



Zaggoulos, G., & Nix, A. R. (2008). WLAN/WDS performance using directive antennas in highly mobile scenarios: experimental results. In *International Wireless Communications and Mobile Computing Conference, 2008 (IWCMC '08)*. (Vol. 1, pp. 700 - 705). Institute of Electrical and Electronics Engineers (IEEE). 10.1109/IWCMC.2008.121

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WLAN/WDS Performance using Directive Antennas in Highly Mobile Scenarios: Experimental Results

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Abstract— This paper presents experimental results from a series of IEEE 802.11g studies to investigate the performance of vehicular to roadside wireless communications. In particular, two high-gain omni-directional antennas were used at the roadside access point, while high-gain omni-directional and directional antennas were compared for use on the vehicle. By employing high-gain antennas at both ends of the wireless link, the range of the WLAN network was dramatically improved. Moreover, the use of directional antennas in highly mobile applications allows communication at higher vehicle speeds (by reducing the Doppler spread) and longer ranges (by reducing delay spread and increasing the received power level). Results show that mobile performance is significantly improved, especially when directional antennas are utilised at the receiving end of the link. As a result, the amount of data that can be exchanged between a moving vehicle and a roadside access point is considerably increased. The use of WDS (Wireless Distribution System) is also investigated in this paper. The reported measurements form part of a larger campaign to compare WiFi, WiMAX and HSPA technologies for vehicular communications.

Keywords: *WiFi, Directional Antennas, Doppler Power Spectrum, Vehicular Communications*

I. INTRODUCTION

Over the last decade, WiFi technology has been widely accepted for short-range applications. Most modern mobile phones, game consoles and security systems include integrated WiFi to enable wireless network connectivity. It is likely that future vehicles will include WiFi units based on the 802.11p standard. This will allow vehicles to communicate with roadside Access Points (APs), or even with other nearby vehicles. These links could be used to broadcast safety or traffic flow between nearby vehicles. Furthermore, navigation and entertainment applications could be offered over these links. WiFi experiences a number of specific problems that are related to multipath fluctuations in the received signal power. Furthermore, the received signal can also suffer delay and Doppler spread. The use of WiFi for vehicular applications remains compelling because of the large number of compatible portable/handheld devices in use today, and also the low cost of the required transceivers.

In mobile applications the relative motion between the transmitter and receiver generates a Doppler shift on each multipath component (MPC), and this is proportional to the carrier frequency and the velocity (relative to the Azimuth angle). In a multipath environment, each MPC experiences a

unique Doppler shift, and this results in a Doppler spread. High Doppler spreads cause fast channel variations, and unless these are mitigated, they introduce an irreducible error floor (i.e. an error rate that is independent of signal level).

This paper examines the potential of directional antennas to improve the link budget and to reduce the Doppler spread in a mobile WiFi link. The use of directional antennas can improve performance without the need for increased digital signal processing. Additionally, experimental results have shown that WDS (Wireless Distribution System) can increase the coverage footprint of a wireless network. Our analysis shows that this is achieved at the expense of throughput.

The rest of the paper is organized as follows: section II presents the required communications theory. The measurement set-up is described in section III. Experimental results are discussed in section IV, and conclusions are provided in section V.

II. COMMUNICATIONS THEORY

It is well-known that the received power at any distance from a transmitter can be predicted from a link-budget. If the transmit and receive parameters are known and a suitable path loss model exists, then the received power (in dBm or dBW) can be estimated using the following equation [1]:

$$P_r = P_t + G_t + G_r - L_t - L_r - L_p \quad (1)$$

where P_t represents the transmit power, G_t and G_r are the gains (relative to an isotropic source) of the transmit and receive antennas respectively. Furthermore, L_t represents the RF cable losses at the transmitter, L_r represents the RF cable and receiver implementation losses, and L_p represents the distance dependent path loss. Using Erceg's empirical path loss model [2], the path loss term can be written as:

$$L_p = A + 10n\text{Log}_{10}(d/d_o) + s; \quad d \geq d_o \quad (2)$$

where n denotes the path loss exponent, d and d_o represent the transmit-receive separation distance and an arbitrary reference distance respectively, s denotes a shadow fading variable, and A represents a fixed quantity that is derived from the free space path loss equation [3].

