Inter-Channel Interference Cancellation in Wireless Mesh Network

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Abstract: - Interference is one of the challenges that limit the performance of Wireless Mesh Networks (WMN). It became a major issue with new devises being equipped with more than one radio interface. This research emphasizes on impact of interference in multi-hop/ multi-radio WMN's throughput as a result of utilizing dual radios in WMN's station. Various laboratory experiments in this research indicates that the IEEE802.11 non-interfering channels for the 2.4GHz band still exhibit some level of interference. Furthermore, we proposed an interference cancellation circuit that showed a noticeable throughput enhancement in our experiments. This validates the proposed solution for interference suppression and throughput enhancement..

Key-Words: - Wireless Mesh Network (WMN), Access point (AP), Netperf, Signal to Interference Ratio (SIR), Non-overlapping channels, UDP throughput

1 Introduction

Wireless multi-hop networks such as MANET and WMN are in high demand to support the increasing need for multimedia communications [1]. WMN is an attractive alternate solution for providing internet access to places with difficult terrain while maintaining low cost and scalability. The term "Wireless Community Networks" is used to describe this kind of wireless mesh networks that aims to deliver wireless communications over large and complex areas where running cables is not cost effective due to terrain limitations [2]. Other advantages of WMNs are the ability to self-organize, auto-configure and self-healing [3], [4].

Interference is one of the challenges that have an effect on Wireless Mesh Network (WMN). As for IEEE 802.11 WMN, since the 2.4GHz ISM band is unlicensed, throughput of wireless network is greatly affected by the interference from nearby devices which utilize this free band. For example, many Bluetooth Pico nets in one area can significantly decrease IEEE 802.11 network throughput [2]. Generally, wireless networks performance is affected by the number of users and the distance from access point due to the shared bandwidth. The probability of channel interference increases with the number of users and the number of access points which access the available bandwidth at the same time. Any slight interference at the receiver antenna could result in a noticeable effect on throughput. Some types of tolerable interference can be removed by simple procedure. Others are more challenging and require additional procedures to eliminate or reduce interference effect [5]. Thus, suppressing channel interference is expected to play an important role in improving the throughput of network.

1.1 Multi-hop Multi-Radio Wireless Mesh Network (WMN)

IEEE 802.11 MAC layer protocol utilizes CSMA/CA mechanism for medium access. This mechanism is based on medium sharing and designed mainly for single hop transmission [4].WMN suffers from limitations in the available bandwidth and unpredicted delays. The reason for that is partly due to the number of radios utilized when forwarding packets. Generally, WMN stations receives and forwards packets using the same physical radio, a (per hop delay) is introduced as a result of utilizing the same channel for successive hops. However, with the rapid decrease in the radio manufacturing cost, it became more feasible to equip multiple radios on the same WMN station. The performance is expected to double with each added radio. That is because the introduction of a second radio enabled the node to transmit and receive simultaneously [6]. Access points equipped with multiple radios operating in the same frequency band (e.g. 2.4GHz) can scan multiple channels simultaneously. As a result, utilizing two radios on a WMN station is expected to improve the performance with factor of 2. This improvement is facilitated by efficient spectrum utilization, improved connectivity and increased coverage area [7]. Fig .1 shows an example of Multi-radio WMN. The multi-radio WMN can consist of stations which are stationary or mobile [8].

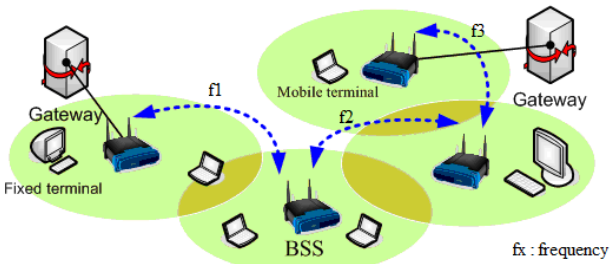

Fig.1 Multi-radio Wireless Mesh Network

The two radios provide the ability for interchanging between multiple non interfering channels and in some case even between different frequency bands (2.4GHz with 802.11b/g and 5GHz with 802.11a). This allows simultaneous communications with multiple neighboring stations while reducing the channel interference. The throughput also is expected to be higher in the multi-radio network.

1.2 IEEE 802.11Non-overlapping channels

The IEEE 802.11 MAC protocol was adopted as the medium access control of choice for the wireless mesh networks. IEEE 802.11 standard for the 2.4GHz frequency band define three non-overlapping (non-interfering) [9] channels as shown in Fig.2. These non-overlapping channels can operate simultaneously with minimal interfering. What it means is that these three channels can co-exist within the same coverage area without interfering with each other. Fig.2 shows that channels 1, 6, and 11 do not interfere with each other. Nevertheless, the Inter-channel interference (Adjacent Channel Interference (ACI)) cannot be completely eliminated even if the nodes use chipsets that satisfy the transmission mask requirements set by IEEE802.11 standard [7]. This channel interference was confirmed in field experiments of reference [10]. Thus, even for multi-radio devices, where the node's own transmission and reception radios utilize different channels, ACI still exists.

