Exploring RSSI Dependency on Height in UHF for throughput optimisation

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***Abstract*—This paper considers exploiting the unique outdoor propagation characteristics of the Ultra High Frequency (UHF) band to optimise wireless network deployments. The relationship existing between signal strength and antenna height in UHF band is analysed. Received signal strength increases steadily with an increase in receiver antenna height up to about 8.5 m above ground, which can be explained in part by the resulting effect of Fresnel zone and obstacle clearance such as typical house height in the area. When raised beyond 8.5 m further signal strength gain stifles, possibly due to effects of multi-path fading. The contribution of this paper is firstly, the implication of Received Signal Strength Indicator (RSSI) dependency on height and secondly, the consideration of throughput corresponding to RSSI thresholds.**

I. Introduction

The success of WiFi can be attributed in part to the free nature of the spectrum band. But as currently deployed, performance of WiFi back-haul links is repressed by obstacles such as walls, interference in some cases and limited transmission range among other drawbacks. To leverage the performance of these license-exempt links, use of Dynamic Spectrum Access (DSA) to utilise alternative spectrum that has better propagation characteristics has been proposed. The initial focus is on the Ultra High Frequency (UHF) band because of the band's propagation properties and spectrum availability in rural areas [1].

IEEE 1900.1-2008 [2] defines Dynamic Spectrum Access (DSA) as, *"the real-time adjustment of spectrum utilisation in response to changing circumstances and objectives"*. These circumstances and objectives include quality of service, interference avoidance (afflicted or inflicted), etc. DSA has also been suggested as the enabler of the degree and extent of connectivity required for 5G networks.

DSA is aimed at maintaining optimum performance amid the dynamics of the wireless medium. Therefore, there is need to have a system in place for performance prediction, which should be used with DSA to determine optimal operating parameters. The task of predicting performance is difficult due to the myriad sources of performance variability.

The intent of this paper is to focus on one of the components affecting performance namely, the effect of receiver antenna height on received signal strength. Other researchers, e.g. in [3], have shown that throughput is dependent on signal strength. These results are used to show achievable throughput by adjusting the height.

II. Background and related work

Throughput is usually among key performance objectives of any communication network. Literature [4], [5], [6], [7] is replete with work on efforts aimed at improving throughput. TABLE I lists the various throughput optimisation techniques commonly applied at each of the layers of the *OSI* reference model. From the literature surveyed, the bulk of effort is concentrated at the upper layers. While higher-layer protocol level optimisation is essential to exploit physical layer capabilities, in practice such enhancements can only improve performance within the confines of the underlying physical connectivity. Therefore, optimisation at the physical layer is of paramount importance.

There are several physical layer components that affect the quality of service but, signal strength and signal-to-noise ratio (SNR) are among the key elements commonly used to describe channel quality.

A. Throughput as a function of Signal strength

Throughput is determined by the signal-to-noise ratio (SNR) and modulation used. A higher modulation scheme requires a higher SNR.

$$SNR = \frac{signalpower}{noise + interference}, \tag{1}$$

$$noise = kTB, \tag{2}$$

Where k is the Boltzmann's constant = 1.38×10^{-23} Joules Kelvin^{-1}, T is absolute temperature in kelvin, B is the channel bandwidth. In our study T = 300K and B = 10 MHz respectively.

Every device supports only a limited number of modulation schemes used. There is a range of SNR values within which it can operate: below a certain SNR no modulation works; above a certain Received Signal Strength Indicator (RSSI), the RF input may get saturated.

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TABLE I
THROUGHPUT OPTIMISATION TECHNIQUES COMMONLY APPLIED AT EACH OF THE LAYERS

Application	Application layer routing techniques
Presentation	
Session	
Transport	Congestion control techniques.
Network	Multi-path routing where data packets are forwarded on multiple paths at the same time.
Data	Link scheduling techniques that try to mitigate interference by assigning a set of time slots to each link in which it can transmit. Link adaptation techniques where transmitter aims to reduce packet error rate by switching to a higher or lower transmission rate in response to changes in link quality.
Physical	Reconfigurable antennas, Multiple input multiple output (MIMO) antennas each having an independent data flow.

