International Journal of Computing and Digital Systems
ISSN (2210-142X)
Int. J. Com. Dig. Sys. 4, No.4 (Oct-2015)

http://dx.doi.org/10.12785/ijcds/040402

Interference Estimation and Mitigation in Wireless Networks

S. Abdulkareem Mustafa

Electrical Engineering Department, College of Engineering, Salahaddin University-Erbil, Erbil, Iraq

Received 31 January 2015, Revised 1May 2015, Accepted 30 June 2015, Published 1 October 2015

Abstract: To improve the resource utilization, the world of wireless communication network has seen suggestion and developing of new frameworks targeting an improved model of resource usage in wireless space by enabling cooperation and collaboration among possibly interfering wireless technologies in a dynamic and adaptive fashion.

An important element of the cooperative framework is the discovery and learning process. The optimization mechanisms the framework will become to support strongly depend on the scope of information and observability of the system. An important part of this information is the effect of wireless networks on each other which is called the “inter-network interference” information. However, there are doubts in the research community on the efficacy or/and correctness of existing interference model for wireless networks. In this paper, the coexistence performance of wireless networks is analyzed in terms of throughput and packet reception ratio. It has been found that while SINR-based interference model necessities including other factors as the interferer's traffic rate, radio design etc. to be more realistic. The process of estimating this relationship is an expensive process and the question has been asked in this project is weather the framework should attempt to gather this information?

Keywords: Inter-network conflict, Interference Estimation, Interference mitigation, PHY/MAC layer interaction, Channel assignment.

1. INTRODUCTION

The world of wireless communications is nowadays facing a serious problem of growing the interference level, that gradually leading to a severe spectrum shortage due to an explosive growth in density, traffic load and technology. Such problem is not only due to real limitations on the available bandwidth, but mainly to inefficient policies in spectrum management. Indeed, today’s wireless communication systems are characterized by a fixed spectrum assignment policy, which often leads to waste large spectrum portions due to sporadic utilization by the licensed users. The current models of resource allocation in wireless world and traditional approaches to address this challenge (such as spectrum regulation, improvements in spectral efficiency, and reducing cell sizes), are running out of steam and will not support the extreme access demands for wireless medium.

In the last years, the research community has suggested new frameworks targeting an improved model of resource usage in wireless space by enabling cooperation and collaboration among wireless networks. An XOR-assisted cooperative diversity scheme in OFDMA wireless networks is represented in [1]. A unifying optimization framework is formulated that jointly considers relay assignment, channel assignment and power allocation to reap different forms of gains. Xu et al [2] proposed a generic theoretical framework to approach the maximum network capacity. Based on a developed multidimensional conflict graph tool, an optimal cooperative networking is studied in optimal network dimensioning and throughput-optimal control aspects. A cooperative framework in [3] is presented a modular and scalable methodology and architecture that enables proactive co-existence and collaboration between diverse nodes, making joint optimization of the scarce spectrum resources possible.

The range of optimization schemes which will become enabled by cooperative and collaborative framework strongly depends on the scope of information, which will be gathered and shared from the environment. An important piece of data under consideration is the estimation of inter-network interference effects. Several research efforts have focused on defining inter-network conflict. Distance-based and measurement-based studies have been done in literature to estimate the impact of co-location and co-channel networks though the challenge in modeling physical and MAC layers interaction, and impact of multiple ongoing transmissions. These models vary from oversimplified to fairly accurate models. Simple abstract models of radio propagation (e.g., the interference range is twice the communication range) are

E-mail:samah.mustafa@su.edu.krd

primitive, while measurement-based interference modeling for shared medium wireless networks is more accurate evidently has received significant attention [4]. Most of the existing works presumes either symmetric interference impact [5], or binary decision of whether or not interference exists [6-8]. Further, they assume that interference happens between link pairs only [9]. Although interference models under such assumptions do not accurately offer actual state, they have been widely used in developing algorithms and protocols in wireless networks. Actual measurement of appropriate metrics and tracking the potential change in channel conditions can avoid unrealistic assumptions. In general, estimating the pair-wise effects of wireless networks specially in a dense environment is an expensive and resource consuming process, and there needs to be a good justification for it in order to add the extra mechanisms needed for the estimation. The general approach in most studies has been to balance specific research goal with a reasonable complexity and low overhead, or the modeling realistic.