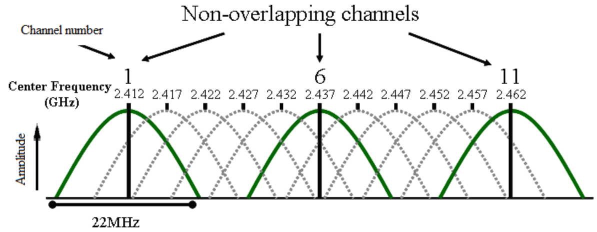

Fig.2 IEEE 802.11 Non-overlapping channels

This unavoidable interference is indicated in the upcoming experimental results. The throughput or system capacity is affected by this channel interference.

2 Interference suppression

It is a challenging task to achieve a robust performance when dealing with transmitter (high-power) in close proximity to receivers. The strong field from transmitters does not allow the receiver to operate efficiently. A specialized filter could help the transmitter to perform better when placed close to the receiver. However, such a case is applicable only to widely separated frequency channels. A proper cancellation technique is required to eliminate or reduce interference at the receiver which is useful for effective frequency reuse [11].

2.1 Interference in multi-radio equipment

Devices equipped with multiple radios are subject to interference between these radios. The access point in Fig.3 illustrates an example of multi-hop/ multi-radio WMN where the access point will receive data with one radio and forward it through the second radio.

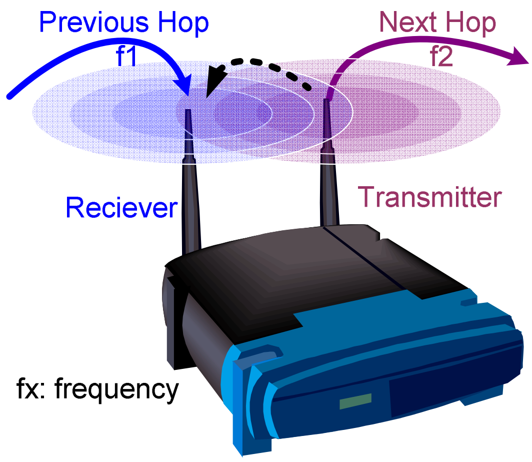

Fig.3 Interference in Multi-radio AP

2.2 Proposed interference cancellation circuit

To reduce interference between the two antennas of an access point, we proposed an interference cancellation circuit shown in Fig.4. This circuit is located between the access point's transmission and reception radios. The circuit consists of two 3dB couplers, variable attenuator and Coaxial Line Stretchers for phase shifting.

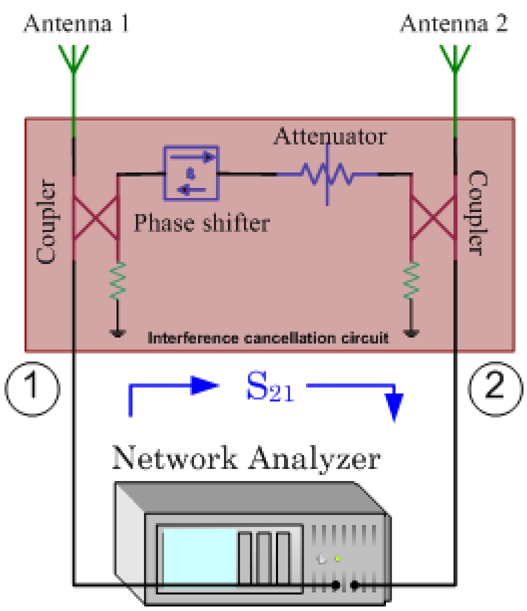

Fig.4 Interference cancellation Circuit

2.3 Phase cancellation

The idea behind the cancellation technique is to obtain a sample of interference and subtract it from the receiver signal with proper tuning in amplitude and phase shift. The interference sample is captured from the transmitter by a coupler (Fig.4).

A phase shifter is used to change the phase of the interference sample. Most of the phase shifters allow signal passing in either direction which makes them reciprocal devices. Phase shifters permit total phase variation up to 360 degrees. Line stretcher is one of the phase shifting devices [12]. Fig.5 illustrates the concept of phase shifting and utilizing two separate antennas to achieve the removal of unwanted singles.

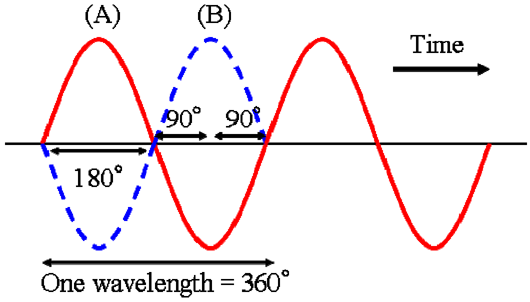

Fig.5 Phase Shift cancellation

The signals (A) and (B) from Fig 4.4 represents the signals from the transmit antenna and the coupled respectively. Since each signal travel in space from transmitter in cycles of 360 degrees, shifting one of the singles (signal B in this case) 180 degrees and superimpose it on top of the other signal will result in cancelling each other [12]. Changing the relative levels with a variable attenuator and combining them using couplers results in a reduction of strength of the unwanted signal.

