Adjacent Channel Interference in 802.11a: Modeling and Testbed Validation

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Abstract — **In this work we utilize the model for calculation of the interference power by partially overlapping channels introduced in [1] and combine it with the Signal to Interference plus Noise (*SINR*) criterion for signal capture to quantify the effect of adjacent channel interference (*ACI*) in 802.11a. We validate the results from our theoretical model by applying it on an in-lab testbed, in which we use signal splitters/combiners and fixed attenuators to emulate the wireless channel. Our experiments show that the neighboring channel interference affects the 802.11a with two mechanisms: the packet capture at the receiver and the Clear Channel Assessment (*CCA*) mechanism. We quantify the effect of ACI in these mechanisms in terms of throughput. Our results indicate that equipping a single node with multiple interfaces requires careful channel allocation and physical antenna separation, since throughput can be severely degraded. Our future work focuses on field experimenting with 802.11a multi-radio mesh nodes in order to introduce the antenna characteristics in our model.**

Index Terms — **adjacent channel interference, ACI, 802.11a, SINR, CCA, testbed, measurements, multi-radio, mesh.**

I. Introduction

In [2] the authors perform 802.11a testbed experiments to quantify the effect of Adjacent Channel Interference (ACI) on a dual-radio multihop network. In their work they use an in-lab testbed and also take field measurements using omnidirectional antennas.

Unlike [2], we have begun our work utilizing the SINR criterion for signal capture along with a theoretical model that quantifies the ACI of partially overlapping channels. Our ACI modeling is that presented in [1]. Combining these two models we can predict how robust a link can be in the presence of ACI, and how much the expected transmission rate can be for a link, using physical layer parameters and Bit-Error Rate requirements set by the 802.11a standard.

This theoretical analysis is important, since such a model can be readily extended to multi-radio mesh nodes, newer standards, such as 802.11n, and gives initial insight on the adjacent channel interference effects prior to any delicate, time consuming testbed experiments such as the ones we carried out ourselves in order to validate our theory. Also this can be the basis for wireless mesh network capacity dimensioning.

In this work we show analytically, that neighboring 802.11a channels have such a power overlap that produces significant interference, whose impact will be especially noticeable the in links with low path loss. We validated our results thoroughly experimenting on a in-lab 802.11a-based testbed, where the wireless channel is emulated by splitters/combiners and a range of fixed attenuators.

Our next steps are to take our testbed for field measurements with directional antennas and also conduct city-wide area experiments with another testbed of 802.11a multi-radio mesh nodes. We also intend to pursue coupling of MAC layer parameters into our model in order to enhance the accuracy of our rate estimations.

This paper is organized as follows: in section 2 we present the ACI calculation model and couple it to the SINR criterion. In section 3 we describe our testbed. In section 4 we present the topologies used for the validation experiments and the results obtained are presented. Finally, in section 5 we summarize our conclusions and briefly describe our ongoing and future work.

II. System model: Enhancing ACI calculations

A. Porting the SINR model in a multichannel system

According to the SINR model for the successful capture of the transmitted data at a receiver, the Signal to Interference-plus-Noise ratio must be at least equal to a threshold θ which depends on the transmission rate, the modulation scheme, and the required bit-error-rate.

$$SINR \geq \theta \qquad (1)$$

Assuming only the presence of path loss, with no shadowing or fast fading effects, the SINR can be expressed as

$$SINR_i = \frac{P_i \cdot G_{i,i}}{N_i + I_i} \qquad (2)$$

Here, $G_{i,i}$ denotes the path loss along the i-th link of a system for a signal sent from transmitter T_i to receiver R_i, N_i is the noise power at receiver R_i and I_i is the received power of the interference at R_i, with:

$$I_i = \sum_{j \neq i} P_j \cdot \xi_{j,i} \cdot G_{j,i} \quad (3)$$

The factor $\xi_{j,i}$ depends on the spectral properties (inter-channel spectral distance, channel width and spectral mask) of the channels used and the channel separation between interferer j and receiver i. Apparently, if links i and j use the same channel then we are reduced to a co-channel case and so $\xi_{j,i}=1$.

B. ACI calculation

In [1] the authors present a simple model to calculate this $\xi_{j,i}$ factor in the case of partially overlapping spectral masks. The key idea of this model is to take an integral over the whole overlapping region of the interfering channels spectral masks. This way they are making the assumption that the transmit spectral mask is acting as a bandpass reception filter, and thus that the receiver is ale to detect signals over an spectrum wider than the nominal channel.