$$A = 20\text{Log}_{10}(4\pi d_o/\lambda) \quad (3)$$

A reference distance d_o of 1 metre is assumed here. The path loss exponent varies depending on the carrier frequency, the height of the antennas, and the channel conditions (most

This work was partly funded by the Technology Strategy Board (TSB), UK via the VISUALISE project.

specifically the degree of shadowing). The elevation of the AP can heavily influence the path loss exponent, as reported in [4]. The higher the AP antenna, the lower the expected path loss exponent is. A value of $n = 2$ is used for free space propagation (i.e. line-of-sight), with n increasing as the number of obstacles between the AP and mobile increases. The path loss exponent can also be lower than 2 in line-of-sight (LoS) cases where energy is channelled down streets or canyons.

The use of directional (or sectorized) antennas is highly desirable in mobile (vehicular) communications. This occurs for a number of reasons. In particular, if the antennas are correctly aligned, they enable 1) enhanced signal levels and operating ranges, 2) reduced Doppler spreads, 3) reduced delay spreads, and 4) reduced co-channel and adjacent channel interference.

A directional antenna is said to perform spatial filtering [5]. When used at the receiver, the antenna significantly enhances the gain of the MPCs over a specific range of azimuth angles. As a result, the characteristics of the channel, such as the received power, the rms delay spread, the rms Doppler spread, and the signal to interference (SIR) ratio can be improved dramatically. However, for channels where the power is received over a wide range of azimuth angles (i.e. spatially dispersive), a highly directional antenna can result in a degree of signal loss (since multipaths outside the main beam of the antenna are suppressed). Nevertheless, this power loss is normally more than compensated for by the directional gain of the antenna. Furthermore, in vehicular communications it is expected that the angular spread at the receiver will be much lower than 360 degrees. This indicates that correctly aligned directional antennas on the vehicle will improve performance compared to an omni-directional device.

A directional antenna with a beam-width α is capable of reducing the Doppler spread from $2f_m$, to $(1-\cos(\alpha/2)) * f_m$ if the boresight is aligned straight ahead or behind the vehicle [6]. This assumes that the vehicle is moving directly forwards or backwards (i.e. does not slide left or right). In the literature [7], it is well reported that the shape of the power delay profile (PDP) does not strongly influence the resulting bit error rate (BER) in a time dispersive channel (assuming a constant rms delay spread). It is well known that delay dispersion and frequency dispersion are duals of one another. By analogy, the error performance in a time-varying channel is strongly related to the rms Doppler spread. Furthermore, while the shape of the PSD will impact the rms Doppler spread, for a given rms Doppler spread, the particular PSD shape is not significant [8]. These conclusions can be easily verified by taking the inverse Fourier transform of different PSDs and comparing the corresponding spaced-time autocorrelation functions (see Fig. 1b). Since the system performance is related to the time required for the correlation to drop to 0.5, any differences in the shape of the lower correlation values are immaterial.

WDS is a feature present in many wireless LANs to interconnect a number of APs. Although it is not mandatory in any standards to date, it is supported by many manufacturers. WDS is proposed for use in future wireless mesh networks. The main difference between WDS and a more traditional wireless bridge is the ability of the former to simultaneously

bridge APs and serve wireless clients. WDS (also known as repeater mode) uses MAC addresses rather than IP assignments to connect clients. Additionally, all participating APs must be preconfigured in order to allow the forwarding of IP packets.

