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Measurements and Evaluations for an IEEE 802.11a based Carrier-Grade Multi-Radio Wireless Mesh Network Deployment

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***Abstract*—Although there currently exists a number of Wireless Local Area Network based mesh network deployments most have been deployed to provide best effort broadband Internet access. Consequently, they cannot meet the requirements of network operators in order to utilise these networks to offer carrier grade services. The goal of providing carrier grade services over a wireless mesh infrastructure requires high performance in terms of throughput and reliability. One way of achieving this increase in performance is to utilise multi-radio Mesh Nodes, however, due to the Physical Layer layer limitations of 802.11a this can have significant problems. This paper analyses these issues and investigates what performance can be expected when frequency multiplexing is considered. The results presented in this paper are based on real measurements taken from multi-radio Mesh Nodes and are evaluated using statistical algorithms. The main contribution of this paper is an analysis of the impact of the Adjacent Channel Interference effect in 802.11a based multi-radio Mesh Nodes.**

***Keywords*-Wireless LAN; Measurement; 802.11a; Multi-Radio Wireless Mesh Network**

I. Introduction

In recent years Wireless Mesh Networks (WMNs) have become increasingly popular. This is primarily due to the high level of penetration achieved by Wireless Local Area Network (WLAN) as an access technology for end user devices and the widespread availability of low cost Wireless Fidelity (WiFi) hardware. Another important factor is that WiFi operates in unlicensed spectrum, therefore, WMNs based on this technology can be deployed without requiring the purchase of expensive spectrum licences. This greatly alleviates what is normally a key barrier to deployment when building a wireless network.

There is a wide variety of WMN architectures and technologies. In order to understand the objective of this paper it is important that the reader has an understanding of how these differ. Basically, a mesh network describes a communication infrastructure where multiple paths exist to the same destination. It incorporates self-healing procedures which can automatically reconfigure the network in case of a link failure. It is this feature of path redundancy that is the main advantage offered by WMNs when compared to traditional multi-hop networks. In the late 90s research groups like RoofNet [1] began deploying a WMN test-bed utilising low cost and license exempt 802.11 hardware. Other community networks such as RoofNet Berlin and Freifunk as described in Sombrutzki et al. [2] soon followed.

The major difference between the different types of WMNs is the objective of the network [3], specifically, the type of services that will be offered over the network and the properties and capabilities of the Mesh Nodes (MNs). One objective is the support of carrier-grade services which means that every accepted data flow within the network can be guaranteed. Furthermore, this includes the full control of every network entity and every network link. In case of deploying such a WMN it is reasonable to describe it as an operator network that is completely closed to the outside. It is quite important to discuss the properties of such networks regarding number of radio interfaces, node reliability, node availability, routing schemes, the considered traffic, and the goals of such a network before providing information about the conducted measurements and the findings. Therefore, WMNs like RoofNet and Freifunk should be rather classified as community networks where every MN consists of just one single-radio interface. Furthermore, based on the unknown number of MNs inside the community network no network planning can be taken place. Consequently, they can be classified as Mobile Ad Hoc Networks (MANETs) which mainly describe networks where every MN is unpredictable in terms of availability and traffic producing or where every MN is mobile, e.g., in a military scenario where every soldier represents a MN. Consequently, a WMN which provides rather carrier-grade support can be classified as a Nomadic Ad Hoc Network (NANET). Due to the physical limitations of WLAN and consequential performance constrains to support carrier-grade services, it is considered to increase the capacity of a WiFi based NANET by equipping every MN with more than one antenna even not just omnidirectional. Due to some constrains based on related work regarding a multi-radio MN in conjunction with Institute of Electrical

and Electronics Engineers (IEEE) 802.11a as the chosen technology this paper will provide first findings on what kind of carrier-grade NANET can be provided.
Since every measured result is dependent on the hardware properties, the hardware used in this work is evaluated prior to the results being presented so that hardware dependencies may be taken into account. Hence, Section II is divided into three subsections; II-A Preliminary Considerations which explains statistical methods and basic formulae to evaluate measured data, II-B that pays attention to the Adjacent Channel Interference (ACI) phenomenon in IEEE 802.11a frequency space and its limitations, and II-C which describes the experimental environment and the obtained data as well as the scientific findings. Finally, Section III provides an overview of the evaluated results, their conclusion with regard to the proof-of-concept consideration, and some future work issues.

