antennas was set to 10 cm with the antenna fed from above. Since the antennas are electrically small the significant near field extends to approximately one wavelength.

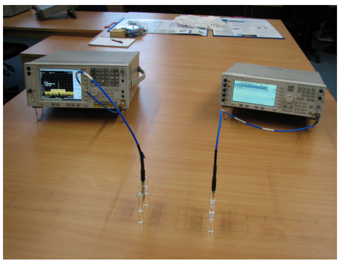

Figure 2(a) - Measurement setup

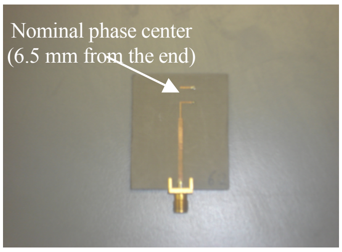

Figure 2(b) - Rectaxial Antenna

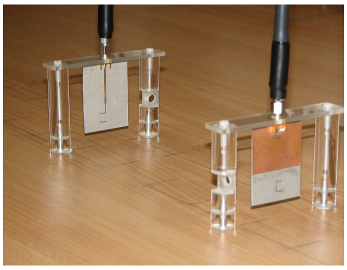

Figure 3(a) - Vertically polarised measurements

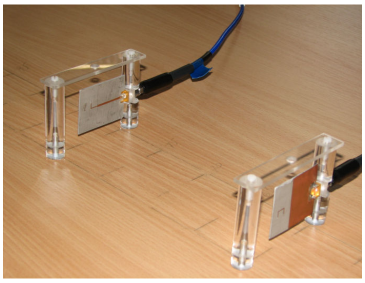

Figure 3(b) - Horizontally polarised measurements

The antenna heights were increased from 0.65 cm to 5.65 cm (since the antenna nominal phase center is 6.5 cm from the end as in Figure 2(b)), in increments of 1 cm. (The heights of both transmit and receive antennas were the same for all measurements.) Antenna separation was increased from 10 cm to 50 cm in increments of 10 cm. Received power was recorded for each distance-height pair. For each distance-height combination ten measurements were recorded, the test-bench being displaced by at least one wavelength between measurements allowing averaging to reduce random errors. (Displacement allows any (weak) spatial fading due to multipath propagation to be treated as a component of random error.)

Additional measurements were carried out for the same range of antenna heights with transmits-receive antenna spacing of 75 cm and 100 cm. Path length, antenna height and received power were measured with accuracies better than ±1mm, ±0.5mm and ±1 nW, respectively.

The above procedure was then repeated with antennas oriented to radiate horizontally (± 2°).

5. RESULTS

The results of the measurements are summarised below.

5.1 **Vertical Polarisation**

Received power measured (after averaging) for vertical polarisation as a function of antenna separation and antenna height is shown in Figure 4.

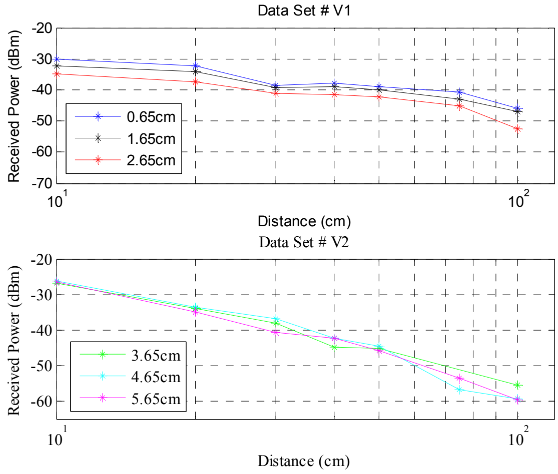

Figure 4 - Received power versus antenna separation and height for vertical polarisation (Data separated in to sets V1and V2 on the basis of antenna height dependence)

The measurements have been divided into two sets. Set V1 contains measurements satisfying $h \leq 2.65$ cm. Set V2 contains measurements satisfying $h \geq 3.65$ cm. The data for each set are shown in Figure 4.

The following observations are made with respect to data set V1.

- Received power decreases with increasing antenna height, see also Figure 5. (A decrease in antenna height from 2.65 cm to 1.65 cm yields a power increase, averaged over all antenna separations, of 2.02 dB. A decrease in height from 1.65 cm to 0.65 cm yields a further improvement of 2.63 dB.) This might be explained by a dominant surface-wave component of coupling between the antennas which gets weaker as the antennas move farther from the surface. This interpretation is consistent with Figure 1(b).
- Mean specific transmission loss is 17.5 dB/decade between 10 cm and 100 cm. This suggests that for data set V1, the measured data follows, at least approximately, a free space law, i.e. 20 dB/decade, see Figure 6.

