Experimental Investigation of Coexistence Interference on Multi-Radio 802.11 Platforms

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***Abstract*—We study coexistence interference that arises between multiple collocated radio interfaces on 802.11 based multi-radio platforms used for mesh networks. We show that such interference can be so severe that it prevents concurrent successful operation of collocated interfaces even when they use channels from widely different frequency bands. We propose the use of antenna polarization to mitigate such interference and experimentally study its benefit in both multi-band and single band configurations. In particular, we show that using differently polarized antennas on a multi-radio platform can be a helpful counteracting mechanism for alleviating receiver blocking and adjacent channel interference phenomena that underlie multi-radio coexistence interference. We also validate observations about adjacent channel interference from previous studies via direct and microscopic observation of MAC behavior.**

I. Introduction

In a multi-radio mesh network, individual mesh routers are equipped with multiple radio interfaces, each configured to multiple different channels. Advantages of such an architecture for achieving high end-to-end network performance, keeping (co-channel) interference low and better utilization of available spectrum is now well established, both theoretically and through simulation-based evaluations of channel allocation protocols (e.g., [1]). Since mesh networks have evolved as multihop extensions of wireless LANs (WLANs), they typically use radio interfaces based on IEEE 802.11, the de facto standard for WLANs. Even infrastructure based WLANs benefit from the use of multi-radio access points (APs) for improved interference management and spectrum utilization.

Realizing the benefits of multi-radio architectures in practice poses challenges that are often abstracted out in simulation based evaluations. These concern interference resulting from collocation and simultaneous operation of multiple radio interfaces within a multi-radio platform. Following [2], we will refer to this interference as *multi-radio coexistence interference*. This interference is described by Zhu et al. [2] as a composition of three phenomena: *receiver blocking*, *transmitter noise* and *intermodulation*. Receiver blocking is a result of limited dynamic range of power amplifier and A/D converter in the receiver; it arises in situations where a transmitting (interferer) antenna is in close proximity of a collocated antenna. If total input power at the receiver is more than the blocking limit (e.g., -30dBm at 2GHz for WiFi) the received signal strength degrades. Transmitter noise or adjacent channel interference (ACI) refers to the out-of-band emission seen by receivers in close proximity of a transmitter (e.g., due to imperfect filtering at the transmitter antenna). Intermodulation is a result of non-linearity of radio components such as amplifier. It surfaces when intermodulation bandwidth due to a pair of concurrent and nearby transmissions overlap with receiver channel bandwidth[1]. In contrast to Zhu et al. who focused on the case of platforms with multiple radios using heterogeneous wireless technologies (e.g., Bluetooth, WiFi, WiMax), our focus is on router/AP platforms with multiple 802.11 radios in concurrent operation.

We experimentally show that performance degradation due to coexistence interference on multi-radio 802.11 platforms can be significant if adequate care is not taken to mitigate it. Physical separation of antennas on 802.11 multi-radio platforms and separation between channels used by different collocated radio interfaces are common ways to avoid performance degradation due to multi-radio coexistence interference [3], [4], [5], [6], [7], [8]. Required amount of antenna and channel separation varies depending on factors such as transmission power and bit-rate. Ideally, we would want these separation amounts to be as small as possible while allowing us to transmit at maximum bit-rates allowed by link/channel quality and at transmit power up to regulatory limit. Small antenna separation will lead to a compact platform that is easier and cheaper to deploy, an especially important consideration for indoor WLAN/mesh scenarios. Smaller channel separation can potentially allow better utilization of available spectrum.

Our experiments show a somewhat surprising result: multi-radio coexistence interference (due to receiver blocking) can be so severe that even collocated radio interfaces operating on channels from *different bands* (e.g., 2.4GHz and 5GHz) interfere with each other when their antennas are in close proximity. This observation holds true across different mesh platforms and 802.11 interface cards. It therefore needs to be kept in mind when designing dual-radio (more generally, multi-radio) mesh networks with multiple radios per node configured to channels in different bands as proposed in recent work [9].