TABLE II
SNR AT BER OF 10^{-6} FOR DIFFERENT MODULATION AND CODING FORMATS

Modulation	**Uncoded**[1] **(dB)**	**Coded (RS200,190)**	**Coded (RS204,188)**
2 PSK	10,5	7,5	6,8
4 QAM	13,5	10,5	6,8
8 PSK	18,8	15,5	14,8
16 QAM	20,5	17,2	16,5
32 QAM	23,5	20,4	19,7
64 QAM	26,5	23,4	22,7
128 QAM	29,5	26,3	25,6
256 QAM	32,5	29,3	28,6
512 QAM	35,5	32,1	31,4
1024 QAM	38,7	34,8	33,9
Derivation of SNR at BER of 10^{-8} and SNR at BER of 10^{-10}			
BER		**SNR "maximal"**	
10^{-6}		3 dB coding gain	
10^{-8}		SNR at BER of 10^{-6}+1,5 dB	
10^{-10}		SNR at BER of 10^{-6}+3 dB	
[1]The values of SNR for uncoded systems from 2 PSK to 512 QAM are taken from Recommendation ITU-R F.1101 [10]			

B. Throughput as a function of SNR and BER

Throughput is often expressed in terms of "goodput" i.e. the amount correctly transferred data per unit time, which is irrespective of the rate of transmission [8]. *"Goodput" G* may be expressed as

$$G = R \times 1d(M) \times (1 - PER), \quad (3)$$

where R is a PHY mode dependent variable, M is the number of constellation points of SNR, PER is the packet error rate approximated from bit error rate (BER) as follows

$$PER \simeq 1 - (1 - BER/b)^N, \quad (4)$$

where b is a variable dependent on SNR and N is the number of bits in the packets [4]. Acceptable BER is dictated by the specific application. TABLE II shows the SNR for a given BER, which is dependant on the coding and modulation format [9].

These expressions show that higher throughput requires higher modulations and thus SNR; higher SNR requires higher signal strength/RSSI and low interference. The next section deals with experimental exploration of this result.

III. EXPERIMENTAL SETUP

The objective of the experiment was to investigate the correlation between RSSI and receiver antenna height and establish the relationship among height, RSSI and throughput in the UHF band. In the absence of additional equipment and to avoid the need for a spectrum license, the local television broadcasting was used as a source of the reference signals. The receiving hardware setup included a R&S FSH4 spectrum analyser, a 2.1 dBi R&S omnidirectional antenna and short cables, all mounted on a boom lifter as shown in Fig. 1. The spectrum analyser was connected to a wireless router placed on the boom lifter and controlled from a laptop in the vehicle over a WiFi network.

The measurement procedure involved lifting the arms of the boom lifter with the measurement setup, measuring the actual height above ground using a laser range finder, and perform a frequency scan (set and triggered from within the vehicle, over the wireless network). The results of a scan would be saved into a data file. This was repeated several times for each value of height.

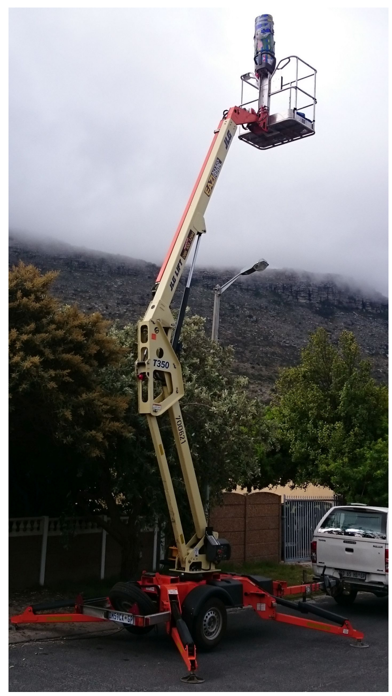

Fig. 1. Setup of antenna covered with a low permittivity radome mounted on boom lifter used to perform measurements.The spectrum analyser (not visible) is placed below the antenna.

Each frequency scan was done from 451.25 MHz until

1,081.25 MHz with resolution bandwidth of 1 MHz and video bandwidth of 3 MHz. The choice of frequency and resolution bandwidth was dictated by two factors: (i) the need to capture the video carriers of analogue television transmissions (which are located around 1.25 MHz from the left edge of a television band), and by the limitations on the number of point in a single sweep that can be used by the spectrum analyser, i.e. fixed to 631 points.