II. Measurements

The objective of deploying a multi-radio NANET is one of the most popular research areas in wireless telecommunications. A key question in terms of designing and deploying a WiFi based NANET is what performance improvements can be achieved by using multi-radio MNs in comparison to single-radio MNs and what interference issues arise when using multiple radios in a single MN. The results presented in this paper provide answers to these questions. The results are measurement based and are conducted with the intent of providing carrier-grade services in a multi-radio NANET and hence are evaluated solely for this purpose.

A. Preliminary Considerations

In order for the results presented in this paper to be accurate and free from external influences, it was necessary that the experimental environment had to fulfil some basic requirements. A direct Line of Sight (LOS) connection must be provided between each pair of transmitting and receiving antennas with no objects which could cause inference due to reflections or shadowing effects. At a minimum the first Fresnel zone must be largely free from obstacles to avoid interference from reflected waves.
Equation 1 shows the simplified formula to calculate the nth Fresnel zone. Using this equation a radius F_n can be obtained which describes a zone that surrounds the straight LOS connection between both antennas that is completely free from obstacles, e.g., trees, hills or walls. Since in the experimental environment the only obstacle is the ground, Equation 1 just comprises the distance d between both antennas. Therefore, the general simplified Fresnel formula is:

$$F_n = \sqrt{\frac{n \cdot c \cdot d}{2f}} \quad (1)$$

In order to verify the accuracy of the results from the experimental environment the overall system loss a_S was computed analytically. A comparison between the actual attenuation experienced in the experimental set-up and the theoretical attenuation predicted was then made. To compute the theoretical attenuation that should be experienced, the following formula was used:

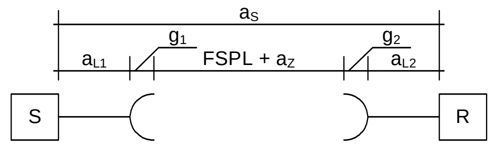

Figure 1. Loss Parameters within a System as shown in Equation 2

$$a_S = a_{L_1} - g_1 + FSPL + a_Z - g_2 + a_{L_2} \quad (2)$$

Equation 2 is made up of the cable losses from MN_1 to antenna a_{L_1} and from MN_2 to antenna a_{L_2}, the gain of both antennas g_1 and g_2, the Free-Space Path Loss (FSPL) shown in Equation 3 and additional unpredictable losses a_Z, e.g., interference due to multipath propagation especially for frequencies less than 10 GHz, loss due to atmospheric absorption or restrictions of the free space propagation. Figure 1 illustrates all system losses which have been described.

$$FSPL = 92.4 + 20\log(d) + 20\log(f) \quad (3)$$

Since most of the results presented in this paper are based on real test-bed measurements, some analytical methods are needed to prove the reliability of the obtained data. As applied by Winkler et al. [4], the results are evaluated by calculating the Confidence Interval (CI) using the method of independent replications as described by Banks et al. [5]. However, in comparison to [4] and [5] some issues will be taken into account with regard to the CI calculation and the minimum number of samples as investigated by Wang [6]. Wang explored and compared the three possible approaches, Normal Theory as used by [4], Boostrap and Box-Cox. Each method of calculating the CI for the mean of non-normal data was analysed and compared based on different numbers of samples. It was found that taking the Normal Theory can be quite inaccurate for non-normal data and is both less effective and efficient for skewed data when only a small number of samples of $n < 50$ is considered. Due to the findings in [6], the results presented in this work were based on at least 50 samples per calculated sample mean. Based on this the CI is obtained as described by Banks et al. [5]

$$\bar{\mu} \pm t_{\frac{(1-\alpha)}{2},\upsilon} \cdot \sigma(\bar{\mu}) \quad (4)$$

where $\bar{\mu}$ represents the sample mean, υ the Degree of Freedom (DF), α the chosen CI and $\sigma(\bar{\mu})$ the standard error or variance of the sample mean. As proposed in [5], the Student's t-distribution will be used to define υ since every sample is independent from the others.

B. Adjacent Channel Interference

There is currently a lot of interest in using IEEE 802.11a to provide backbones for NANETs while using IEEE 802.11b/g to provide user access. This means that each MN may have multiple 802.11a radios operating in close proximity and hence ACI issues in 802.11a is of particular importance. These issues must be addressed prior to deploying an 802.11a based NANET infrastructure.