In this work we make their model more flexible in terms of channel limits to be closer to the theoretical limits. In the case their width assumption is used, our model fully maps theirs. We calculate the ξ factor normalizing the spectral mask $S(f)$ within a bound that can be as narrow as the nominal channel width and then filter this normalized $S'(f)$ over the frequencies that will be within the band-bass filter of the receiver. Ideally this should be a flat band-pass 20MHz filter, but in the typical case the assumption of the authors of [1] above holds, and so in the general case we have:

$$S'(f) = \frac{S(f)}{\int_{-\frac{w}{2}}^{\frac{w}{2}} S(f)df} \quad (4)$$

Where w is the real receiver filter bandwidth, and so:

$$\xi_{i,j} = \int_{-\frac{w}{2}}^{\frac{w}{2}} S'(f) \cdot S'(f - f_{\text{int}})df \quad (5)$$

Using our model and the spectral mask for the 802.11a mandated by the standard in [3] we analytically calculated the theoretical power leakage (the product $P{\cdot}\xi$ of equation (3)) from two neighboring 802.11a channels (See Table I).

III. Testbed Description

We conducted our experiments on a testbed platform of 4 laptops running linux with the 2.6.20-16 kernel. The wireless interfaces we used were 4 Atheros-based Ubiquiti SRC a/b/g pcmcia cards running on the madwifi-ng driver (svn 2594). We chose to emulate the wireless medium, removing the non-deterministic characteristics of fast fading and shadowing, in order to remove uncertainty factors from our investigations. Therefore, we used signal splitters/combiners with a variety of fixed signal attenuators ranging from 3 to 50dB. We also equipped a Rohde&Schwarz FSH6 Spectrum Analyzer in order to verify the power levels at various points on the testbed, and the spectral masks produced by the wireless interfaces and thus validate our results in table I. For udp traffic generation we used the iperf program (v2.0.2). Finally, we used a laptop with the Airmagnet Laptop Analyzer (v.4), to have a sniffer's view of the actual 802.11a MAC layer.

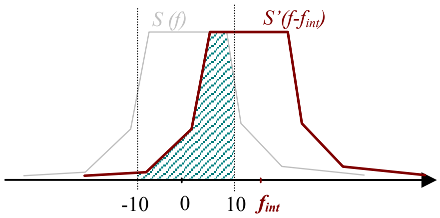

Fig. 1. Calculation of the ACI ξ factor, for the case of an ideal 20MHz receiver.

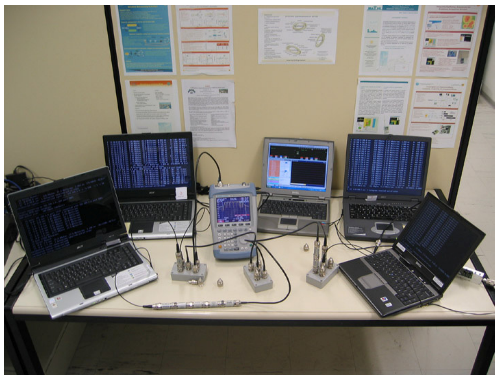

Fig. 2. The actual testbed setup.

IV. Experimental Results

In this section we present the experiments we conducted to verify the model previously presented for porting the SINR criterion under the effect of ACI and also to quantify how ACI affects the 802.11a CCA mechanism. For this we constructed the following two experimental setups that completely separate the two cases.

A. ACI effect on the 802.11a CCA mechanism

In order to examine the ACI effect on the 802.11a CCA mechanism we set up the testbed as shown in figure as shown in figure 3. Both in figure 3 and figure 4 the nodes marked as 'T_i' are nodes that are producing traffic (senders), while nodes marked as 'R_i' are the sinks (destinations) of that traffic. Each $T_i \rightarrow R_i$ link is tuned to a specific channel. In our experiments we always consider the link $T_1 \rightarrow R_1$ as the baseline link and have it tuned to channel 60 (5.3GHz). The best way to emulate a pure sender with 802.11a was to create UDP flows from the 'T_i' nodes to the respective 'R_i' nodes. Even so, the 'R_i'

nodes still transmit MAC layer acknowledgements, which are not subject to the CCA mechanism. In both this and the next setup we had to ensure that MAC layer ACK's would not be the cause for any misleading conclusions.