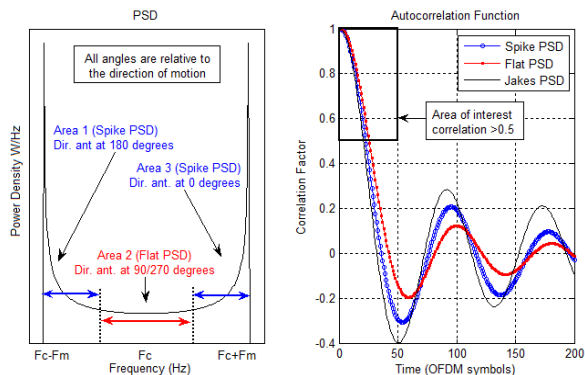


Figure 1. a) PSDs with directional antennas and different relative orientations, b) Space-time autocorrelation functions for different PSDs, but for the same Doppler spread (225 Hz)

III. MEASUREMENT SETUP

The roadside APs used in our experiments operated with a transmit power of 17dBm. Each AP was equipped with a pair of antennas to support spatial diversity. The original antennas were replaced with high-gain omni-directional devices, each offering approximately 4 dB more gain than the original. This additional gain enhanced the EIRP in the link budget to 23 dBm, which lies at the upper limit of the UK OFCOM regulations [9]. The AP was connected to a laptop PC, which hereafter is referred to as the *server*. The *client* device comprised a second identical laptop PC, which was placed inside a vehicle. An external WLAN card was connected to the client via USB, and its antenna was easily replaced and/or relocated on the vehicle. In the first trial the directional antenna under test on the vehicle tracked the direction of the transmitting AP. In the second experiment the vehicular antenna had a fixed orientation (relative to the direction of motion).

Both laptops had sufficient processing power to service the WLANs without adding any significant delay, or contributing to the observed packet error rate (PER). This is important since an overloaded PC can drop packets at the application layer that are successfully received by the MAC and PHY layers. Customised logging software originally created in the EU project: Wireless cameras and audio-visual seamless networking (WCAM) [10], and further developed jointly between the University of Bristol and ProVision Communications Ltd, was used to record the RSSI, data throughput, delay (mean and variance), PER, operating mode, GPS location and vehicular speed. Other than the GPS data, which were recorded on a one second snapshot basis, all other values were recorded as a 'per-second' average. Measurements were performed in six different environments; and data analysis is now presented for two of these locations.

The first set of measurements was performed in Paphos, Cyprus, in an open, relatively flat area of land with no

obstructions between the server (AP) and client (WLAN card) for approximately 90% of the route (see Fig. 2). However, a few large industrial buildings exist around 300m from the server, which are expected to create some strong reflections. Several metallic farm structures exist on the east side of the test route; however these do not cause any major reflections during the first drive test. No other road traffic was present during the trial since the roads were closed for the duration of the measurement.

The server was stationary during both drive tests (Tx1 and Tx2 in Fig. 2), while the client was mobile within a vehicle, driven at speeds of up to 100 km/h. The first drive test was based on an anti-clockwise loop, as indicated by the dots starting from point A in Fig. 2. The length of the loop was 1310m. Data from multiple runs, using two types of external antennas, was collected in order to verify the repeatability of the experiment and compare the two antennas. The antenna at the server was mounted at a height of 4.3m above ground level, while at the client the antenna height was 1.6m. During the tests with the directional antenna installed on the vehicle, the antenna was manually orientated to keep its main-lobe pointing in the direction of the server. During the second drive test, the transmitter was moved from location Tx1 to location Tx2 in order to provide Line of Sight (LoS) coverage along the entire route. The new AP location resulted also in a richer multipath environment due to its higher altitude and its position relative to the surrounding buildings and metallic farm structures.

The measurements at the second location were performed at Cribbs Causeway (Bristol, UK) using an almost identical configuration. However, for this trial two APs were used (located 400m apart). The APs were connected using WDS. In this second environment, the road was open to the public and significant traffic was present. The use of WDS effectively halved the available bandwidth (since all data traffic is relayed in-band between the two APs). However, coverage is significantly enhanced with WDS (due to the second co-operating AP). The server was connected to AP1 and the client was installed in a vehicle. Each test began at point A with the vehicle moving towards the roundabout (point B), and then turning back towards the second roundabout (point C). The WDS feature was manually tested in order to maintain repeatability among the tests. Therefore, during each test, the client was initially connected to the server via AP2 and AP1. As soon as the received power fell below -75 dBm, and the distance to the other AP was shorter, we manually switched to the closer AP using the connection manager window on the client laptop. Automatic hand-over was found to work just as well when all the participating APs shared a common SSID. The maximum speed during this measurement was also 100 km/h.