To relieve the need for increased antenna/channel separation without limiting transmit power/bit-rate, we consider *antenna polarization*, for the first time, as an extra knob to introduce

[1]In this paper, we mainly focus on the impact of a transmitting antenna on the reception over a collocated antenna, so we explicitly only consider receiver blocking and transmitter noise effects.

an additional coupling loss[2] up to 20dB between collocated antennas. Polarization is the direction of the electric field of a radio wave relative to the ground [10]. Linearly polarized antennas are commonly used in 802.11 networks and they typically are polarized either vertically or horizontally — electric field is perpendicular to the ground for vertically polarized antennas, whereas it is parallel to the ground with horizontally polarized antennas. Antenna orientation and polarization are closely related in the sense that changing the orientation of the antenna changes its polarization.

- We experimentally show that having differently polarized antennas for different 802.11 interfaces on a multi-radio node reduces required antenna separation to as low as 3cm in multi-band configurations.
- When widely separated channels within single band are used for different collocated radio interfaces, up to four times higher bit-rates are made possible by differently polarized antennas compared to using identically polarized antennas for the same antenna separation and transmit power.
- On the other hand, when nearby channels are used between different interfaces on a multi-radio 802.11 platform, the required amount of channel separation to avoid performance degradation is reduced when interfaces use differently polarized antennas.
- Crucially, the above benefits do not come at the cost of network connectivity. Using measurements from an actual indoor multi-radio mesh network testbed, we show that the use of differently polarized antennas has a small effect on the mesh network topology and link qualities. Essentially, we exploit the fact that after a few reflections the polarization of the signal at transmit antenna does not have a bearing on the polarization of the signal at receiver side [11]. This is particularly true in non-line-of-sight environments as also experimentally demonstrated in previous work [12].

It is important to note that omnidirectional antennas that allow changing polarization are only slightly more expensive compared to those that do not offer such flexibility.

Compared to previous work [3], [4], [5], [6], [7], [8], our main contributions lie in:

- Highlighting the severity of multi-radio coexistence interference due to receiver blocking even when using different frequency bands.
- Demonstrating the use of antenna polarization as a means to alleviate multi-radio coexistence interference with little negative side effects.
- Characterizing adjacent channel interference using direct observation of MAC behavior and validation of observations from prior work based on indirect packet delivery ratio measurements (e.g., [6]).

[2]Coupling loss refers to the amount of drop in strength of interference to alleviate multi-radio coexistence interference. If it is greater than the *minimal coupling loss* then coexistence interference can be eliminated [2].

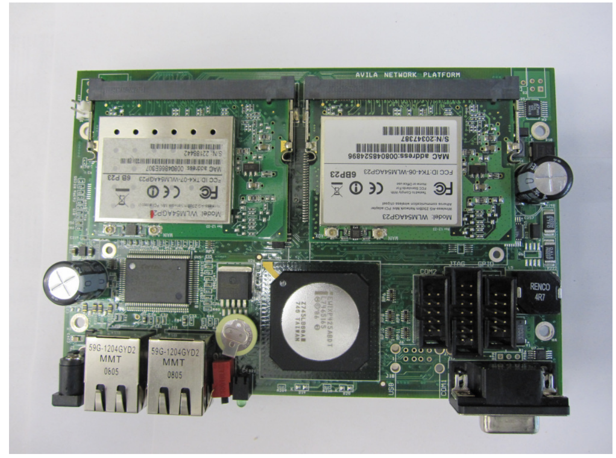

Fig. 1. Gateworks Avila multi-radio platform equipped with two Compex WLMAG54-23dBm mini PCI cards.

We start by describing our experimental methodology in the next section.

II. Experimental Methodology

Several factors influence the nature and extent of multi-radio coexistence interference, including: platform, types of radio interfaces and antennas, antenna and channel separation, transmit power and bit-rate. When characterizing coexistence interference these factors and their mutual interaction have to be considered. For our experimental study, we consider three different multi-radio platforms: Gateworks Avila[3], Gateworks Cambria[4] and Ubiquiti RouterStation[5]. As we found similar results using these different platforms, for the sake of brevity, we only present results for experiments based on the Avila platform. For the operating system on the platform, we use OpenWrt Linux. For 802.11 radio interfaces, we use two different types of miniPCI cards: Compex WLM54G-23dBm[6] and Mikrotik R52Hn[7]. As with the platform, we mainly present results for experiments using Compex cards. Fig. 1 shows the Avila platform with two compex cards installed. Both Compex and Mikrotik cards used in our study are based on Atheros chipsets. We use open-source ath5k/ath9k device drivers[8]. Previous studies have reported that Atheros based cards have some undocumented features such as Ambient Noise Immunity (ANI) and antenna diversity [13]. We found that they are not helpful in mitigating multi-radio coexistence interference; as such they are not relevant for our study. Coming to the antennas, we use two types of dual-band omnidirectional antennas, one from Cisco and the other from