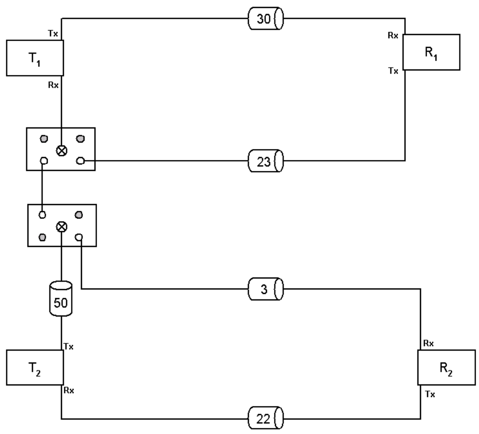

Fig. 3. The schematic for the testbed setup used for the quantification of the ACI effect on the CCA mechanism.

With the setup of figure 3 we emulate the case of a link ($T_1 \rightarrow R_1$) in which the transmitting node is sensing the channel while a second transmitter T_2 is continuously pushing packets in an adjacent channel link, unable to sense the first. One important detail is that although T_2 constantly senses its channel as clear, it complies to the MAC timings of 802.11a, and so there are inter-packet periods at which the link ($T_2 \rightarrow R_2$) is idle. The values of the attenuators in figure 3 are so planned as to allow T_2 when set to a transmission power of 0dBm and tuned to channel 56 to affect the CCA mechanism of T_1. Channel 56 is in 802.11a the adjacent channel to channel 60. This attenuation budget is not sufficient to interfere with T1, when T2 is tuned to channel 52 (two channels away from 60). Raising the power though to 18dBm results in the overall power received by T1 to exceed the CCA threshold (which is typically the receiver sensitivity for the 6Mbps rate) and even then the channel is perceived as busy.

With this setup and using also the spectrum analyzer we were able to verify that the model we presented earlier correctly predicts the ACI power. Our throughput results presented in ? indicate that the effect of ACI on the CCA mechanism is nearly binary in nature: if the received power in the sensing channel is high enough, regardless of the channel distance or the transmission power of the interfering transmitter, then the channel will be sensed as busy.

B. ACI effect on the 802.11a packet capture mechanism

In order to examine the ACI effect on the 802.11a packet capture mechanism we set up the testbed as shown in figure as shown in figure 4. From the receiver sensitivity of the cards used we calculate the minimum SNR that is required for the card to receive at rate R:

$$ReceiverSensitivity(R) = SNRmin(R) + (N_f + N_{thermal}) \quad (6)$$

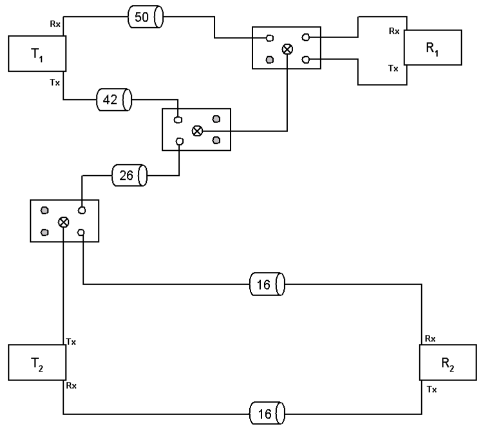

Fig. 4. The schematic for the testbed setup used to examine the effect of the ACI on packet capture mechanism.

Calculating $N_{thermal}$ using Boltzmann's equation and assuming a N_f of 2dB we produce the minimum SNR required for each rate, as in Table II. The SINR at the R_1 in each transmission rate of T_1 and each transmission power for T_2 should be above the corresponding SNRmin, in order to achieve the theoretical BER mandated by the protocol and therefore the throughput of the baseline experiment (three first columns in table III).

In the experiment we present in table IV we used the attenuation values of figure 3, a tx-power of 16dBm in T2 and a tx-power of 0dBm in T1. The link budget for $T_2 \rightarrow R_2$ when set to channel 56 results in an SINR value at R_1 near 4 (verified with the spectrum analyzer), which is below the minimum one in table II. Despite this, we see in table IV that all rates manage to push data through the $T_1 \rightarrow R_1$ link and one can notice that as the rate goes higher the drop in throughput increases. This can be attributed to the increase of bit-error-rate as the rate increases. The fact that the rate of 24Mbps is achieves the best throughput can be assumed to be due to synchronization issues of the two links, for the high utilization of the T2→R2 link. As one can see in figure 5 the interfering channel utilization is of critical importance to the resulting throughput as in this testbed our interference is patterned according to the 802.11a MAC DCF.