This work is started with the goal of designing efficient inter-network effect estimation techniques. The coexistence performance is evaluated based on interface's PHY and MAC layers behavior. Our study models the more common case of unicast transmissions with saturated and controlled traffic demands at interfering node. Extensive simulations have been done on an indoor 802.11g wireless network. The effort is concentrated on studying interference and carrier sensing in wireless network over a single channel and trying to find out whether the common SINR-based model is 100% accurate? The study has found that the carrier sensing of the coexisting transmitters has a crucial role in defining SINR threshold and interference model-based on a single SINR threshold may offer inaccurate results. The results also demonstrate the importance of considering more factors mainly the transmission rate of an interferer to portray more realistic channel state. This work also formulates the general optimization problem and relates it to the inter-network conflict graph modeling of interference effects: inter-network interference is estimated as the utility loss of a network service operating along another network. The results show that quality of service can be guaranteed with access to pair wise interference relationships and a cooperation framework.

Section 2 briefly discusses the previous related works and shows their connection to the general problem formulation given in this paper. Section 3 presents simulation results of the coexistence performance based on interface's PHY and MAC interaction. Section 4 formulates the optimization problem and models the inter-network conflict graph. In section 5 a special simplified optimization scenario is presented which illustrates the importance of cooperation and pair-wise interference information. The section portrays an application aware channel assignments as a case study over friendly homogenous networks. In Section 6, the conclusions are stated.

2. RELATED WORK

The quality of a wireless link, the interference it faces and its PHY and MAC layers behavior determine its capacity. Wireless network optimization has specially been receiving attention within the research community as deployments of wireless networks are getting denser and their traffic load are raising up. The resource allocation of wireless networks plays a crucial role in defining the inter network interference [10]. Several works in literature have looked at this issue and several interference models have been considered in wireless networks. Measurement-based interference modeling for shared medium wireless networks has received significant attention. Maheshwari et al. [11] showed experimentally that the physical SINR model is more accurate than other interference models. In [12] the authors presented measurement-based study on the impact of link quality, and a measurement-based study to estimate link interference. This work to address this issue is most related and complementary to that done by Lee et al. [13], in which the authors characterize distinct cases based on their carrier sensing and interference at the intended receiver relation.

Different Interference mitigation techniques has been proposed and presented by the WLAN research community. In radio resource management for wireless and cellular network, channel allocation schemes are required to allocate bandwidth and communication channels to the base stations, access points and terminal equipment. The objective is to achieve maximum system spectral efficiency by means of frequency reuse, but still assure a certain grade of service by avoiding co-channel interference and adjacent channel interference among nearby cells or networks that share the bandwidth. The earlier channel assignment schemes proposed for WLAN such as Least Congested Channel Assignment [14] relied only on individual access point observations and was non-cooperative. Mishra et al. [15] was the first to propose the usage of client observations as part of the channel assignment scheme showing an improved resulting performance. The authors define and use the following metric between two access points:

$$\omega_{i,j} = \frac{Num_{i,j}+Num_{j,i}}{Num_i+Num_j} \qquad (1)$$

Where Num_i is the number of periodic site surveys performed by the clients of access point i, and $Num_{i,j}$ is the fraction of those surveys which a packet from access point j is received by clients from access point i. The metric gives a rough estimate of the flow conflict. The authors have portrayed symmetric inter-network conflicts while those relationships are asymmetric. The metric is used to define an objective functions as given by:

$$L_{sum(i)} = \sum_{\forall e=(i,j)\in E} I_{i,j} \, * \, \omega_{i,j} \qquad (2)$$

The I function is the indicator of the channel overlap between the access points i and j. This objective is used to design channel assignment algorithms.

Rozner et al [16] augment the above metric with the sending and receiving rate of the wireless networks and demonstrate that the channel assignment will improve especially when the traffic demands are concentrated around few heavily-loaded access points located close to each other. A more recent work by Yue et al [17] claims an efficient and simple distributed channel assignment algorithm for uncoordinated WLANs, where the access points can self-configure their operating channels based on traffic information retuned by the clients.

This class of literature papers is mostly targeted at WLAN industry and is not targeting the more general heterogeneous case. Nevertheless the connection is important and educational. The goal in this class of algorithms is to come up with good and efficient estimation schemes of the inter-network effects and develop conflict resolving schemes based on that.