Angelakis et al. [7] qualifies the effect of ACI in terms of throughput within a single node equipped with multiple interfaces. Angelakis et al. investigated that neighbouring 802.11a channels have a spectral overlap that produces a significant level of interference which can lead to lossy and unstable links. However their experiments were conducted under laboratory conditions using attenuators and couplers to demonstrate the ACI effect. Due to this experimental environment the ACI effect on two transmitters with a channel separation of two 11a channels could not be shown. Further, in the results the level of attenuation was too high and the signal level was below the sensitivity threshold of a common WiFi card. Therefore, based on the obtained results it was not possible to conclude what level of channel separation is required to provide stable and reliable links.

Surprisingly, Mishra et al. [8] assumed that the overlap between neighbouring channels in IEEE 802.11a is so low that it can be ignored for practical purposes. Indeed Mishra et al. showed that by using 802.11b and measuring the throughput, a channel separation of three, i.e., exactly the space of two adjacent non-overlapping channels, and a distance of 10 m is enough for both links to send the actual amount of data as operating without interference from another transmitter. However, just measuring the throughput is not sufficient enough to come to the conclusion that there is no interference, as will be shown in Section II-C. Furthermore, the assumption of Mishra et al. is definitely wrong for 802.11a. This can easily be answered with the more complex and the more susceptible spreading technique and higher modulation scheme in 802.11a, i.e., Coded Orthogonal Frequency Division Multiplexing (COFDM) and 64 Quadratur Amplitude Modulation (QAM), respectively, for a nominal Data Rate (DR) of 54 Mbps. Additionally, their assumption has already been disproved by many researchers, such as [7] [9] [10], ACI issues must be taken into account when conducting multi-radio measurements with IEEE 802.11a hardware. One of the most important pieces of work in relation to this issue are the results of Nachtigall et al. [9]. They demonstrated that the number of available non-interfering channels depends on both the antenna separation and the Physical Layer (PHY) modulation.

For this reason the spectrum mask of the WiFi cards used in the work presented in this paper have been analysed to examine if it corresponds with the IEEE guidelines [11]. Figure 2 depicts the measured spectrum of a MikroTik R52 mini-PCI WiFi card using the IEEE recommended guidelines for performing spectrum measurements of 802.11a; specifically the spectrum analyser was set with a 100 kHz Resolution Bandwidth (RBW) and a 30 kHz Video Bandwidth (VBW) [11]. Although, Cheng et al. [10] had previously conducted this spectrum analysis, they considered a spectrum mask that should not exceed -20 dB at 11 MHz and similarly -30 dB at 22 MHz. Furthermore, Cheng et al. stated that they used Transmission Power (Tx) values of 30 dBm, 36 dBm and 99 dBm which were allegedly performed using the MadWiFi driver. Since the considered Power Sepctral Density (PSD) limits and the chosen Tx values do not fit to IEEE 802.11a, 802.11b or 802.11g specifications, the work and results obtained cannot be considered accurate. For operating in the 802.11a band the IEEE recommend for a 20 MHz channel spacing, a maximal bandwidth of 18 MHz at 0 dBr and offsets of at least -20 dBr at 11 MHz, -28 dBr at 20 MHz, and -40 dBr at 30 MHz. Figure 2 depicts the measured PSD of the WiFi cards used in our experiments. To compare each of the different Tx curves the area around the centre frequency f$_c$ of 5.2 GHz was normalised to Received Signal Strength Indication (RSSI)$_N = 0$. Therefore, for every Tx curve the sample mean $\bar{\mu}_a$ between 5.191 GHz and 5.209 GHz was calculated and afterwards added as a fixed value to the series of measurements. Since the result was consistently above zero, half of the belonging standard deviation $\sigma(\bar{\mu}_a)$ was also subtracted, as shown in Equation 5 which gave very accurate results.