The optimum attenuation depends on the distance between the two antennas and it's calculated using Eq. (1):

$$\text{Attenuation value} = 20\log\left(\frac{4\pi L}{\lambda}\right) - 4.3\text{dB} \quad (1)$$

where L is the distance (mm) between the two antennas and is the wavelength (mm). Each antenna gain is 2.15 dBi (Half-wavelength dipole antenna).

2.4 Scattering Parameters

Scattering parameters or S-parameters mostly used in communications systems to describe the behavior of the currents and voltages in a transmission line when they meet discontinuity. The parameters are measured in terms of complex amplitude. Moreover, many electrical properties of networks or components may be expressed using S-parameters, such as gain, attenuation and return loss.

To evaluate the effect of the proposed circuit, the scattering parameter S_{21} measured using a network analyzer with two antenna ports as shown in Fig.4. Fig.6 shows a comparison in the S_{21} parameter before and after applying the interference cancellation circuit. A drop in the S_{21} parameter after applying the cancellation circuit indicates a 10dB reduction in channel interference between the two antennas at 100MHz in the 2.4GHz band. Since the two antennas utilize two different channels, the aim is to have the lowest S_{21} value possible at any of the two channels.

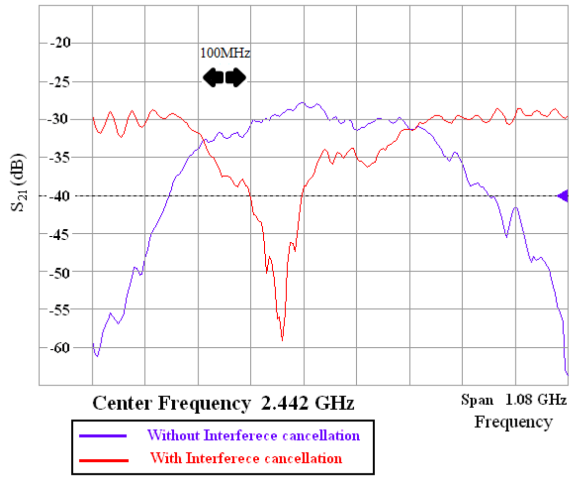

Fig.1 S_{21}Parameter comparison

As mentioned before, it was shown in the field experiment in [10] along with our own experiments that the Adjacent Channel Interference (ACI) exists even if the nodes use chipsets that satisfy the transmission mask requirements set by IEEE802.11 standard. This interference caused from the node's own transmission and reception radios although they utilize separate channels [10].The proposed cancellation circuit is applied to enhance the total throughput in the multi-hop network by reducing interference in the next chapter.

3 Experimental Study for the Throughput of Indoor Multi-hop Network

A series of experiments on WMN are carried out to identify and improve the throughput degradation in Indoor environments. Indoor Wireless networks experiments can be relatively challenging due to many factors such as high probability of attenuation, multipath, fading and noise. Any small changes in the environment can result in big changes in results collected form the experiments.

For UDP throughput measurement, Netperf [13] and Qcheck [14] are utilized to capture the throughput while transferring data from any desired source to destination through the assigned network and with any number of hops. The equipment utilized through out the experiment are, IPN-W100AP Trinity Security Systems, Inc access points with dual radio module 2.4GHz [15].

AirMagnet Surveyor [16] was utilized to measure the field distribution.

Channel utilization in the environment which we experiment has a huge influence on the experiment results. Because of that, the environment is carefully checked for any possible interference form outside source prior to performing the experiment. Moreover, distances between access points and antennas are carefully maintained throughout all experiments

3.1 Scenario 1: Signal to Interference (SIR) Ratio characteristics

In the first part of this scenario, the aim is to plot the relation between the throughput and Signal to Interference ratio (SIR) for one hop network using a signal generator as the interference source.

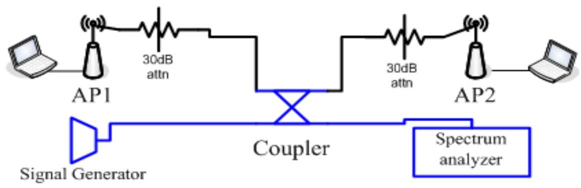

Fig.7 SIR Measurement using Signal generator

Fig.7 shows the experiment setup. It consists of two networks interconnects at the Coupler. The upper section consists of one hop WMN by IEEE 802.11. Cables are used in this experiment instead of wireless to avoid any unwanted interference from outside source. 30dB attenuators are used at the access points to limit signals from damaging the AP. The signal generator from the lower section produces an RF signal at same frequency channel as the upper network; which then is fed into the upper network to act as interference to the original communication between the two APs. The generated signal is increased to a level which the measured throughput becomes very low to indicate a break in the communication between the two APs. The results are shown in Fig.8.