3. SIMULATION SETUP

A. *Propagation Model*

A more widely used model is the shadowing model. It introduces fluctuations and predicts the signal level averaged over a few tens of wave lengths, typically 40 wavelengths. This is a medium-scale effect. Multipath fading has small-scale effect that leads to rapid fluctuations of the phase and amplitude of the signal if the vehicle moves over a distance in the order of a wave length or more. The large and medium scale effects of the medium are adopted in the propagation model. Specifically, the received power at any distance $d > d_o$ is computed relative to $P_r(d_o)$ as

$$P_r\,(d)|_{db} = P_r(d_o)|_{db} - 10 * \alpha\, log\left(\frac{d}{d_o}\right) + X_{db} \quad (3)$$

X_{db} is a Gaussian random variable with zero mean and standard deviation σ_{db}. It reflects the variation of the received power at certain distance such that a node near the edge of transmission range of another can only probabilistically communicate. α is the path loss exponent at distance d from the transmitter that characterizes how quickly a signal strength degrades in a particular network environment. It is usually 2 for outdoor environment and 4 for indoor environment. d_o is used as a close-in distance reference (d_o usually 1 meter) and the average signal power at reference distance can be predicted by path loss model as [18]

$$P_r\,(d_o) = \frac{P_t * G_t * G_r * \lambda^2}{(4\pi d_o)^2 * L} \quad (4)$$

P_t is the transmitted power, G_t and G_r are the gain of transmit and receive antennas respectively, and L is the system loss and usually equals 1. λ denotes the wavelength.

B. *Coexistence Performance Based on PHY and MAC Layer Interaction*

In this section, the coexistence performance is evaluated based on interface's PHY and MAC layers behavior, and factors such as SINR threshold and demanded traffic rate. Simulation-based studies on the performance of wireless communication links are presented in the presence of another ongoing transmission. The simulations have been done using NS-2.34 which incorporates the capture behavior based on the physical operation of IEEE 802.11 radio modem. It emulates the design of the MIM (Message In Message) mode: a receiver can correctly receive the stronger frame even when it has already engaged in receiving an earlier frame. Further, the model allows each station to keep track of all frames that it can detect and the aggregated background signals to make the capture modeling more realistic [19]. The nodes uses 802.11g technology with default parameters defined according to the corresponding standards [20]. The simulation is restricted to simultaneous one-hop unicast UDP traffic, where there is a unique receiver for each packet. Each simulation run lasted for 50 seconds and the results are averaged over multiple runs. RTS/CTS virtual carrier sensing is disabled during the simulation.

The performance metrics are the PHY layer throughput at the sender and Packet Reception Ratio PRR as the absolute number of detectable packets at the receiver relative to total number of transmitted packets from the sender. The performance is evaluated directly versus SINR using three nodes set up: sender, receiver and interferer. The radio propagation reflects the shadowing model in an indoor environment. The simulation is repeated in a variety of channel conditions as portrayed in Fig. 1 to evaluate the coexistence performance and the physical interference model. Each zone represents the carrier sense range of a sender. Solid and discrete arrows indicate the direction of data transmission and interference signal from a surrounding sender, respectively.

Under the physical interference model, a transmission is successful if and only if SINR at the intended receiver exceeds a threshold. However, a model based on blind use on single SINR threshold may not precisely predict the conflict. Other factors should be highlighted:

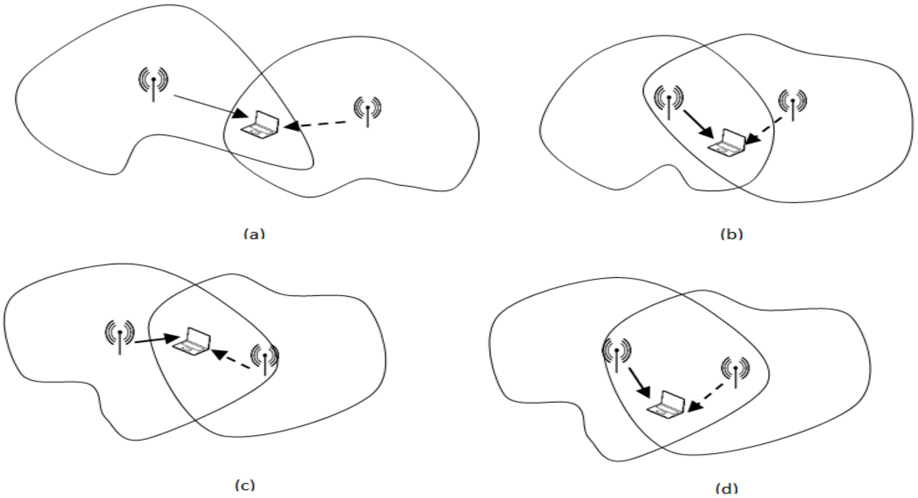


Figure 1. Two competing senders are presented with variety in channel state. The carrier sense range is represented as an ideal circle. Solid and discrete arrows indicate the direction of data transmission and interference signal from a surrounding sender, respectively.