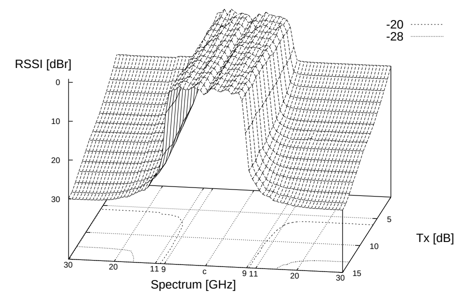

Figure 2. 3D Spectrum Analysis of a MikroTik R52 IEEE 802.11a/b/g Card for 5.2 GHz Carrier with a 20 MHz Bandwidth

$$RSSI_N = x + \bar{\mu}_a - \frac{\sigma(\bar{\mu}_a)}{2} \qquad (5)$$

Due to the small Signal to Noise Ratio (SNR) of the lower Tx measurements as shown in Figure 2, the PSDs for $f_c \pm [9\,MHz, 11\,MHz]$ could not be obtained as their values were already equal to or less than the noise floor. However, based on the achieved results of Figure 2 it is reasonable to say that the MikroTik R52 WiFi cards fit to the IEEE guidelines.

C. Multi-Radio Experiments

By taking the results of [7] and [10] into account, the following measurements will provide values for the link capabilities that can be expected when using a multi-radio equipped MN. The relationship between the channel separation and Throughput (T), Re-Transmission Rate (RTR) and RSSI are also investigated.

The measurements were conducted in a field with no obstacles which could cause possible reflections and no interference from other sources operating in the 802.11a band. Taking the objective of providing carrier grade quality into account, the transmitting MN consisted of two sectorised antennas with a 12 dBi gain and an aperture angle of 120° in the horizontal plane. Both antennas were secured to a tripod and configured to cover a combined area of 240° in the horizontal plane with no gap between the two coverage areas. To exclude the possibility of interference between the two mini-PCI R52 WiFi cards or pigtails, each was put into a different machine. Previous experiments in which both cards were in the same MN had given unpredictable results; this was most likely due to interference within the MN primarily caused by the pigtails and connectors used to connect the antennas to each mini-PCI card. Both receivers were equipped with a 5 dBi omnidirectional antenna. Due to environmental limitations of the outdoor experiment, i.e. length of Ethernet and power supply cable, the distance between the sectorised antennas and the omnidirectional receivers was set to 10 m. Each R52 WiFi mini-PCI card was connected to the antennas using an RG-178 U.fl to Sub Multi Assembly (SMA) pigtail of 20 cm length extended by a 2 m H-155 coaxial cable with N connectors. An adapter SMA to N was used to connect the pigtail and the coaxial cable. This configuration was chosen instead of an SMA to N cable due to better loss characteristics. Channels 36, 40, 44 and 48 were chosen to perform the experiments with the channel bandwidth set to 20 MHz.

The first Fresnel zones were calculated using Equation 1 and produced $F_1 \sim 0.54$ m. Hence, all antennas were set to 1 m above the ground to keep the first three Fresnel zones clear. To run the experiments and obtain the values for T the bandwidth measuring tool IPERF version 2.0.4-3 was used. The RSSI and RTR were obtained on the receiver side using TSHARK which provides the desired information out of the radio-tap header. The spectrum analysis results shown on Figure 2 showed that the worst interference issues will occur when using higher Tx values. Based on this assumption measurements were only conducted with Tx values between 10 dBm to 15 dBm. In comparison to other previously published work, such as [9] and [10], the following results show every combination of Tx and DR with T and RSSI, respectively.

As explained in detail in Section II-A for every calculated sample mean $\bar{\mu}$, CI is also be provided. Due to the 50 values

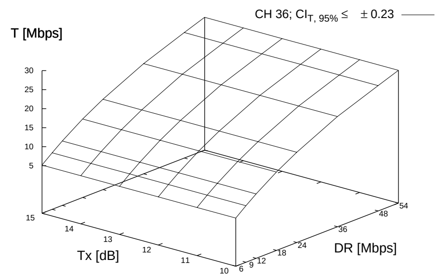

Figure 3. Single Radio T Measurement on Channel 36

taken for one sample mean $\bar{\mu}$, every value of $\bar{\mu}$ lies within the borders of CI, stated within the legend of every figure, with a confidence level of 95 %. Based on Student's t-distribution and DF of 49, CI was calculated by using $t_{0.025,49} = 2.01$ for $\alpha = 95\,\%$ [5].