Compared to the propagation environment in the first trial, the received signal in the second includes many more multipaths. This occurred because of the higher number of surrounding buildings and trees around the test route (see Fig. 3). Additionally, although a LoS exists around the route, it was often blocked by other vehicles sharing the dual carriage way. The height of the serving APs was 2m above ground level (significantly lower than the Paphos measurement). The alignment of the directional antenna on the vehicle was also

different in this second trial. The orientation of the directional antenna was fixed and pointed directly in front of the vehicle. Table 1 summarises the key AP and antenna parameters for both experiments.

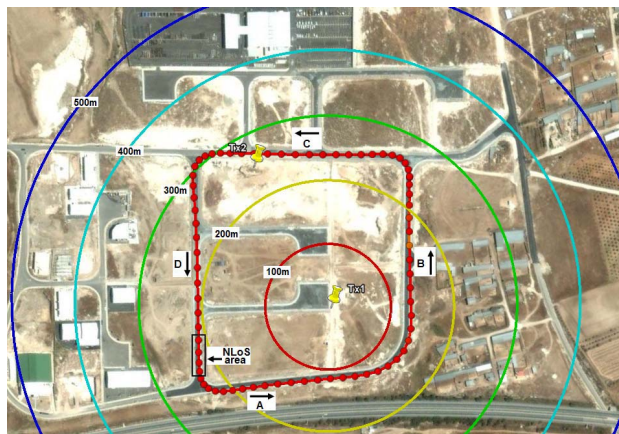


Figure 2. Measurement Location in Paphos, Cyprus.

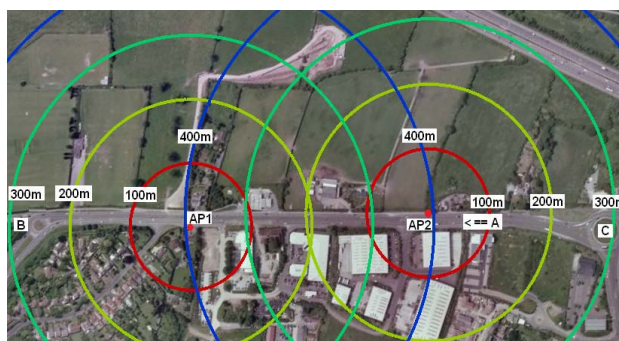


Figure 3. Measurement Location in Bristol, UK

TABLE I. ACCESS POINT AND ANTENNA PARAMETERS

<i>Tx Power</i>	17 dBm
<i>Tx Antenna Gain</i>	6 dBi
<i>Rx Antenna Gain (Omni.)</i>	6 dBi
<i>Rx Antenna Gain (Dir: 60 deg.)</i>	10 dBi
<i>Modes tested</i>	QPSK 1/2, QPSK 3/4,
<i>Packet Lengths tested</i>	700, 900, 1100, 1300 bytes
<i>Throughputs Tested</i>	1, 2, 4, 8 Mbps
<i>Protocols Used</i>	TCP, UDP, BCT

IV. RESULTS

The analysis of the results is presented separately for the two locations described in section III. Fig. 4 shows the mean recorded received signal strength indication (RSSI) for the first drive test (averaged over 4 routes, with each route comprising two laps of the industrial estate) as a function of time normalised to the start of the first route. Each lap took around 80 seconds, hence in Fig. 4 a single run required 160 seconds to complete. From this plot, it is clear that the directional antenna (which was orientated towards the AP) offers the stronger received signal for the majority of the route. The sections where the received signal from the directional antenna

is weaker than that of the omni-directional antenna's (70-78s and 145-153s) correspond to the lower left-hand corner of the loop (see NLoS area in Fig. 2). This can be explained by the elevation of the road at this location, which is lower than the surrounding terrain. Hence, at this point most of the recorded power arrives via multipath scatter from surrounding buildings in the opposite direction to the AP. Even though the gain of the directional antenna is 4 dB higher than the gain offered by the omni-directional device, the average gain measured over the route (offered by the directionality of the antenna) is just over 2 dB. Clearly, manual tracking of the directional antenna towards the server is not optimal for those sections of the route where the LoS is blocked, and hence the received power is based on scattered multipath. Furthermore, some of the stated antenna gain is lost due to losses in the external antenna connector.