a. Different SINR threshold for different settings

Fig. 2 depicts PRR vs. SINR relation obtained at 6Mbps PHY bit rate using unicast packets with payload size of 1000 bytes. Equal traffic rate are flowing on the stream pairs. The variation in SINR values is obtained by changing the distances between nodes pairs, and the radio interference is reflected by the variation in PRR value. The relative strength of the receiver's signal, and the accumulative power level of the interferer's signal and the receiver's background noise, determines whether the transmitter's packet is correctly received.

10 quantization levels are used to present PRR results and the curve is described as a step function changing from 0 to 1 at specific values of SINR under the assumption of packet reception threshold equal to preamble capture threshold γ_P of 4db, and frame body capture threshold γ_D of 10db. The values of γ_P and γ_D are defined in IEEE standards [20].

Fig. 2a depicts PRR in presence of a hidden terminal that causes collision at the receiver. Transmitting packets of both senders are independent and the backoff timer is randomly chosen within the contention window size of a sender (Fig. 1a). The PRR trails down to 0 below 4db and gets up with increasing SINR. The inter-arrival times define what signal to interference ratio ensures capturing and correctly detecting the reference signal. SINR=4db is demanded for the reception of first or later arriving packet within the preamble interval of interferer's signal. On the other hand, SINR=10db is necessary for the reception of overdue packet while the radio is already engaged to interferer's packets. The results show that for SINR ≥10db, PRR is almost 100%. A graded SINR model is observed in a practical scenario in [21] with a smooth transition between close to 0 and close to 1 reception rate that typically spans 5-10dbs, but rather the results in this simulation present sharply thresholded under the assumption of correctly detection of received packet if SINR exceeds certain thresholds with probability equal to 1.

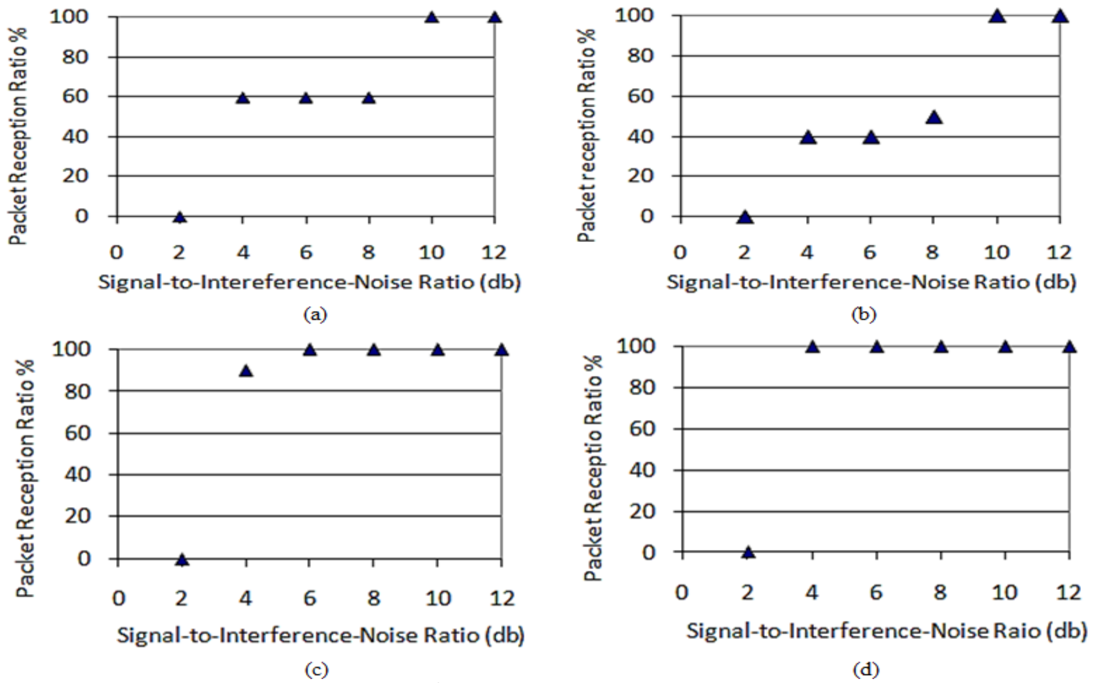
Lower PRR is recorded for SINR less than 10db at the receiver if the sender being oblivious of ongoing transmission, coexists within carrier sense range of a surrounding interferer (Fig. 1b and Fig. 2b). Variety in channel state or transmit power or carrier sense threshold may lead to asymmetric carrier sense ranges. The interferer defers its transmission if the reference sender is currently transmitting, which does not preclude any transmission request from upper layers. Parallel transmissions may lead to a collision and probably discarding the packet depending on the attained SINR and inter-arrival time. If the sender commences a transmission on an actual idle channel then SINR of 4db is significant for the reception. Otherwise, SINR=10db is demanded to retrieve the sender's overdue packet wherein the receiver is already synchronized with an earlier interferer's packet.