[3]http://www.gateworks.com/products/avila/gw2348-4.php
[4]http://www.gateworks.com/products/cambria/gw2358-4.php
[5]http://www.ubnt.com/support/routerstation
[6]http://www.compex.com.sg/fullDescription.aspx?pID=27
[7]http://routerboard.com/R52Hn
[8]Mikrotik card is actually a 2x2 MIMO supporting 802.11n standard but we use it in legacy SISO mode via the ath9k driver.

TABLE I
EXPERIMENT HARDWARE AND SOFTWARE

Router Platforms	Gateworks Avila and Cambria, Ubiquiti RouterStation
Platform OS/Firmware	Openwrt attitude r27891
Radio Interfaces	Compex WLMAG54-23dBm and MicroTik R52Hn mini PCI cards
Device Drivers	ath5k / ath9k r2011-06-22
Antennas	Cisco dualband dipole omni (2dBi@2.4GHz, 5dBi@5GHz) Laird dualband omni (3dBi@2.4GHz, 5dBi@5GHz)

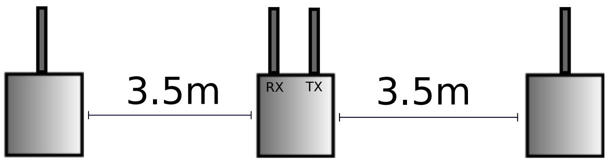

Fig. 2. Experiment setup with a dual-radio node in the middle.

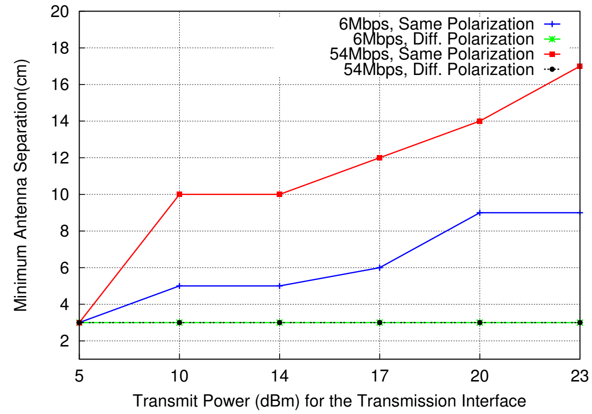

Fig. 3. Minimum antenna separation required to avoid throughput degradation on Avila based dual-radio 802.11 platform at different bit-rates, antenna polarizations and collocated interferer transmit power levels.

Laird Technologies with Cisco antennas[9] being our default as they allow changing antenna orientation (polarization). The above settings are summarized in Table I. Other parameters such as antenna separation and transmission power are varied in our experiments.

Like in previous studies on characterization of coexistence interference on multi-radio 802.11 platforms [3], [4], [6], [7], we use the three node experimental setup as shown in Fig. 2. The middle node in the setup is equipped with two radios and performance of transmissions/receptions on those radios while varying other parameters is the main focus of the study. As per the traffic workload, we use Iperf[10] UDP tests and measure throughput performance. We also study other metrics derived using or related to throughput such as minimum antenna separation and maximum achievable bit-rate.