VII. CONCLUSIONS

We presented a model that takes into account the physical characteristics of the transmission in an environment with ACI present. We enhanced the model proposed in [1] for the calculation of partially overlapping channels power leakage coupling it with the SINR criterion for data capture. Our model was verified by predicting the neighboring channel power leakage leverls and the SINR on an in-lab testbed. Our predictions were validated by the achieved throughput on a link suffering from ACI.

This analytical tool is indeed important, since such a model can be be used to give initial insight on the adjacent channel interference effects, prior to any delicate, time consuming experiments or installations and so it can be the theoretical core for a mesh network dimensioning and design tool.

Our next steps are to take our testbed for field measurements with directional antennas and also conduct city-wide area experiments with another testbed of 802.11a multi-radio mesh nodes. We also intend to pursue coupling the MAC layer parameters into our model in order to finally perform throughput estimations

TABLE I
THEORETICALLY CALCULATED ACI POWERS IN dB

Interferer Power	Receiver Bandwidth	Adjacent Channel Power Leakage	Next Adjacent Channel Power Leakage
0	20Mhz	-22.04	-39.67
	∞	-19.05	-36.67

TABLE II
CALCULATED SNRmin IN dB

Tx Rate	6	9	12	18	24	36	48	54
SNRmin	4.8	5.8	7.8	8.8	12.8	15.8	21.8	24.8

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TABLE III
ACI EFFECT IN THROUGHPUT (IN Mb/S) FOR 1000 BYTES UDP PAYLOAD IN THE $T_1 \rightarrow R_1$ LINK FOR HIGH UTILIZATION IN THE $T_2 \rightarrow R_2$ LINK THE DUE TO THE CCA MECHANISM

Tx Rate	Without ACI	$T_2 \rightarrow R_2$ ch60, 0dBm	$T_2 \rightarrow R$ Ch56, 0dBm	$T_2 \rightarrow R$ Ch52, 0dBm	$T_2 \rightarrow R$ Ch52, 18dBm
6	4.94	2.21	2.74	4.84	2.24
9	6.94	2.99	3	6.83	2.12
12	8.86	3.03	2.76	8.64	2.05
18	11.9	3.25	2.73	11.7	2.36
24	14.2	3.19	2.7	14.2	2.58
36	18.1	3.45	2.79	18.1	2.56
48	21.3	2.9	2.85	21	2.44
54	22.1	3.36	2.98	21.9	2.68

TABLE IV
ACI EFFECT IN THROUGHPUT (IN Mb/S) FOR HIGH UTILIZATION IN THE ADJACENT CHANNEL WHEN ONLY THE PACKET CAPTURE MECHANISM IS AFFECTED

Tx Rate	Without ACI			With ACI		
	udp payload (*bytes*)					
	1470	1000	500	1470	1000	500
6	5.24	4.94	4.12	2.64	2.6	2.22
9	7.36	6.94	5.71	3.64	3.2	2.51
12	9.41	8.86	6.96	3.95	3.9	2.93
18	13.1	11.9	9.04	4.34	3.73	3.1
24	16.2	14.2	10.2	5.79	4.69	3.66
36	21.9	18.1	12.2	4.4	4.69	2.61
48	25.4	21.3	13.8	3.69	3.14	2.18
54	27.2	22.1	14.1	3.78	3.16	2.15

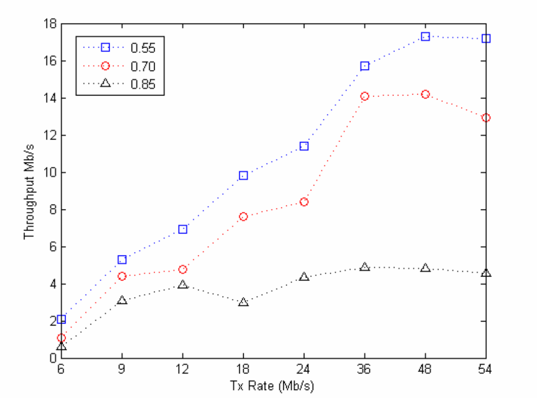

Fig. 5. Throughput achieved at the available transmission rates for various utilization values of the interfering channel. Utilization in the interfering channel is increased by increasing the packet size of the active udp flow.