The previous results show a transition region between 4db to 10db where packets are received with a probability less than 1, in contrary to the observation in the next scenarios wherein sharp transition in PRR is recoded at 4db. Fig. 1c shows a different scenario where an interferer coexists within the carrier sense range of the sender but not vice versa. Whenever the sender observes idle channel, it transmits if there is any request that may collide with an overdue packet from the interferer. Such that, the target PRR is attained at SINR ≥ 4db that satisfies the appropriate condition either to detect non-overlapped packet or to capture the first arrived packets. The sender will never transmit if there is an ongoing interference signal since the sender can sense the last.

Coexistence with a station that does not interfere with the delivered packets such as presented in Fig. 1d, obtains similar PRR vs. SINR relation in Fig. 2d where SINR ≥ 4db is required to correctly detect non-overlapped packets. The sender and the interferer are sensing each other and will avoid transmitting concurrently. To that end, though high SINR guarantees link's quality, different thresholds should be considered in different scenarios. As illustrated, carrier sensing scenario has a crucial role in defining SINR threshold and interference model-based on a single SINR threshold may offer inaccurate results.

b. Radio design

Based on the scenario set up in Fig.1, the simulation is re-run with disabled MIM mode in PHY layer (Fig. 3) to depict the impact of the radio design on the physical interference model. Based on the scenario in Fig.1a and Fig.1b, the results depict that SINR ≥ 10db has no role in leveraging PRR to the maximum. The receiver cannot engage to a new stronger reference packet when it is already locked with an earlier interfering packet. Without MIM capable radio interface, it is unable to retrieve the stronger overdue packet. No explicit difference in the performance compared to that recorded in Fig.2 has been observed in scenarios as in Fig.1c and Fig.1d. SINR ≥ 4db ensures the capture phenomenon of reference packets that either have been delivered before the interferer's packets or transmitted on actual silent channel. Carrier sensing of the coexisting wireless nodes schedule the transmission of each, as it is already discussed. The results confirm that physical interference model is not precise enough.



(a) (b) (c) (d)

Figure 2. PRR vs. SINR relation for the scenarios in Fig.1. PRR values are quantized into 10 levels.

c. Interferer-receiver pair link quality

In contrast to that considered earlier, wherein the receiver is within the transmission range of the interferer, the simulation set up in Fig. 1 is repeated with a receiver that does not hear interferer's preamble. The distance between the receiver-interferer pair is set such that the probability of the receiver to lock with an earlier foreign packet is 0. The transition region does not exist and PRR for SINR greater than 4 db is almost 100%, quite similar to the results in Fig. 2d. The same observation has been seen either with MIM mode or without.

d. Interferer's traffic rate

Simulation trials have been performed with different transport layer traffic rate at the sender and interferer; 4Mbps and 2Mbps, respectively. In scenarios as in Fig.1c and Fig.1d, quite similar transition in PRR values versus SINR at the receiver, to that in Fig. 2 has been noticed since SINR=4db is satisfying to retrieve the delivered packets.

Higher PRR is recoded in scenarios as in Fig.1a and Fig.1b during a transition range: 4-10db (Fig. 4), wherein the sender can successfully transmit during those gaps in between the interferer transmission. Lower interfering traffic rate alleviates the probability of collision and achieves higher frame delivery rate although same SINR is observed. Thus the SINR-based physical interference model should be extended to include interferer's traffic transmission rate.