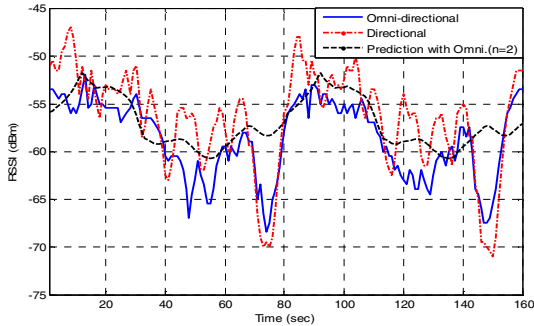


Figure 4. RSSI over Time with different Antennas

In order to verify that the measured received power follows the theoretic predictions given in section II, Figs. 5 and 6 show the RSSI relative to the server-client separation distance for the different antennas under test, recorded from both drive tests.

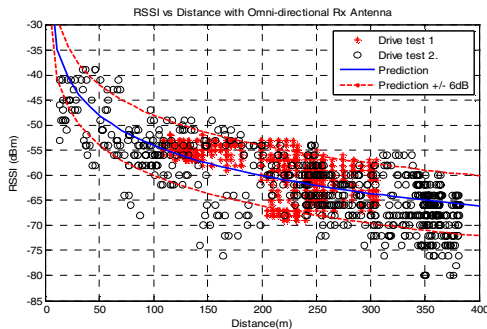


Figure 5. RSSI over Distance with omni-directional antenna

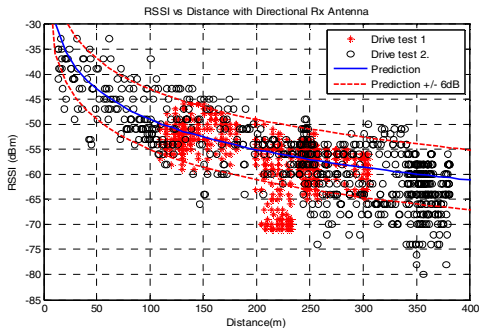


Figure 6. RSSI over Distance with directional antenna

In these trials a path loss exponent of 2 was selected since a strong LoS existed for most of the test route. We observe that the measured received power distribution is in good alignment with the predicted power levels (Figs. 5 and 6). We also see that for double the distance, the received power drops by 6 dB, as expected for a LoS dominated link.

For the first drive test, apart from several locations around 220m from the server, the majority of the measured power lies within ± 6 dB from the theoretic predicted levels. As explained earlier, these lower power levels (compared to the predictions) are mainly a result of terrain blocking. For the same reason, during the second drive test we observe much lower power levels recorded at around 350m from Tx2. However, those levels recorded near 160m from Tx2 are possibly due to a human error in the orientation of the antenna.

While the focus of the first drive test was mainly to collect RSSI and PER data, the objective of the second was to investigate the PER related to Doppler spread. In addition to TCP protocol tests, UDP and BCT protocols were also tested in the second drive test. These latter protocols enable packet loss statistics to be recorded. In the case of the WiFi BCT protocol, no MAC layer or network layer packet retransmission is used (allowing the raw packet loss performance of the PHY layer to be observed). The PER data collected in the second drive test is shown in Figs. 7 and 8 respectively as a function of elapsed time and vehicle speed.