III. MULTI-RADIO COEXISTENCE INTERFERENCE: MULTI-BAND CASE

In this section, we study the nature of multi-radio coexistence interference in a configuration argued to be more practical in recent work [9] for 802.11 based multi-radio mesh networks. In this configuration, each mesh node is equipped with two radios configured to use channels in two different frequency bands. Towards this end, we use the 3-node setup from Fig. 2 with the middle dual-radio node having 2 Compex cards, each configured to a channel in 2.4GHz and 5GHz unlicensed bands, respectively. The 2.4GHz interface is used to transmit Iperf UDP traffic to an end node while the 5GHz interface receives identical traffic from the other end node[11]. Transmission power on the 2.4GHz interface is varied over a wide range from 5dBm to 23dBm while keeping the bit-rate on the interface fixed to 6Mbps. Our focus is on measuring the extent to which data can be successfully received on the 5GHz interface. We use two extreme bit-rates of 6Mbps and 54Mbps for the 5GHz link to capture the reception performance at widely different transmission rates. We define a metric called *minimum antenna separation (in cm)* that corresponds to the smallest antenna separation between transmitting and receiving interfaces in the dual-radio node that yields closest to maximum throughput for the bit-rate in question (around 5Mbps for 6Mbps bit-rate and 29Mbps for 54Mbps bit-rate). This metric directly captures the impact of multi-radio coexistence interface on the platform size.

Results are shown in Fig. 3. Focusing on the typical configuration where multiple collocated radios use identically (vertically) polarized antennas, we observe that the minimum antenna separation increases with increase in transmit power of the other transmitting (2.4GHz) radio and increase in reception bit-rate of the receiving (5GHz) radio. Both these are along expected lines — higher transmit power causes more interference, whereas reception at higher bit-rate requires higher SINR (or alternatively, lower interference). However, the fact that this happens even collocated interfaces use widely different frequency bands is quite remarkable. We attribute this behavior to the receiver blocking effect mentioned at the outset. We obtained greater confidence in this conclusion when we found that MAC on the receiving (5GHz) interface never got into BUSY state [14] when the collocated 2.4GHz interface is transmitting.

In order to reduce the undesirable interference from a collocated transmitting radio, we experiment with having the two collocated antennas use different polarizations (one using vertical and the other horizontal). Results for this configuration are also shown in Fig. 3, which are significantly different from the earlier results. Minimum antenna separation now always remains at the minimum 3cm and is unaffected by increase in transmit power of the collocated interfering interface regardless of the bit-rate used by the receiving interface.

[9] http://www.cisco.com/en/US/docs/routers/access/wireless/hardware/notes/antdip.html
[10] http://sourceforge.net/projects/iperf/
[11] Although the traffic direction is found to make a difference as previously observed in [7], results are qualitatively similar and do not affect our conclusions

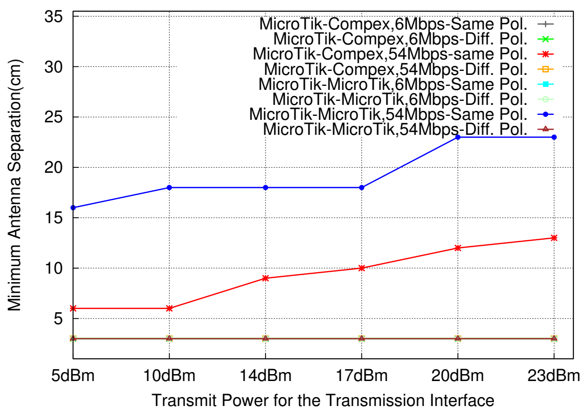

Fig. 4. Impact of using a different radio interface card and different radio interface cards in combination on minimum antenna separation required to avoid throughput degradation on Avila based dual-radio 802.11 platform at different bit-rates, antenna polarizations and collocated interferer transmit power levels.

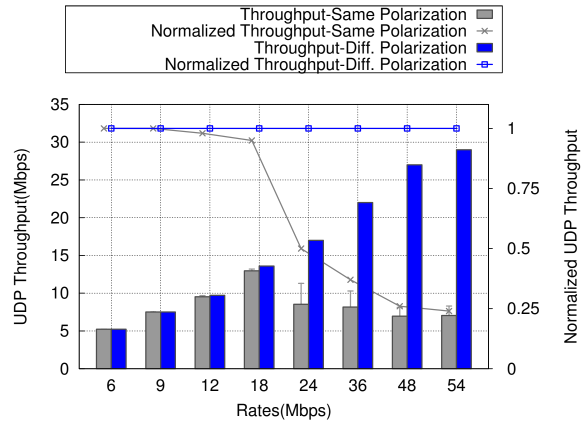

Fig. 5. Received UDP throughput as a function of different bit-rates when antenna separation is fixed at 6cm and power level of the interfering transmit interface on 2.4GHz is set to 17dBm.