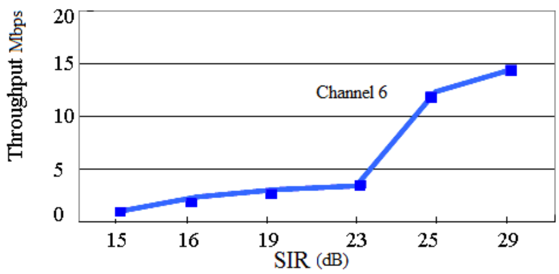

Fig.8 SIR vs Throughput

The results indicate that at SNR 15dB, the communication is nearly stops between the two access points. There was a steep change in the line between SNR 25 and 23dB which resulted in a significant change in the throughput. These results may be due to the carries sense level at the APs. The interference generated by the secondary network is a continuous signal which is not the case in a realistic interference from other sources.

Fig.9 illustrates the second part of this scenario. It consists of two networks interconnect with an isolator. The upper section consists of one hop network. 30dB attenuators are utilized at the access points to guard the AP.

The lower section of the experiment (indicated by the blue devices), acts as interference to the upper network. While operating at the same frequency channel, the signals from the lower section are fed into the upper network while changing the transmission power of the interference network. The isolator allows a single direction signal pass to prevent affecting the interference circuit with the signal from the upper network.

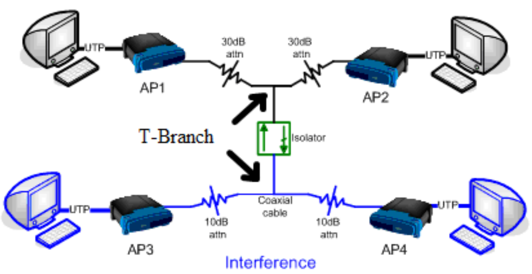

Fig.9 SIR Measurement using two interfering networks

The results obtained are shown in Fig.10 It is concluded that severe throughput degradation occurs at low Signal to Interference Ratio (SIR) values. In order to avoid the interference effect, the SIR values at the reception radio must be more than 25dB [17].

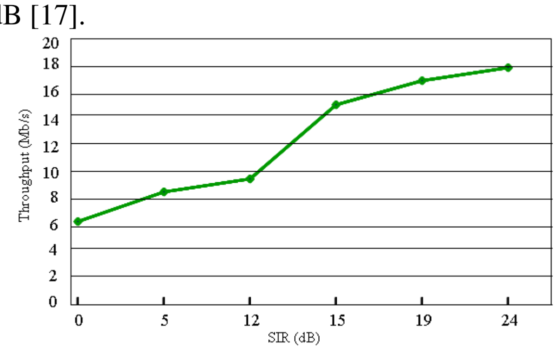

Fig.10 Throughput vs. SIR

It is also noticed that the network didn't arrive to a state where the throughput is zero even with SNR=0dB which indicates that the interference is equal to the signal. That is because the signals are timely sharing the channel medium between them. So the communication not be completely halted regardless the intensity of the interference,

3.2 Scenario 2: Throughput vs. number of hops

The aim of this scenario is to determine the effect of number of hops on the throughput .Up to three hops was experimented with as shown in Fig.11. For the first part of this scenario, only single radio AP was utilized

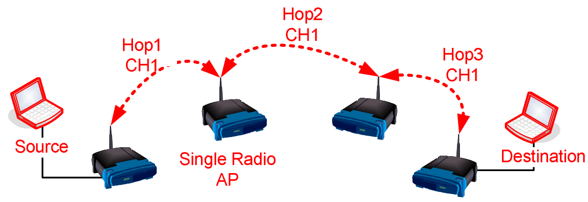

Fig.11 Three hop WMN with Single radio AP

Fig.12 shows the resultant throughput from the experiment. The line represents the throughput for 1, 2 and 3 hops with a single radio interface. Channel 1 was utilized for the three hops. This result indicates there is the nearly a 50% reductions in the throughput with each hop added to the network. 50% is very severe drop but reasonable because all three hops will utilize the same channel for communication.

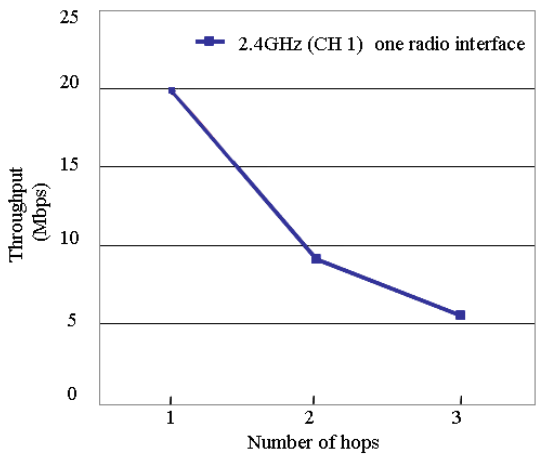

Fig.12 Number of hops vs. throughput for one radio AP

In the second part of the scenario, the two radios of the access point were utilized. The experiments were conducted with different frequency bands for successive hops to reduce the effect of interference between hops. IEEE 802.11a (5GHz) was utilized for the first and last hop (CH 44 and 36 respectively). For the middle hop, CH 11 was used with IEEE 802.11g (2.4GHz) as shown in Fig.13.