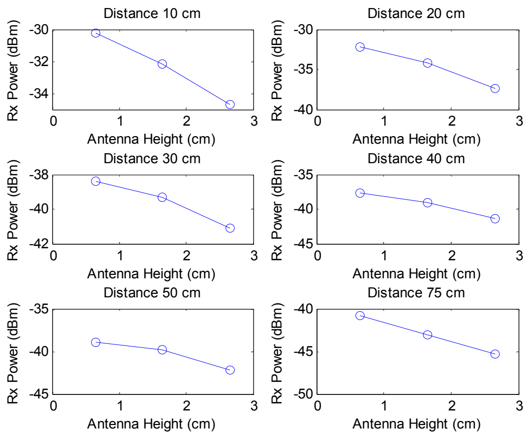

Figure 5 - Received power versus antenna height (Data set V1)

The following observation is made with respect to data set V2.

- Increasing antenna height above 2.65 cm has no significant effect on received power. This suggests that any surface-wave effect has decayed to a negligible level leaving only space-wave (LOS plus surface reflection) coupling between the antennas.
- For antenna height greater than 2.65 cm the gradient of the measured data (mean specific transmission loss is approximately 40 dB/decade), further suggesting two-ray behaviour for separations greater than the cross-over distance, see Figure 6.

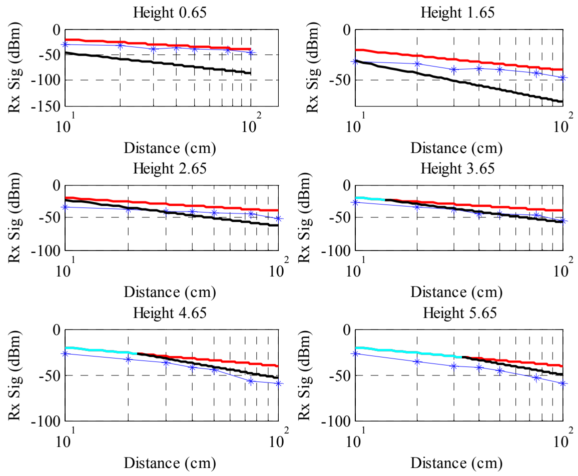

Figure 6 - Received power for vertical polarisation (in blue), free space model (in red and cyan), two-ray model (Black)

5.2 Horizontal Polarisation

Received power measured (after averaging) for horizontal polarisation as a function of antenna separation and antenna height is shown in Figure 7.

The measurements have been divided into two sets. Set H1 contains measurements satisfying h ≤ 2.65 cm. Set H2 contains measurements satisfying 3.65 cm ≤ h. The data for each set are shown in Figure 7.

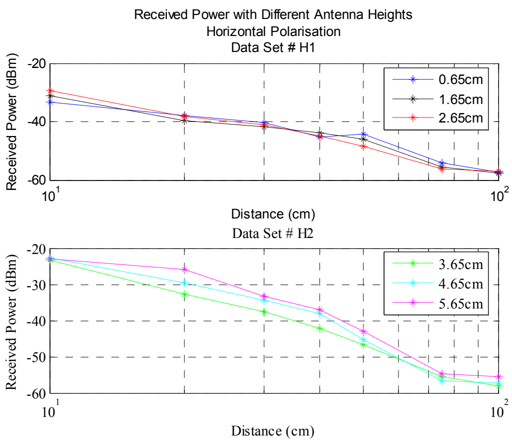

Figure 7 - Received power versus antenna separation and height for horizontal polarisation (Data separated in to sets H1and H2 on the basis of antenna height dependence)

The following observations are made with respect to data set H1.

- There is no clear, systematic, dependence of received power for antenna height ≤ 2.65 cm. Also the propagation loss is greater for horizontal polarisation (for $h \leq 2.65$ cm, data set H1) than for vertical polarisation (data set V1), see also Figure 8. The mean difference between vertical and horizontal polarisation (data set V1 and H1) for three different antenna heights is given in Table 1. Since horizontally polarised electric field is parallel to the surface the induced surface currents are higher than those for a vertically polarised field. This might be expected, therefore, to give rise to greater attenuation due to higher conduction and/or displacement current losses.