The results highlights the dependency of the attained utility on the experienced SINR at the end-users of the corresponding link, and the traffic rate emitted from a neighbor. For further investigation, simulation trials have been performed with different transport layer traffic rate at the interferer between 6M and 1Mbps, to investigate its effect on the reference utility. For the sake of space limitation, the results just of one scenario are presented of two senders and two receivers comprising two heterogeneous links in terms of communication quality: the S_j-R_j stream is getting complete channel utilization while S_i-R_i stream starves. When S_i transfers a data, R_i cannot hear it due to simultaneous S_j's transmission. The only time S_i can successfully transmit is when its data arrives during those gaps in between S_j's data transmission.

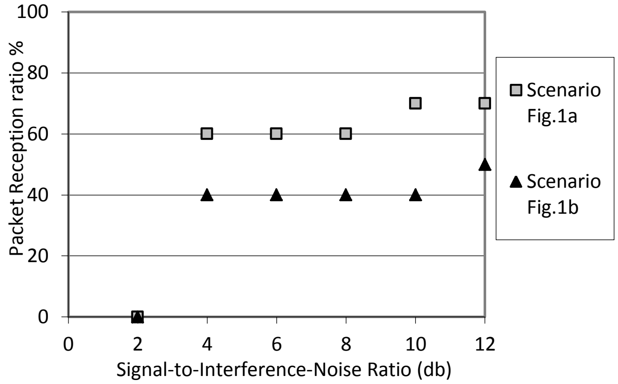


Figure 3. PRR vs SINR relation for the topologies in Fig. 1a & 1b. PRR results are quantized into 10 levels and determined with disabled MIM mode.

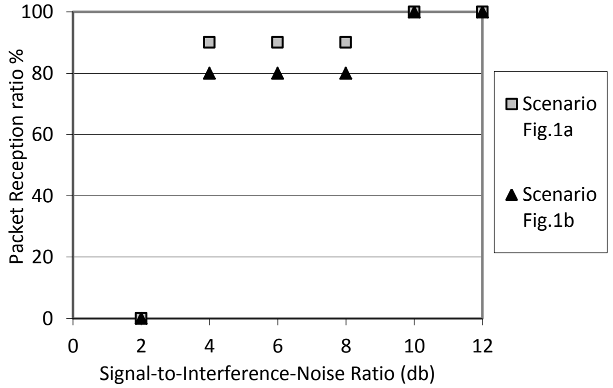


Figure 4. PRR vs SINR relation with enabled MIM mode. The traffic rate of the reference and surrounding interferer is 4Mbps and 2Mbps, respectively.

Fig. 5 shows the simulation results; throughput and PRR have been recorded by S_i's PHY layer and R_i's MAC layer, respectively. Higher transmission rate from the interferer increases the probability of S_i's packets to be corrupted at the intended receiver although same SINR is observed. The S_i's backoff is doubled after each collision such that the S_i-R_i stream starves. As the load traffic from S_j decreases, S_i accesses the channel more often i.e. more packets from sender S_i are able to go through the channel and be correctly received by the receiver. R_i captures the reference frames in interference free channel and the link achieves higher frame delivery rate even though SINR at the intended receiver is fixed. Thus the SINR-based physical interference model should be extended to include interferer's traffic transmission rate. The S_i-R_i stream can transmit efficiently; decode the delivered packets correctly and subsequently leading to a higher PRR coexists with lower traffic rate of co-channel transmission.

As the load traffic from S_j decreases, S_i accesses the channel more often i.e. more packets from sender S_i are able to go through the channel and be correctly received by the receiver. The S_i-R_i stream can transmit efficiently; decode the delivered packets correctly and subsequently leading to a higher PRR coexists with lower traffic rate of co-channel transmission even though SINR at the intended receiver is fixed. Thus the SINR-based physical interference model should be extended to include other factors as interferer's traffic transmission rate.

The simulated results in Fig.2-5 demonstrate more accurate interference estimation by extending the common physical model, however, the process of gathering this information can be expensive. The author realizes the necessity of a better understanding of the underlying optimization problem and potential gains in the case this information was accessible.