From Fig.7 it is clearly observed that the number of packets in error is much lower when a directional antenna is attached to the mobile receiver (compared to an omni-directional antenna). Additionally, as expected, it is shown that by enabling MAC layer retransmissions (i.e. by using UDP instead of BCT) the PER can be greatly reduced. In the case of TCP, no missing packets are observed (although this is achieved at the expense of increased latency and jitter [11]).

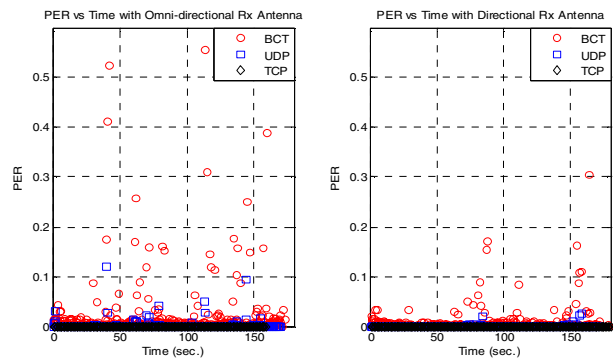


Figure 7. PER over Time with different antennas

As shown in Fig. 8 the PER remains below 5% at speeds less than 40 km/h for broadcast (BCT) and 65 km/h for unicast (UDP) transmission when omni-directional antennas are used at both ends of the communication link. However, by replacing the receiving antenna with a directional device, the errors are minimized allowing higher vehicle speeds. The data collected indicate that broadcast transmission can be supported up to speeds of 65 km/h (offering a 60% increase in allowable speed). When UDP is used, even at the highest speed (around

90 km/h) the PER is no greater than 2%, thus showing a dramatic increase in the supported vehicle speed.

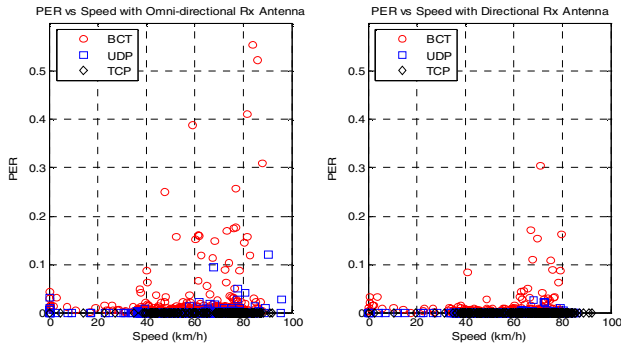


Figure 8. PER over Speed with different antennas

In Fig. 9, the PER recorded with an omni-directional receiving antenna (for a BCT transmission) is shown on a map using coloured circles. The plot shows that the errors occur only in a few select locations around the route. This supports the statement that errors due to Doppler spread are not exclusively generated by high vehicle speeds, but also require large angular spreads in the DOA at the vehicle. The latter is responsible for the increase in the rms Doppler spread, which we believe causes packet errors [8]. The errors recorded with the directional receiving antenna are also located in the same areas; however all of them are either minimised or completely eliminated.



Figure 9. PER over Speed with different antennas

Figs. 10, 11 and 12 present results from the second set of measurements, performed in the UK. In Fig. 10 good agreement is seen between measured and predicted power levels using omni-directional antennas. A path loss exponent of $n = 3$ aligns better with the measured power levels observed in this environment. The higher path loss can be attributed to a number of factors, including the lowering of the AP height (compared to Paphos) and the presence of vehicles blocking the link back to the AP. The RSSI using the directional antenna is not included in Fig. 7 since the high volume of traffic did not allow us to maintain the same timing during multiple runs. Nevertheless, a comparison of the measured power level is

shown in Figs. 11 and 12, where the RSSI is plotted against distance.

In Fig. 11, the measured power levels are once again very close to the predicted values. However, in Fig. 12, the measured power levels appear higher than the predicted values. One possible explanation is that the buildings on the sides of the dual carriageway form a strong waveguide, as explained in [12] (the electromagnetic energy is focused and propagates parallel to the route). Alternatively, a strong LoS component may be present during the periods of high received power.