Table 1

Mean Difference in Receive Power for vertical and horizontal polarisation (data set V1 and H1)

Height [cm]	Mean Power difference [dB]
0.65	8.64
1.65	7.77
2.65	5.43

- It has been observed in Figure 9, that at low antenna heights (h ≤ 2.65 cm) the mean gradient is 24.0 dB/decade. The gradient is larger (more negative) than that for vertical polarisation indicating greater attenuation.

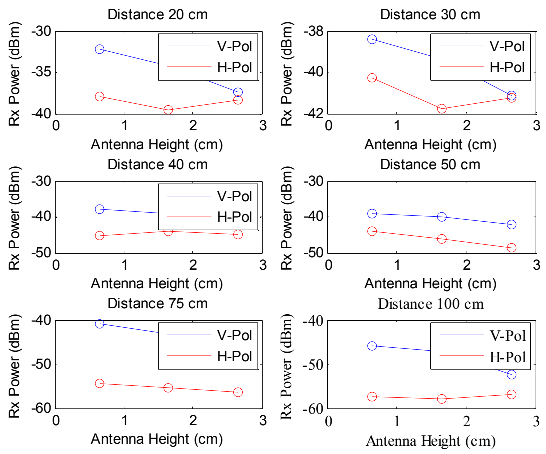

Figure 8 - Received power for vertical and horizontal polarisation (date set V1 and H1).

The following observations are made with respect to data set H2.

The losses generally increase as transmit and receive antenna heights are reduced until height ≤ 3.65 cm. (This is not true for the shortest path length, i.e. 10 cm.)

- For antenna heights ≥ 2.65 cm, the gradient for separations greater than the cross-over distance (42.0 dB/decade) suggests a two-ray model.

- Received power averaged over antenna height is less for data set H1 than for data set H2. This suggests an increasing propagation loss with decreasing height for horizontal polarisation as in Table 2.

Table 2

Average Difference in Receive Power for horizontal polarisation (data set H1 and H2)

H	Average Received Relative Power [dB]					
	10	20	30	40	50	100
cm	cm	cm	cm	cm	cm	cm
H1	-30.9	-38.3	-41.2	-44.6	-45.8	-57.3
H2	-23.0	-28.5	-30.6	-38.5	-44.7	-56.9
Diff	7.9	9.8	10.2	6.1	1.2	0.4

- The spread of received power for various antenna heights decreases with increasing antenna separation (Table 3). This may reflect the diminishing surface-wave effect with distance. If this interpretation is correct then for antenna separations greater than 50 cm, the surface-wave effect could be neglected, see Figure 7.

Table 3

Standard Deviation for Horizontal Measurement

Antenna Height [cm]	Separation Distance [cm]	Standard Deviation [dB]
0-5	10	4.67
0-5	20	5.49
0-5	30	3.61
0-5	40	3.57
0-5	50	1.98
0-5	75	0.92
0-5	100	0.87

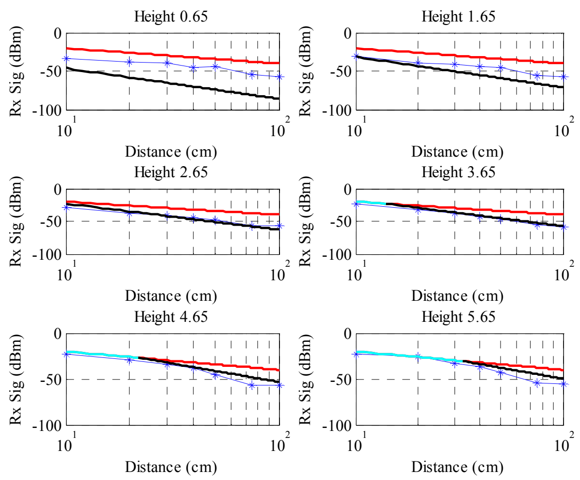

Figure 9 - Measured powers for horizontal polarisation (in blue), Free space model (in red and cyan), Two Ray model (Black)

6. CONCLUSION

The study has related transmission loss to antenna height and polarisation for short wireless links as envisaged by specknet [10]. Speck nodes are autonomous with there own energy source. They are small in size (< $5mm^3$) and are meant to communicate for short ranges (< 15 cm). Since the specks are small and are likely to be deployed close to surfaces, significant improvement in received power can be achieved by appropriate selection of antenna height. Vertical polarisation results in smaller transmission loss than horizontal polarisation.

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ACKNOWLEDGEMENT

The specknet consortium (www.speckmet.org) is acknowledged for its role in the funding and shaping this program of work.