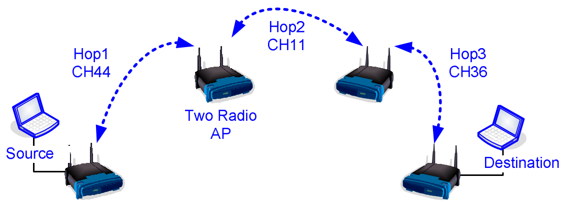

Fig.13 Three hop WMN with two radios AP

From Fig.14 the result shows that this setup achieved the high throughput compared to the previous case. The throughput for three hops was above 10Mbps which is significantly higher then using only 2.4GHz for all hops. Although, the performance was the same in single hop for any channel, the inter-channel interference effect on the throughput is small with the increase in number of hops.

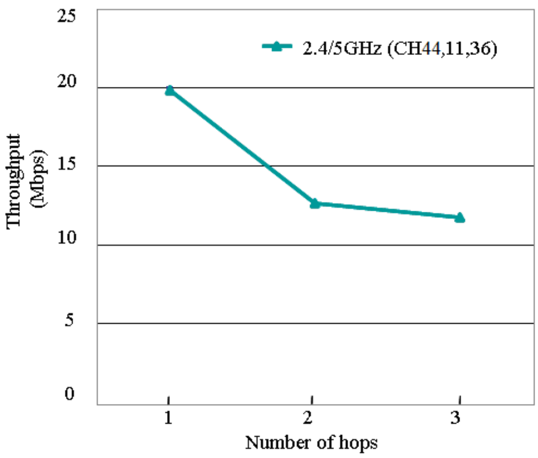

Fig.14 Number of hops vs. throughput for two radios AP (2.4GHz and 5GHz)

3.3 Scenario 3: Channel selection vs. throughput

Although, the previous results indicated the presence of interference as a result of utilizing the same channel for all the hops, our aim in this scenario is to examine the channel selection effect on the throughput for single and two radio AP for two hops WMN. In this scenario, we utilized the 2.4GHz frequency band only. The introduction of the second radio in access point is expected to improve capacity, connectivity and better utilization for the frequency band. Figure 5.12 indicates the two WMN that were tested in this scenario.

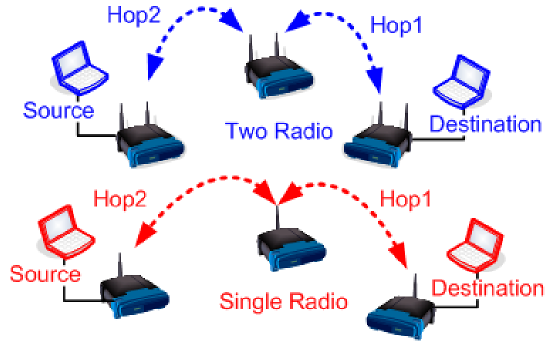

Fig.15 Single radio vs. Multi-radio

The upper network in Fig 5.15 utilizes two radios at the middle access point to route the data between the source and destination. The red network on the other hand utilizes only a single radio to do the routing. For this simple two hop WMN, it was expected to achieve better throughput with the two radio setup since they utilized different channel for the two hops. However, the results summarized in Table 1 show that the single radio setup achieved slightly higher throughput than the two radio setup.

Table 1 Throughput of Mutli-hop WMN

Multi-Radio	Throughput (Mbps)
Channel 1/Channel 3	8.408
Channel 1/Channel 6	9.094
Channel 1/Channel 11	9.00
Single radio	Throughput (Mbps)
Channel 1	10.25

The first column indicates the channel combination used for the fist and the second hops. For the multi -radio setup, we notice that as the channel separation increase, the throughput is slightly improved. The small improvement in throughput is due to utilizing non overlapping channels. In case of a single radio, the only channel 1 is utilized, and the throughput achieved was the highest among the other combination. In the two radios case, the first hop and the second hop do not tightly interfere with each other since they utilize different frequency channels. The degradation in throughput is due to the dropped packets as a result if interference between the transmitting and receiving radios on the access point. On the other hand, the single radio case do not face such a problem since the two hops utilizes the same frequency channel. As a result, when hop 1 is using the channel, hop 2 cannot transmit until hop 1 finishes transmitting. For this reason, the dropped packet may be decreased and slightly higher throughput is achieved.

3.4 Scenario 4: Throughput measurement for distance varying and hop count in Indoor closed corridor environment.

In this experiment we performed a site survey using Air Magnet Surveyor. The aim is to measure the field distribution in a long corridor of the venture building at the Yokosuka research park (YRP). The total length is 88m with a slight bent at the middle as shown in Fig.16. Fig.16 also demonstrates the results obtained from our site survey. A single access point was placed at one end of the corridor. It is a typical indoor office corridor with glass doors and office partitions.