The measured values, in dBm, reflect the power at the input of the spectrum analyser. These can be translated into the field strength E_{inc} incident onto the antenna by taking into account the losses in the cables and connectors (about L_c=1dB) and applying the antenna factor AF for the selected antenna (which is a function of this antennas gain G_A and wavelength $\lambda = 3{\times}10^8/f$, where f is the frequency in Hertz (Hz)). The antenna factor AF is defined as the ratio of electric field $E_{inc}(V/m)$ to voltage at the antenna terminals V (Volts), i.e.

$$AF = \frac{E}{V}, \tag{5}$$

where AF = antenna factor (m^{-1}), E = electric field (V/m) and V = voltage at antenna terminals [11]. When AF and the signal level at the antenna are given in decibels and decibel-microvolts ($dB\mu V$) respectively, E is calculated by adding the signal level at the antenna and the antenna factor as shown in equation (6).

$$E_{[dB(\mu V/m)]} = V_{[dB(\mu V)]} + AF_{[dB(m^{-1})]}, \tag{6}$$

The voltage induced at the antenna terminals, V, may be related to the power sent from the antenna into the cable, P, as $V = \sqrt{50\Omega \times P}$. AF may be expressed in terms of wavelength and gain in a 50-ohm system as follows:

$$AF = \frac{9.73}{\lambda\sqrt{G_A}}[m^{-1}], \tag{7}$$

In dB, it may be written as

$$AF_{[dB(m^{-1}]} = 19.8 - 20.log_{10}(\lambda) - 20.log(G_A), \tag{8}$$

where G_A is the antenna gain, which is 2.1 dBi for the equipment used in this study. The conversion of the signal level measured in dBm to $dB\mu V$ for a 50Ω system is done as follows:

$$dB\mu V = dBm + 90 + 20 \times log(\sqrt{z}), \tag{9}$$

where z is the system impedance, which was 50Ω for the setup used in this study.

A. Calculating RSSI on a channel

The *START* and *STOP* frequencies of television channel $N \in [21, 69]$ can be determined as

$$\begin{aligned} START &= 470 + W(N-21)\ [MHz] \\ STOP &= 478 + W(N-21)\ [MHz], \end{aligned} \tag{10}$$

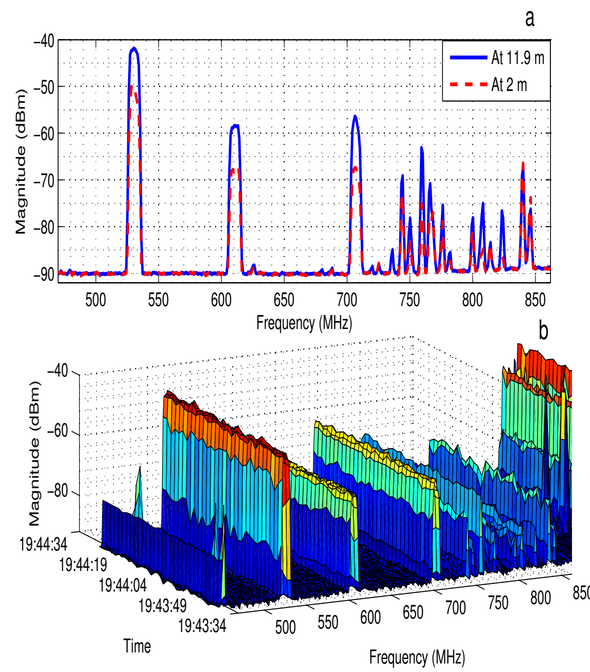

Fig. 2. Overview of measured spectrum scan results.

where W = 8 MHz is the channel width. In this paper the RSSI on a channel is computed by (i) converting the received signal in dBm to power in Watts, (ii) summing the elements within W MHz channel, and (iii) converting the sum back to dBm. In each channel, the channel power is computed as integral power within $START$ and $STOP$ at the channel.

IV. Discussion of results

Fig 2 (a) shows the raw measured spectrum scan results from 470 MHz to 862 MHz encompassing television channels 21-69. The figure shows the signal strength measured at 11.9 m and 2 m above ground, averaged over 31 samples. There is a small marginal difference between the measurement at 11.9 m and 2 m when the signal is weak (typically below -80dBm). However, we observe a significant difference in the measured electric field strength between the two heights for stronger signals (above 50 $dB(\mu V/m)$).

In order to get an idea of variations in spectrum during the measurement period, the electric field at the main height is plotted against the time of measurement as shown in Fig. 2 (b).

The graph of the measured RSSI at each height is shown in Fig. 3. The results presented here are for a single selected channel, UHF channel 27. A similar trend in the dependency of RSSI on height was observed for other channels that had a strong signal.

WiFi cards adjust modulation rate based on RSSI value in accordance with the *modulation and coding scheme* (MCS) value. The change is done at specific optimal threshold values.