This shows that the additional coupling loss introduced from using differently polarized collocated antennas is sufficient to have the two links function concurrently without hurting each other and more importantly, without needing increased antenna separation (platform size).

In order to confirm that the above results are not peculiar to the specific type of hardware used, we experiment with a different interface card (MikroTik), using different cards in combination (MikroTik and Compex) and with other platforms (Cambria and Ubiquiti RouterStation). Corresponding results when using different cards are shown in Fig. 4. Although the absolute numbers increase a bit for the case with identically polarized antennas, results are qualitatively similar to Fig. 3 and previous conclusions still hold. We did not observe any noticeable difference in the results by changing the platform (not shown).

We now look at the impact of multi-radio coexistence interference on received UDP throughput in different configurations. For this, we use the same setup with Compex cards as before but set the transmit power of the transmitting (2.4GHz) interface to 17dBm, default for Compex cards, and fix the antenna separation to 6cm, which from Fig. 3 is the minimum required to avoid degradation at 6Mbps bit-rate when the interfering radio transmit power is 17dBm and identically polarized antennas are used. Unlike before where we only considered the extreme rates, we now measure received throughput at *all* bit-rates as shown in Fig. 5. These results confirm that using differently polarized antennas always yields maximum throughput, whereas maximum throughput is achieved only till about 18Mbps bit-rate with the typical configuration using identically polarized antennas and throughput degrades beyond that point only providing less than quarter of the maximum throughput at 54Mbps rate.

Overall conclusion from our study of dual-radio platform in multi-band configuration is that use of differently polarized antennas is a very effective remedy to counter multi-radio coexistence interference and achieve high performance without increasing platform size.

IV. Multi-Radio Coexistence Interference: Single Band Case

So far, we studied multi-radio coexistence interference when multiple radios operate in different bands. We now consider the case where different radios in a multi-radio platform are configured to use channels from within a single frequency band, focusing on the 5GHz unlicensed band that has a number of channels making it suitable for 802.11 based multi-radio networks.

We first consider the situation where two radios on a dual-radio platform are configured to use *far apart channels within the same band*. Specifically, we assign channels 36 (5.18GHz) and 157 (5.785GHz) to the two radio interfaces on the middle node in Fig. 2 with end nodes using different channels chosen from 36 and 157. From repeating the same experiment as in the previous section to determine the minimum antenna separation for different power levels and bit-rates, we find that antenna separation has to be greater than 40cm, maximum that is practically feasible across all the platforms we used, to avoid performance degradation across all power levels and bit-rates, especially higher bit-rates and power levels. This is the case even when using differently polarized antennas. Using differently polarized antennas is still relatively beneficial though. For example, minimum antenna separation requirement with differently polarized antenna case is five times lower than with identically polarized antennas (6cm vs. 30cm) for 6Mbps rate and 17dBm transmit power level. To better capture the benefit from using differently polarized antennas, we provide a comparison in terms of maximum achievable bit-rate at different power levels in Fig. 6 when the antenna separation is fixed at 40cm. We observe that using differently polarized antennas permits using bit-rates that are up to 4 times higher for the same interferer power level (see rates comparison for the 20dBm power level).

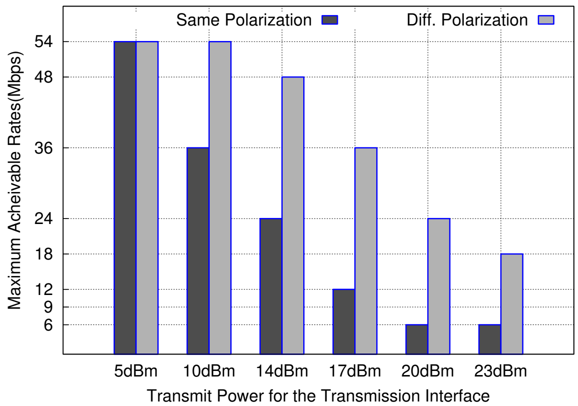

Fig. 6. Maximum achievable bit-rates on the receive interface at different power levels for the transmit interface when both interfaces are tuned to far apart channels within the 5GHz and their antennas are separated by 40cm.