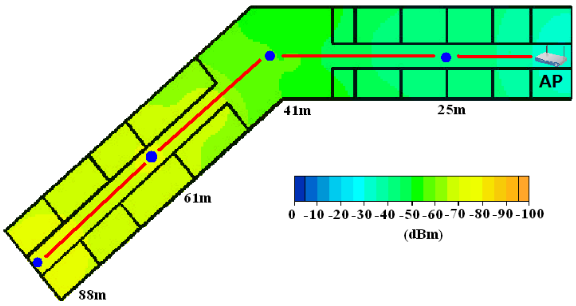

Fig.16 Single access point field intensity

The stronger received power is indicated by the blue region. The yellow region represents a weak received power.

In general, the relation between path loss and the distance between the transmitter and receiver at 2.4 GHz is approximated in [8] as shown in Eq. (4):

$$PathLoss(dB) = 40 + [35\log_{10} D(meters)] \quad (4)$$

were D is the distance between the transmitter and the receiver.

Fig.17 indicates the relation between the received power and distance from access point. The figure shows that the coverage range is relatively high through corridors. This is explained by the waveguide property for the corridor, which state that the signals travel longer distances through corridors and narrow paths.

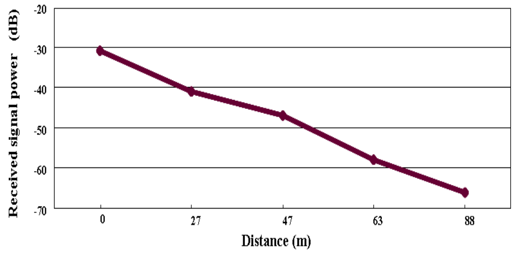

Fig.17 Received signal power versus range in a corridor

After the site survey, we intended to plot a graph of distance against throughput in a closed corridor environment. We placed one AP at one end point of the corridor and measure the single hope throughput while changing the position of the second access point as shown in Fig.18.

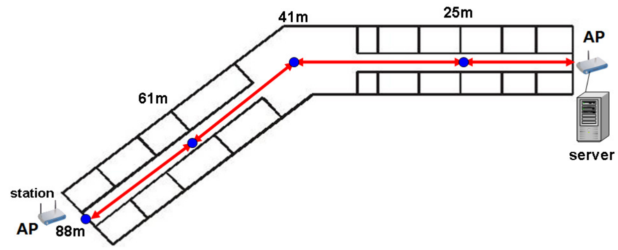

Fig.18 Received signal power measurement points in the corridor

Table 2 indicates the throughput achieved at different separation distance with the corresponding receiving power level. IEEE 802.11g was utilized with channel 7 at 2.4GHz. The degradation in throughput was not severe in the corridor which agrees with the wave guide property for corridors.

Table 2 Throughput measured at different hop distance

Distance	25m	41m	61m	88m
Received power (dB)	-41	-53	-69	-72
Throughput (Mbps)	15.5	14.26	13.68	13.22

3.5 Scenario 5: Interference cancellation experiment for 2 hops WMN

The proposed interference cancellation circuit is utilized in this scenario to test its impact on the throughput. The circuit is expected to cancel interference between the two antennas of a WMN access point equipped at the center of the corridor. Fig.19 shows the structure of the circuit and antennas.

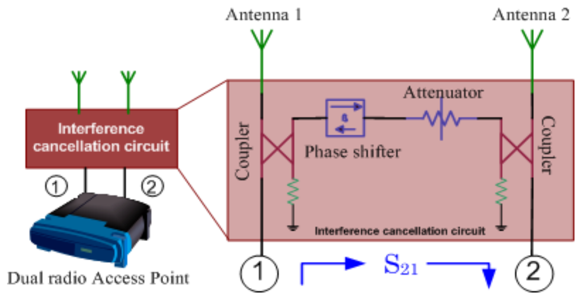

Fig.19 Interference cancellation Circuit connected on two radios AP

Fig.20 demonstrates the actual experiment setup and components of the interference circuit.

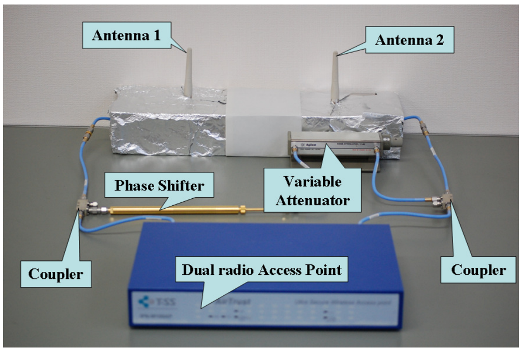

Fig.20 Actual Interference cancellation Circuit

A two hop WMN with three IPN-W100AP Trinity Security Systems, Inc. access points operating by 2.4GHz IEEE802.11g with dual radio were utilized for this experiment as shown in Fig.21.