In order to verify that the experimental environment provides the anticipated behaviour, the expected RSSI is calculated using Formula 2. The attenuation of the cables and pigtails was obtained from their data sheets, however, the information provided does not consider connectors. For the SMA to N adaptor no attenuation value was given by the manufacturer. Hence, as depicted in Figure 4, the real-time RSSI deviates from the calculated RSSI by about 1 dB less than was calculated; this deviation was traced to loss being experienced in the crimps. The most noteworthy point of Figure 4 is the area of Tx$(14, 15)$ and DR$(48, 54)$ where the RSSI drops down by 3 dBm and occurs in every further RSSI Figure. However, this has no impact on T. Since the RTR increased within this area from zero up to 2 %, the use of this should be avoided in a carrier-grade NANET. Furthermore, any unpredictable interference would increase the RTR and decrease T before the network could react. In comparison to the RSSI in Figure 4, the measured T plane shown in Figure 3 provides quite unspectacular results. As seen in other papers, T matches an almost flat plane with a small surface curvature in the middle at approximately DR values of 24 Mbps and 36 Mbps. Based on the statements of Mishra et al. regarding the influence of the overlap between adjacent channels, Figure 5 and 6 depicts exactly the described situation in [8]. The measurements in both figures show two transmissions, one on channel 36 and one on channel 40. As can be seen T on both transmissions drops by 5 Mbps and the RSSI drops down by 2 dBm. Furthermore, the CI increases which shows a much higher variance in the obtained data. Considering these measurements Mishra et al.'s assumption that the overlap between adjacent channels in 802.11a does not have any influence on the performance is clearly disproved. However, the occurrence of the RSSI decrease in the area Tx$(14, 15)$ and DR(54) does not have any visible effect on T as the RTR

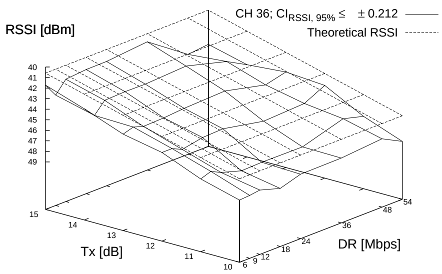

Figure 4. Single Radio RSSI Measurement on Channel 36 and the calculated RSSI based on Equation 2

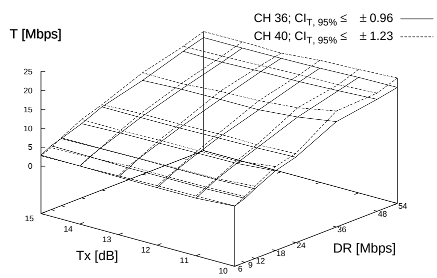

Figure 5. Dual Radio Throughput Measurements with Sender one acting on Channel 36 and Sender two on Channel 40

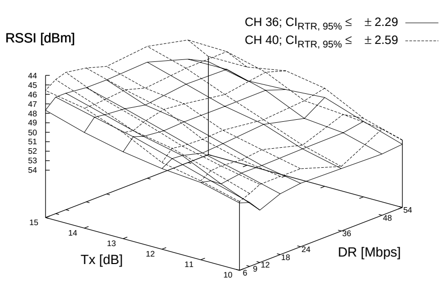

Figure 6. Dual Radio Throughput Measurements with Sender one acting on Channel 36 and Sender two on Channel 40

was again increased by 2 %. Equal to Angelakis et al. [7], the Figures 5 and 6 show the impact on ACI of neighbouring channels. Now Figure 7 depicts the exact same experiment with a channel separation of two non-overlapping 802.11a channels with MN_1 acting on channel 36 and MN_2 on channel 44. As would be expected the achieved values of T get closer to the single radio case as shown in Figure 3. However, the value of the CI which is even higher than in the previous case leads to the assumption that the links are still quite unstable and have unpredictable behaviour. The RSSI values prove that a channel separation of two in terms of IEEE non-overlapping channels is still not sufficient enough to provide carrier-grade links. The channel separation was again incremented by one channel. Hence, MN_1 is acting on channel 36 and MN_2 on channel 48. The results obtained for T are shown in Figure 9 where the maximum value as well as the plane appearance shows a high level of correlation with the initial single radio measurement depicted in Figure 3. Even the CI for both transmissions returned to the initial value of 0.23. Nevertheless, the obtained values of the RSSI, depicted in Figure 10 still do not look identical to those in Figure 4. The high CI for both transmissions indicates the impact of ACI in both 802.11a channels 36 and 48.