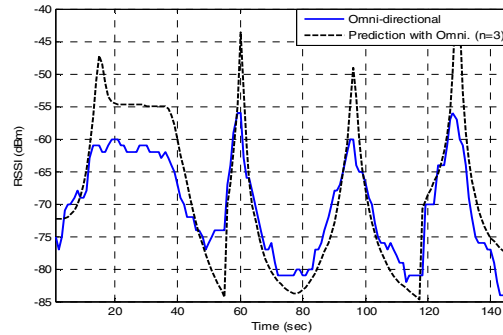


Figure 10. RSSI over Time with omni-directional antenna

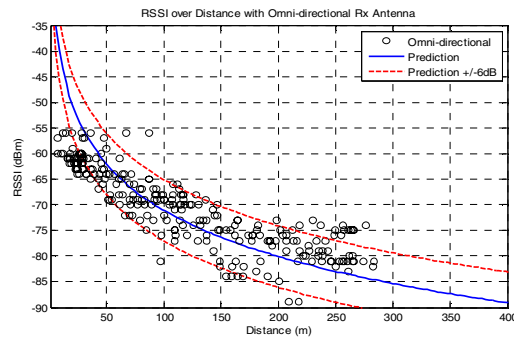


Figure 11. RSSI over Distance with omni-directional antenna

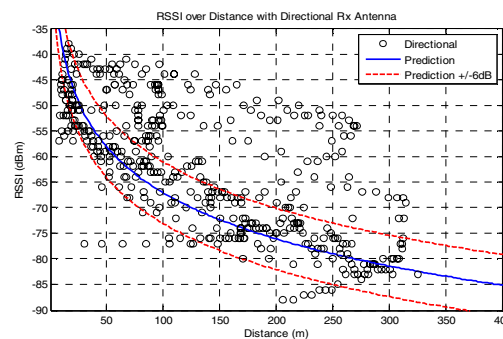


Figure 12. RSSI over Distance with directional antenna

Using WDS, the hand-over between the two APs was found to work well; requiring around 2-3 seconds to complete. For the test results presented in Fig. 9, the first hand-over (from AP2 to AP1) was performed 58 seconds into the measurement. The second handover (from AP1 to AP2) occurred at 125 seconds. The point of handover is visible as a sharp rise in the received power level. This also results in a large jump in the received data throughput. WDS uses hard hand-over, and

hence the throughput drops to zero between the 'break' and 'make' phases of the connection.

Looking at the power over distance figures for the two trials, it is clear that the measured power levels in Cyprus are higher for the same separation distance. This indicates a lower path loss due to reduced multipath and shadowing. As can be observed from the photographs, the Cyprus route has fewer buildings and no foliage. Furthermore, there were no other vehicles blocking the signal in the Paphos experiments.

During both trials, throughput tests were performed at rates up to 4 Mbps (measured at the application level) using packet lengths of 700-1300 bytes. Different link-speeds and IP packet lengths were also explored. Results from the first trial indicate that a throughput of 8 Mbps was also achievable using the $\frac{3}{4}$ rate QPSK mode in 802.11g for IP packet length of 1300 bytes, even at vehicular speeds up to 100 km/h. From the Bristol trials it was confirmed that the use of 2 APs in WDS mode halves the available bandwidth, offering a mean throughput of around 3 Mbps using the $\frac{1}{2}$ rate QPSK link-speed at both APs. However, when the client was connected directly to the AP attached to the server, the target throughput of 4 Mbps was achievable (where received power levels permitted). For direct connections the data is not exchanged between the two APs.

For WLAN systems, UDP packets enjoy wireless retransmission at the MAC layer. As a result, the observed PER is almost always zero. Yet, when retransmission is required, the throughput is seen to drop significantly. By extending the distance axis in Figs. 5, 6, 11 and 12 we are able to predict that for a receiver sensitivity of -80 dBm, the omni-directional antenna (offering a 6 dBi gain) can operate at distances up to 600m. Using the directional antenna (which offers up to 10 dBi of gain) the service can be extended up to 900m in LoS (and near-LoS) conditions. Furthermore, recent changes within regulatory bodies such as OFCOM [9] intend to allow increased transmit powers for WiFi systems using directional antennas. This could enable a WiFi AP to offer services over a range of several kilometres, providing a more cost effective solution for vehicular communications.