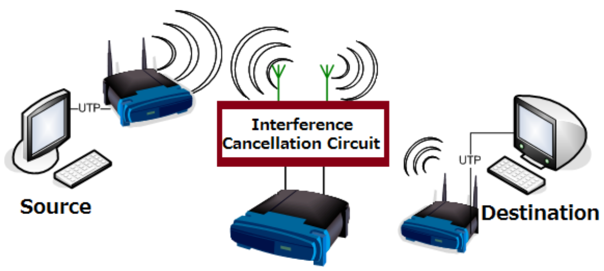

Fig.21 Two-hops WMN with cancellation circuit

The APs connected to the source and destination use only one antenna. The second AP will utilize both antennas to route the data from the source to destination. Fig.21 indicates how the cancellation circuit is installed between the two antennas of the middle access point. Netperf software was utilized to evaluate the UDP throughput while transferring data from the source to the destination.

The distance between the access points is maintained throughout the experiment at 1.5m. The distance between the two antennas in the cancellation circuit was fixed to 21cm which is similar to the original spacing between the two antennas before utilizing the circuit.

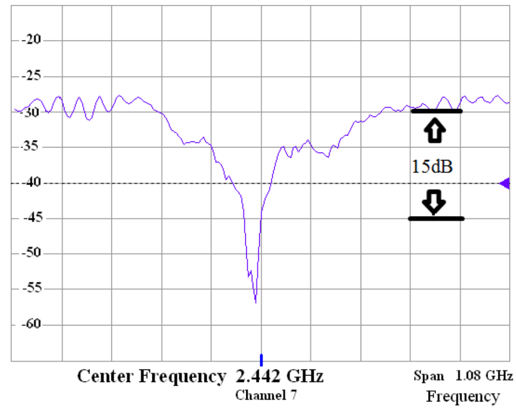

Fig.22 S_{21} Parameter

In this experiment we utilized channel 2 for the first hop and channel 7 for the second hop. Fig.22 shows a plot of the S_{21} Parameter to achieve the highest possible cancellation. The aim was to have the lowest possible value of S_{21} at channel 2 or channel 7 to achieve the desired cancellation. The centre frequency was 2.442GHz which represents Channel 7. Using the combination of the phase shifters and the attenuator, we managed to suppress interference around 15dB.

The selection of the channels is governed by channel utilization in the field. That is to minimize interference from outside sources. Channel 2 and 7 are almost non-overlapping channels according IEEE 802.11 standard for 2.4GHz band. We measured the change in throughput as a result of using the interference cancellation circuit. The green line (at 7.984Mbps) in Fig.23 represents the throughput achieved in a normal case (with the presence of interference).

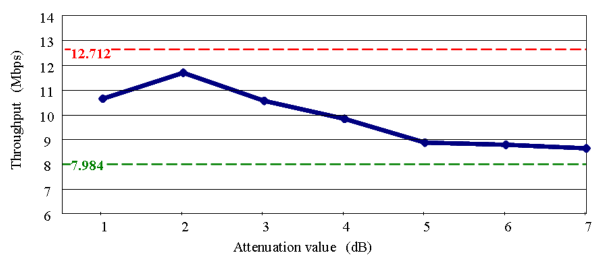

Fig.23 Attenuation value vs. throughput

In order to achieve the no interference ideal case for two hops WMN, we utilized coaxial cables between the access points to avoid any possible interference between the radios. The throughput was 12.712Mbps (red line). The blue line indicates the results obtained after tuning the variable attenuator values (1dB-7dB) while fixing the Phase at 180°. The highest throughput achieved was 11.7 Mbps at 2dB attenuator value. To compare that result with the normal case (the green line at 7.984Mbps), we managed to achieve an improvement of nearly 4Mbps.

Qcheck [14] software was utilized for UDP data streaming estimation of the interference cancellation circuit. Streaming 1Mbps for 30sec resulted in a 25% dropped data from the total data streamed without using a cancellation circuit. The dropped data reduced to 0.1% in case of cancellation circuit.

The cancellation circuit was tested in the closed corridor environment to measure the improvement in throughput. The experiment of interference cancellation for 2 hops in long corridor is shown in Fig.24

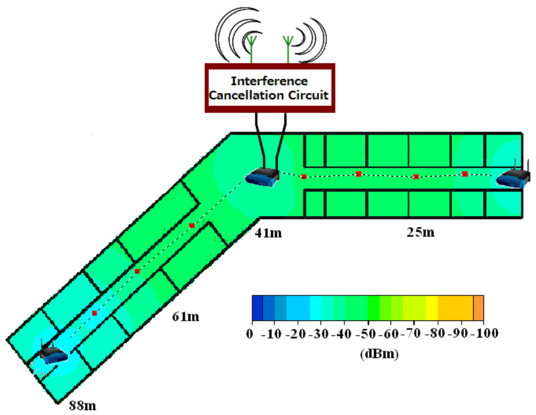

Fig.24 Two hop WMN in closed corridor with cancellation circuit

Fig.24 shows the setup of a two hop WMN along with their coverage field intensity. The cancellation circuit was installed at the middle access point (at 41m).