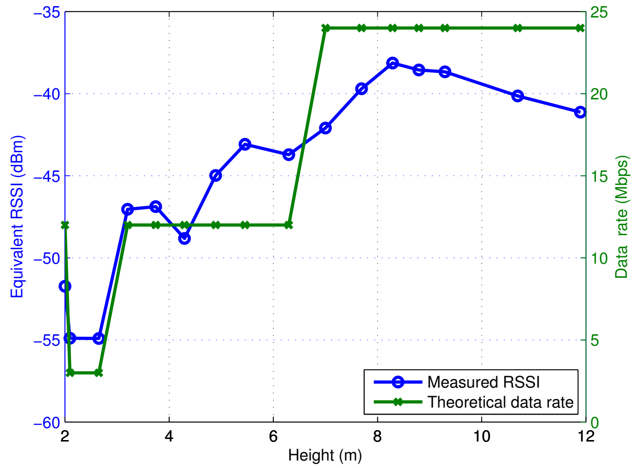

Fig. 3. Measured RSSI dependency on height and achievable throughput (Mbps) for given RSSI thresholds.

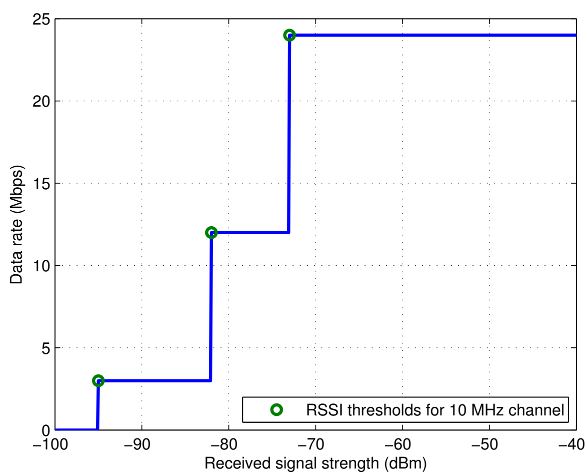

Fig. 4. RSSI thresholds for 802.11g radio data rates. These values are based on Doodle lab DL587-78 wireless cards [12].

The data rate corresponding to RSSI threshold is shown in Fig. 4. This assumes a low (e.g -100 dBm) steady unchanging noise floor. The results of achievable throughput improvement resulting from the gain in RSSI are shown in Fig. 3. The curve *"theoretical data rate"* shows the results of applying a model to the measured RSSI value shown as the *"measured RSSI"* curve on the same plot. The model down-scales the measured TV signal power by 30 dB to model a TVWS transmitter signal. Fig. 4 curve is then used to translate the resultant TVWS RSSI value into the theoretical data rate. These thresholds depended on the PHY mode. The data rate corresponding to RSSI threshold is expected to hold the most in places such as rural areas with clean spectrum and no television signal even in side-bands that could push-up the noise floor due to non-perfect spectral masks. The baseline performance of the wireless cards used in the study is shown

TABLE III
EXTRACTED FROM DL587-78 WIRELESS CARD DATA SHEET

Parameter	**Tx/Rx Specification**					
	5 MHz channel			10 MHz channel		
Radio Data Rate (Mbps)	1.5	6	12	3	12	24
Typical TCP/IP data throughput	1.3	4.3	7	2.5	8	14
Modulation	BPSK	16 QAM	64 QAM	BPSK	16 QAM	64 QAM
Rx Sensitivity (± 2 dBm)	-96	-86	-76	-95	-82	-73

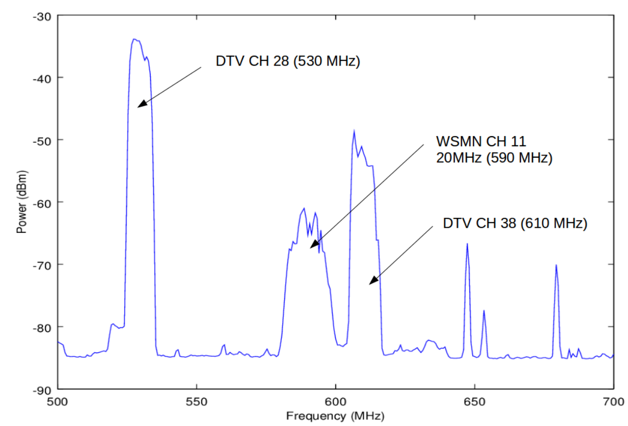

Fig. 5. Spectrum scan of WSD transmission on Channel 11 (590 MHz centre frequency) with 20 MHz bandwidth achieving 479 kbps TCP throughput from 1.5 km away (Signal strength -62 dBm, Noise: -73 dBm).