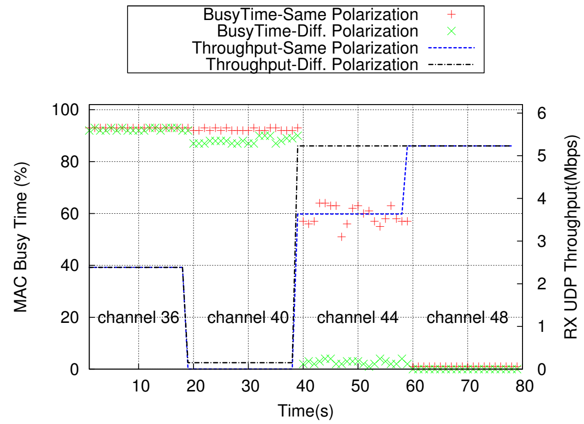

Fig. 7. The effect of adjacent channel interference (ACI) on receive MAC BUSY time and throughput at different channel separations and polarizations between collocated interfaces.

Let us now consider the case where collocated interfaces on a multi-radio node are assigned *nearby channels*, thereby introducing the additional possibility of *adjacent channel interference (ACI)* besides receiver blocking, which was the only phenomenon causing coexistence interference in our experiments so far. Although ACI characterization in multi-radio 802.11 networks has received a fair amount of attention in the literature [3], [4], [5], [6], [7], [8], it was done indirectly using packet delivery ratio measurements. We aim to complement and validate observations from previous work by taking a direct and microscopic look at MAC behavior in presence of ACI and correlate it with packet delivery ratio.

An 802.11 interface can be viewed as being in one of the following four states: transmit (TX), receive (RX), channel busy (BUSY) and IDLE [14]. The BUSY state occurs when energy detected on the channel is more than a specified threshold (e.g., -62dBm for Atheros chipset in 802.11a). In Atheros based chipsets, three counter registers are updated at 40MHz frequency and show the percentages of time that the MAC is in RX, TX or BUSY states. We access the values of these registers from user-level at 1Hz using shell scripts.

As before, we use the 3-node setup shown in Fig. 2 with Compex cards and Cisco antennas. Separation between antennas on the middle dual-radio node is 40cm. One of the interfaces on that node is receiving data on channel 36 (5.18GHz) sent at 6Mbps bit-rate. The transmit power level of the other interface is set to 17dBm and it shifts channels every 20 seconds from 36 – 40 – 44 – 48 while continuing to broadcast traffic on each of those channels. Result of this experiment is shown in Fig. 7. Percentage of BUSY time of MAC on the receiving interface of the dual-radio is computed based on tracking register values as described above. Receive throughput is also shown in the figure.

Focusing on the case of identically polarized antennas on the dual-radio node, we see that MAC of the receiving interface finds the channel to be fully busy not just when both collocated interfaces use the same channel (36) but also when the interfering interface uses the immediately adjacent channel (40). Received throughput differs quite widely between these two channels — channel sharing happens between the two interfaces on channel 36, whereas throughput of the receiving interface drops almost to zero due to the high level of ACI from nearby transmission on channel 40. As the broadcasting interface moves to channel 44, receive interface finds the MAC to be busy only 60% of the time and its throughput proportionately increases. With a separation of three channels (i.e., when transmitting interface is on channel 48), the effect of ACI on receive interface MAC busy time and throughput becomes negligible.

Similar qualitative behavior holds when antennas on the dual-radio are differently polarized except that now only 2 channel separation is required between the collocated interfaces to avoid performance degradation, once again demonstrating the benefit of using antenna polarization to mitigate multi-radio coexistence interference.