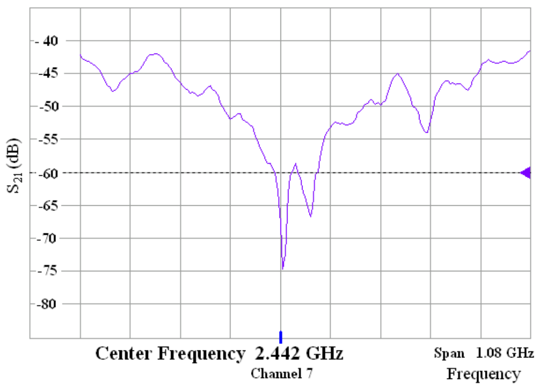

Fig.25 S_{21} Parameter

Fig.25 illustrates the S_{21} parameter for the cancellation circuit which gave the highest improvement in throughput for the circuit in Fig .24. The proposed circuit in a closed corridor environment resulted in nearly 3Mbps improvement in throughput (from 5.3Mbps to 8.3Mbps).

4 Conclusion

In this work we investigate the effect of interference on the throughput of multi-hop multi-radio WMN. The experiments results demonstrated the severe impact of interference on the WMN throughput. It was found that access points equipped with multiple radios exhibits interference which degrades its throughput.

The proposed interference cancellation circuit managed to suppress interference between two antennas of the access point and achieve improvement of nearly 30 dB reduction in S_{21}parameter. Moreover, the circuit managed to improve the throughput from 7.9Mbps to 11.9Mbps in typical indoor environment and from 5.3Mbps to 8.26Mbps in a long corridor environment. The improvement also results in a reduction in packet dropped for the two hops WMN from 25% packet dropped to 0.1% in case of interference cancellation.

As for future work, the circuit will be further improved to achieve higher signal cancellation and it will be implemented.

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References:

[1] A.N. Al-Khwildi, S. Khan, K.K. Loo, H.S. Al-Raweshidy, “Adaptive Link-Weight Routing Protocol using Cross-Layer Communication for MANET”, WSEAS TRANSACTIONS on COMMUNICATIONS, Issue 11, Volume 6, November 2007, pp.833-839.

[2] Ondřej Hynčica, Františ̂ek Zezulka, Petr Fiedler, “Wireless Standards for Mobile Platform”, WSEAS TRANSACTIONS on COMMUNICATIONS, Issue 5, Volume 4, May 2005, pp.199-210.

[3] Rui Zhao, Walke, B. and Einhaus, M., “Constructing efficient multi-hop mesh networks”, Proceedings of The IEEE

Conference on Local Computer Networks, 30th Anniversary, November 2005, pp. 166- 173.
[4] Tzu－Jane Tsai and Ju－Wei Chen, "IEEE 802.11 MAC protocol over wireless mesh networks: problems and perspectives", Proceedings of 19th International Conference on Advanced Information Networking and Applications (AINA 2005), March 2005, pp. 60- 63 vol.2.
[5] Albert A. Lysko, David L. Johnson,"A Study of Propagation Effects in a Wireless Test Bed", WSEAS TRANSACTIONS on COMMUNICATIONS, Issue 8, Volume 7, August 2008, pp.857-871.
[6] Richard Draves, Jitendra Padhye and Brian Zill, "Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks", Proceedings of the 10th annual international conference on Mobile computing and networking, September 26 - October 1, 2004, pp. 114-128.
[7] Lin Chen, Qian Zhang, Minglu Li and Weijia Jia, "Joint Topology Control and Routing in IEEE 802.11-Based Multi-radio Multichannel Mesh Networks", IEEE Transactions on Vehicular Technology, September 2007, Volume: 56 Issue: 5 Part 2, pp. 3123-3136.
[8] Spread Spectrum Scene, Indoor Radio Propagation, http://sss-mag.com/indoor.html#tutorial
[9] Jing Zhu and Roy, S., "802.11 mesh networks with two-radio access points", Proceedings of IEEE International Conference on Communications ICC 2005, May 2005, pp. 3609- 3615 Vol. 5.
[10] Chen-Mou Cheng, Pai-Hsiang Hsiao, H. T. Kung and Dario Vlah, "Adjacent Channel Interference in Dual-radio 802.11a Nodes and Its Impact on Multi-hop Networking", Proceedings of Global Telecommunications Conference 2006 (IEEE GLOBECOM '06), November 27- December 1, 2006, pp. 1-6.
[11] Venskauskas, K.K., "Adaptive filters application for improving EM.G of Radio electronic equipment", Proceedings of 1984 International Symposium on EMC. Tokyo, 1984, vol.2, 650-654.
[12] http://www.microwaves101.com/encyclopedia/phaseshifters.cfm
[13] http://www.netperf.org/netperf/
[14] http://www.ixchariot.com/products/datasheets/qcheck.html
[15] http://www.trinity-ss.com/en/
[16] http://www.airmagnet.com/products/survey/
[17] Wadhah H.Al-Mandhari, Nobuo Nakajima and Pham Huy Hoang, "The Effect of Channel selection and interference on throughput in multi-radio wireless mesh networks", Proceedings of Triangle Symposium on Advanced ICT 2008 (TriSAI), October 2008, pp. 74-77.