V. CONCLUSIONS

In this paper, results from experimental trials based on 802.11g devices in high mobility scenarios were presented. Various vehicle speeds up to 100 km/h and different antenna types were tested. Results showed that a directional antenna on the vehicle can offer extended range compared to an omni-directional device, especially under LoS conditions. This benefit can be achieved even when a fixed orientation (aligned to the direction of the vehicle) is applied. The advantages of using directional or sectorized antennas (in highly mobile scenarios) in terms of PER were also exploited. Particularly, it was argued that directive receiving antennas can support communication links at much higher speeds compared to omni-directional ones. The use of WDS was also explored in the trials. Two APs were connected to offer combined coverage of approximately 1 km of carriageway, even during rush hours. The drawback of this approach is a reduction in throughput brought about by the need to forward packets between the

connected APs. The time required for hand-over between the APs was found to be in the order of several seconds.

Overall, the trials showed that WiFi is capable of supporting wireless links to and from fast moving vehicles, and that directional antennas in conjunction with higher transmit powers can increase the operating range/time of a connection between vehicles and/or to a roadside AP.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Pierre Ferre, David Halls, Stephen Ierodionou (University of Bristol) and Dr. James Chung How (Provision Communications) for their assistance in the Bristol trials. George Zaggoulos would like to thank his wife Maria, Savvas Telemachou and Christodoulos Pavlou, for assistance in the Paphos trials.

REFERENCES

- [1] J. G. Proakis, *Digital Communications*, 4th ed: Mc Graw Hill, 2001.
- [2] V. Erceg, L. Greenstein, S. Tjandra, S. Parkoff, A. Gupta, B. Kulic, A. Julius, and R. Bianchi, "An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments," *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 1205-1211, 1999.
- [3] J. D. Parsons, *The Mobile Radio Propagation Channel*, 2nd ed: Wiley, 2000.
- [4] M. J. Feuerstein, K. L. Blackard, T. S. Rappaport, S. Y. Seidel, and H. H. Xia, "Path loss, delay spread, and outage models as functions of antenna height for microcellular system design," *Vehicular Technology, IEEE Transactions on*, vol. 43, pp. 487 - 498 1994.
- [5] M. J. Gans, "A Power Spectra Theory of Propagation in the Mobile Radio Environment," *IEEE Transactions on Vehicular Technology*, vol. 21, pp. 27-38, 1972.
- [6] R. H. Clarke, "A Statistical Theory of Mobile-Radio Reception," *The Bell System Technical Journal*, pp. 957-1000, 1968.
- [7] M. Jeruchim, P. Balaban, and K. Shanmugan, *Simulation of Communication Systems*, 2nd ed: Kluwer Academic/Plenum, 2000.
- [8] G. Zaggoulos, A. Nix, and A. Doufexi, "WiMAX System Performance in Highly Mobile Scenarios with Directional Antennas," presented at IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications, Athens, Greece, 2007.
- [9] Office of Communications, "Higher power limits for licence exempt devices - Understanding the Scope for a Power Increase at 2.4 and 5 GHz," <http://www.ofcom.org.uk/consult/condocs/powerlimits/statement/>, 2006.
- [10] P. Ferre, D. Agrafiotis, T. K. Chiew, A. Nix, and D. Bull, "Multimedia Transmission over 802.11G WLANs : Practical Issues and Considerations," presented at International Conference on Consumer Electronics, Las Vegas, USA, 2007.
- [11] V. Sgardoni, P. Ferre, A. Doufexi, A. Nix, and D. Bull, "Frame Delay and Loss Analysis for Video Transmission over time-correlated 802.11A/G channels," presented at 18th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07), Athens, Greece, 2007.
- [12] B. Sklar, *Digital Communications*, 2nd ed: Prentice Hall, 2001.