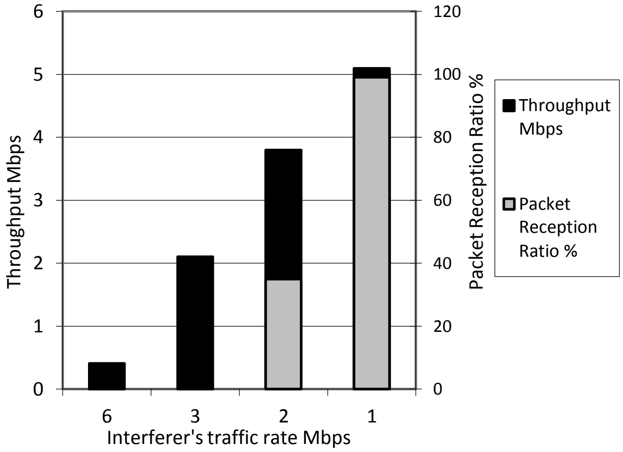


Figure 5. S_i-R_i stream's throughput on the primary y-axis and PRR on the secondary y-axis, with different traffic rates from S_j at fixed location and power level.

Utility Optimization Problem

This section demonstrates utility optimization problem by a general cooperative and collaborative scheme, describing when it reduces to interference mitigation problem. Consider an environment where heterogeneous networks share part of the spectrum and potentially interfere with each other. The total utility of the resources Υ_{tot} can be defined as a function f of network resources' utilization by different demanded application services:

$$\Upsilon_{tot}(\underline{\text{þ}}) = f(\Upsilon_{app1}(\underline{\text{þ}}), \Upsilon_{app2}(\underline{\text{þ}}), \Upsilon_{app3}(\underline{\text{þ}}), \ldots) \qquad (5)$$

Υ_{appi} is the utility of application *i*. The resource utilization is either efficient or not based on many parameters as the channel quality, transmit power, interference traffic rates etc. (as investigated in the previous section). Such parameters can be represented as a vector $\underline{\text{þ}}$, and each application service has a different demand to reach the target service quality.

The function *f* is based on a system design and for simplicity the function can be defined as a summation function. Hereby, Equation 5 can be rewritten as:

$$\Upsilon_{tot}(\underline{\text{þ}}) = \sum \Upsilon_i(\underline{\text{þ}}) \qquad (6)$$

Over a wireless network there are numerous parameters which are being continuously optimized by different dynamic resource management such as: transmit power, traffic window size, back-off counter, radio interface frequency assignment, etc. For example**,** it might adapts the channel assignments only or jointly with transmit power, and leave other parameters to be set by the default methods. Hereby, the inferences between coexisting networks are necessary to be estimated.

Now assume each one of wireless networks is able to work in isolation; i.e. one could shut down all the other networks and only activate network *i*. The achieved utility by network *i* is denoted as Υ_i when it works on interference free channel. Inter-Network Interference Ratio ϑ_i^j is defined as a new metric to present the normalized utility loss of network *i* when faces interference from ongoing transmission of network *j*, and the network parameters are set to $\underline{\text{þ}}$.

$$\vartheta_i^j(\underline{\text{þ}}) = \frac{\Upsilon_i(\underline{\text{þ}}) - \Upsilon_i^j(\underline{\text{þ}})}{\Upsilon_i(\underline{\text{þ}})} \qquad (7)$$

By a possible tweaking of the transmission parameters to adapt the user demand and transmitting environment $\vartheta_i^j(\underline{\text{þ}})$ can be maximized to 1 though the existence of neighbor transmission. ϑ_i^j can be applied in the conflict graph model as the weights on the edges to depict the negativity of the relationship when the network parameters are set to $\underline{\text{þ}}$ and networks *i* and *j* are operating concurrently in isolation (Fig.6).

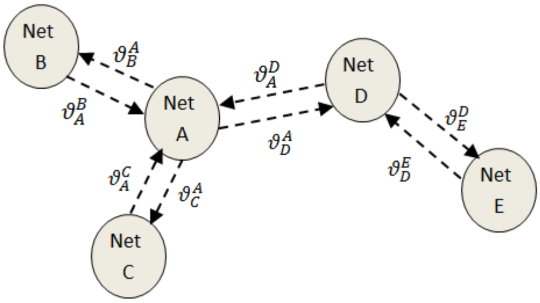


Figure 6. Inter-Network Conflict Graph.