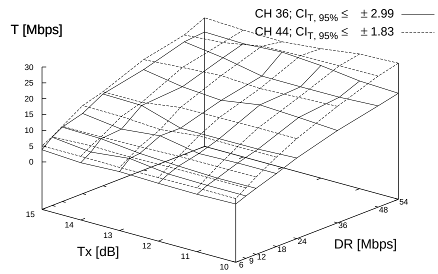

Figure 7. Dual Radio Throughput Measurements with Sender one acting on Channel 36 and Sender two on Channel 44

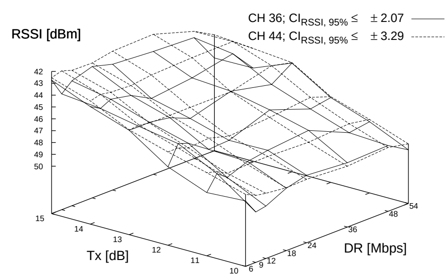

Figure 8. Dual Radio RSSI Measurements with Sender one acting on Channel 36 and Sender two on Channel 44

III. Conclusion and Future Work

This paper has shown that there are still significant issues with multi-radio WiFi based MNs particularly if these networks must be capable of supporting carrier grade services. The presented results have demonstrated that the ACI effect in IEEE 802.11a is an important issue especially with a channel bandwidth of 20 MHz as used in the described experiments. Generally, it is fair to say that it will never be possible to provide a carrier-grade multi-radio NANET when both transmitters are operating on adjacent channels and both transmitting antennas are relatively close to each other, i.e., less than 10 cm. This has been shown by conducting measurements with two sectorised antennas using the

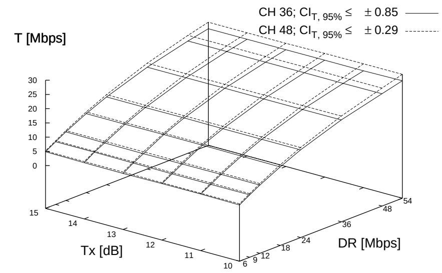

Figure 9. Dual Radio Throughput Measurements with Sender one acting on Channel 36 and Sender two on Channel 48

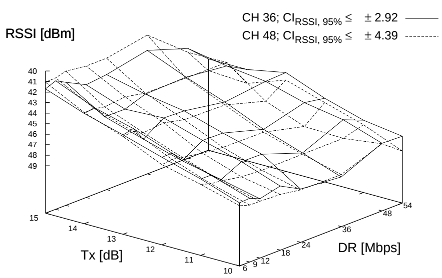

Figure 10. Dual Radio RSSI Measurements with Sender one acting on Channel 36 and Sender two on Channel 48

popular MikroTik R52 WiFi cards installed in two different machines to mitigate interference between the pigtails.

Based on an analysis of the R52 spectrum mask it was shown that the mask meets the requirements of the IEEE and hence it can be concluded that the results obtained are not specific to the MikroTik WiFi cards used. The ACI issues are mainly affected by two different parameters. Firstly, when a channel bandwidth of 20 MHz is used, in 802.11a adjacent channels interfere significantly with their neighbouring channels. Secondly, there is a non-negligible amount of interference between multiple radios operating in the same MN; this is primarily due to the cables used to connect the antennas to the WiFi cards and can also impact the reliability of mesh links.

To investigate these issues the channel separation between both transmitters was increased incrementally while measuring T, RSSI and RTR. Not until a channel separation of 60 MHz is reached does T of each radio in the multi-radio MN equal what would be achieved in a single-radio system. However, even with a channel separation of 60 MHz, the measured RSSI and RTR still show the ACI effect in terms of a high CI which should be interpreted as unpredictable link parameters.

Based on the goal of developing a NANET which can support carrier-grade services future work will conduct measurements with increased distance between the transmitter and receiver in order to take full advantage of the sectorised antennas. Additionally, the antenna separation will also be increased to investigate what impact this will have on the important link parameters T, RSSI and RTR. The interference between pigtails has to be decreased if both WiFi cards are to operate within the same node; this will be investigated using higher quality pigtails which can provide a higher level of shielding. Finally, the bandwidth of each channel will be decreased to 15, 10 and 5 MHz to investigate what reduction in ACI this can achieve.

ACKNOWLEDGEMENTS

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