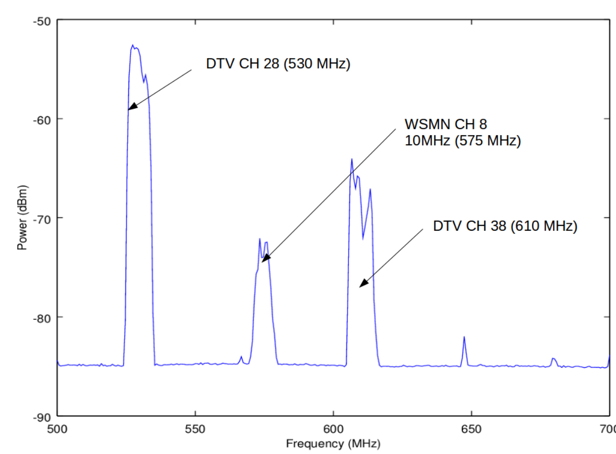

Fig. 6. Spectrum scan of WSD transmission on Channel 8 (575 MHz centre frequency) with 10 MHz bandwidth achieving 2813 kbps TCP throughput from 1.5 km away (Signal strength -63 dBm, Noise: -93 dBm)

in TABLE III.

As Fig. 3 shows, when the height increases, RSSI increases and higher RSSI thresholds correspond to higher data rates. Based on the measurements conducted, the RSSI dependency

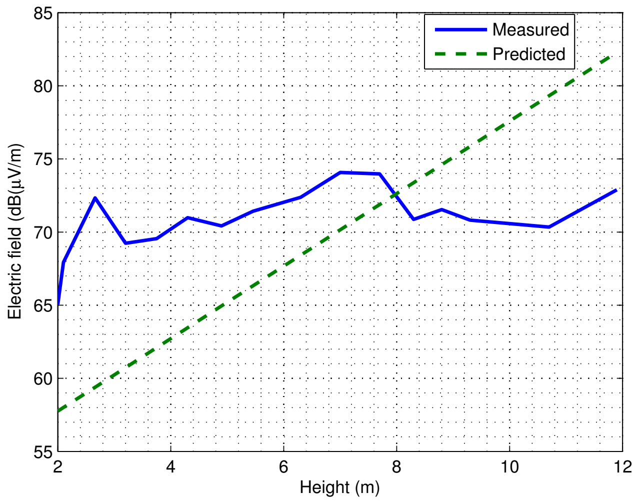

Fig. 7. Predicted vs measured electric field strength at 775.25 MHz. Electric field strength is considered at 775.25 MHz because television transmitter information at this frequency is available.

on height holds only up to 8.5 m above ground. The lack of further increase in signal strength beyond 8.5 m may be attributed to availability of line of sight above 8.5 m and sufficient clearance of Fresnel zone.

Furthermore, the noise floor increases as the television white space devide (WSD) moves spectrally" closer to a television signal as observed from Fig. 5 and Fig. 6. The observed increase in RSSI as height increases is desirable however, we expect the noise floor to have a stronger negative impact at height when the WSD is spectrally near television signals compared to when the WSD is spectrally far from television transmissions. Nonetheless, the signal strength of a TV white space device is expected to rise faster than the noise floor and hence still get the benefit of height but the exact impact of the height benefit can only be done with further measurement.

A. *Predicted vs measured electric field*

In Fig. 7, we try to show the electric field strength predicted by the Okumura-Hata model as specified in [13], at 775.25 MHz for transmitter height of 25 at a distance of 10 km and compare with the measured value processed as described in section 5, formula (8) - (9).

V. Conclusion and Follow on Work

This paper looked at the relationship between RSSI and throughput. Adjusting receiver height from 2 m to 8.5 m results in about 17 dBm increase in RSSI. Higher RSSI corresponds to higher data rates. Therefore, throughput can be improved by placing the receiver at a sufficient height. In the next phase of the study, we intend to investigate the height, RSSI and SNR interdependency and establish the trade-off for the RSSI gain. This will include field measurements of throughput for different PHY modes at different receiver heights and compare with theoretical expectations. In addition, there is little observable variation in spectrum during the period of measurements. Therefore, future work will include an extension of the study over a longer period of time to gain more insight into the time-dependant spectrum dynamics.

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