V. Effect of Using Different Antenna Polarizations on Network Topology

Our study of multi-radio coexistence interference in both multi-band and single band configurations in the previous two sections showed that using differently polarized antennas on a multi-radio node is helpful in mitigating such interference. However, changing polarization changes the radiation pattern of the antenna, thus it could potentially have a negative impact on mesh network topology and link qualities. To investigate this issue, we use the indoor multi-radio mesh network testbed deployed in the Informatics Forum building at the University of Edinburgh. The testbed consists of 9 Avila based mesh nodes running OpenWrt and equipped with 4 Compex 802.11a/b/g wireless cards each. Positions of testbed nodes on the floor plan is shown in Fig. 8. In order to isolate the impact of changing antenna polarization, we only consider one radio interface on each mesh node and configure it to use channel 36 common to all nodes. All nodes run the OLSR

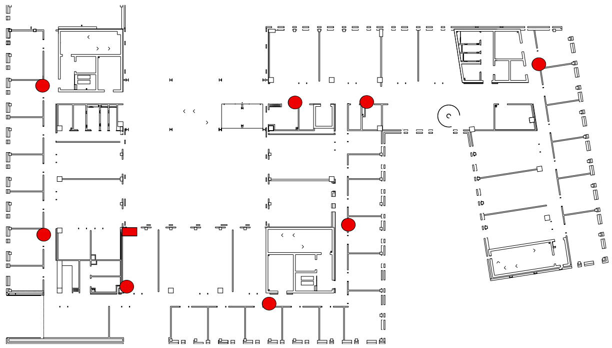

Fig. 8. Indoor multi-radio mesh network testbed deployed in the Informatics Forum building at University of Edinburgh. Node positions on the floor plan are shown in the figure. Rectangular shaped node is the one where antenna polarization is changed from vertical to horizontal to study the impact of changing polarization on network topology and link qualities.

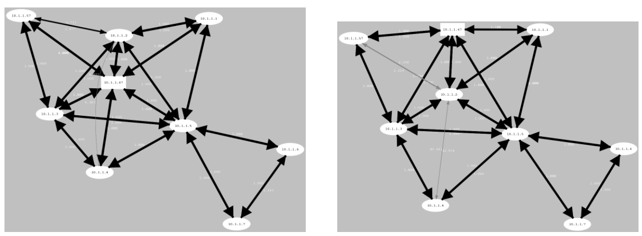

Fig. 9. Snapshot of mesh testbed topology when antenna polarization of rectangular shaped node is changed from vertical to horizontal. Polarization of radio interface on all other nodes remains fixed at vertical.

mesh routing protocol which relies on the ETX metric to assess link quality[12].

Fig. 9 shows the impact of changing antenna polarization on rectangular shaped node on network topology. We observe that connectivity remains unaffected at the node whose antenna polarization is changed from vertical to horizontal. To get a more detailed understanding of the effect of changing antenna polarization, Table II shows various statistics related to topology and link qualities as measured using ETX metric in OLSR. They confirm that changing antenna polarization does not significantly alter the topology or link qualities. For example, average node degree drops by around 5% and mean ETX increases by around 20%. We also found that using differently polarized antennas at end nodes of a link only marginally degrades the throughput (by about 17% on average) compared to using identically polarized antennas. For most links throughput degradation is less than 10%. These results are consistent with earlier modelling and measurement efforts studying the effect of polarization in indoor environments [12].

VI. Conclusions

In this paper, we have experimentally investigated the extent and nature of coexistence interference that occurs between collocated interfaces on multi-radio 802.11 platforms. We show that interfaces with antennas in close proximity on such

[12]ETX of a link represents the expected number of transmissions on that link and is inversely proportional to the quality of the link in each direction.

TABLE II
Topology and Link Quality Statistics

	Vertical Polarization	Horizontal Polarization
Average Node Degree	4.22	4.00
Node Degree Standard Deviation	1.856	1.803
Mean ETX	1.266	1.538
Median ETX	1.031	1.452
90th Percentile ETX	2.0	2.202

platforms suffer severe performance regardless of channel separation (including use of different frequency bands). We demonstrate in both single and multi-band configurations and with different channel separations that antenna polarization can alleviate this effect without adding to the expense or causing any serious negative side effects. Moreover, using a direct and microscopic look at MAC behavior we confirm observations from prior studies on adjacent channel interference characterization on the need for a minimum amount of channel separation. Our study also reiterates that we cannot do away with antenna and channel separation in the design and configuration of practical multi-radio 802.11 platforms. In future, we intend to study multi-radio coexistence interference in the context of 802.11n, which is increasingly getting deployed.

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