Note that the process of estimating ϑ_i^j can be expensive and having access to ϑ_i^j values does not imply easily estimation of the aggregate utility losses when a network transmits in the existence of more than one network. However, an objective functions over the estimated interference ratio values can be defined. If the defined objective function correlate strongly with the aggregate utility losses, algorithms which minimize the objective function will also minimize the aggregate utility losses. Thus, interference mitigation would maximize resource utilization function in Eq.(6):

$$\text{minimize}_{\underline{\text{þ}} \in P} \sum_i \vartheta_i(\underline{\text{þ}}) \qquad (8)$$

Nevertheless, it is typical to define an objective as a function of the estimated pairwise interference effects and design an algorithm based on the proposed objective, showing that the resulting solution reduces the actual objective function (in other words showing that the chosen objective function strongly correlates with the real objective function). Summation over the edge weights or max of the edge weights seems to be the first candidate as a helper objective.

Within a single network, the users operate in a band coordinate with each other to share a spectrum using a media access protocol and packet scheduling, however how should heterogeneous wireless networks operate and share the resources where there is no common physical or link layer. Therefore setting up a collaboration framework would mitigate the interference and manage the resource distribution among the networks. Though, designing a collaboration framework is not in the scope of this work. It is just demonstrating its gain through a common channel to share some information and cooperative networks.

4. CASE STUDY: APPLICATION AWARE CHANNEL ASSIGNMENT

The earlier defined metric ϑ_i^j is a very general metric which portrays as an aggregate of many different effects. To better understand the underlying effects the contributing factors to ϑ_i^j are qualitatively divided into two categories. The first category is concerned with PHY/MAC interactions and friendliness of the technologies and links, as it has been discussed earlier. For an example, when a single technology of type 802.11g is considered and virtual sensing RTS/CTS is enabled, links are able to contend for the medium in a relatively fair and efficient manner. Nevertheless when RTS/CTS is disabled, the wireless network would face hidden terminal problem (Fig.1a) and exposed in which some links will not be able to receive their fair share of the channel. In the heterogeneous environment it is much more likely that some links end up in a situation very similar to the presented in Fig.1b and Fig.1c due to asymmetries. When links either cannot contend for the channel or starve to make successful transmission due to interference from the other surrounding transmissions, the performance metric ϑ will significantly degrade and might get zero.

The second category is derived from application requirements. Assuming that all links can contend for the channel in an equitable fashion, one can still formulate an optimization problem by considering the application requirements in terms of delay, loss, throughput, etc. For example if one of the networks is dominated by loss and delay sensitive traffic such as Voice over Internet Protocol (VoIP), and the rest are dominated by File Transfer Protocol (FTP) traffic, it can be seen that the negative impact on the VoIP network is much more significant and the interference effects are strongly asymmetric. In contrast to VoIP, FTP demands reliable delivery, and higher packet size.

Over a wireless network there are numerous resources as transmit power, channel assignment, time to transmit etc. can be optimized based on interference estimation to leverage the networks utilization. This work adapts the channel assignment to mitigate the interference.

A. Application Aware Channel Assignment over Friendly Homogeneous Links

To achieve a better understanding of the earlier discussions, a simplified and special case of channel assignment optimization was studied. It shows that having access to estimates of inter-network interference effects is a critical key to support the service quality and improve access experience by the applications.

The networks are assumed as single link. Radios are of the same type and they communicate on one of the three orthogonal channels using single transmit power level. Furthermore, the traffic on the links is considered to be either FTP traffic links or VoIP traffic. The virtual carrier sensing RTS/CTS is enabled in order to avoid the hidden-terminal problem as possible though the overhead it loads. The links in such case study are able to contend for the channel in a relatively fair manner and the inefficiencies of a random channel assignment is not mainly due to destructive link interactions but due to not exploiting the extra degrees of freedom provided by underutilized channels.

Network topologies of 21 FTP links and 7 VoIP links are randomly generated, as shown in Fig.7. The dashed line among two nodes indicates that the two nodes are within the radio range of each other. Based on a simplified model of two links either can operate simultaneously with no negative impact on each other or they are conflicting and cannot fully operate simultaneously. The simulation assumes there is either symmetric or asymmetric conflict between two links even when any of their radios can hear other's transmissions as long as the sensing link will not get the target utility i.e. $\vartheta_i^j < 1$. Further, the simulation study has found the traffic rate of the heard transmission plays a strong role to define the performance degradation.

VoIP traffic in general is more sensitive to packet loss and increased inter-packet delays. The large packet size of FTP traffic typically is able to block the VoIP from accessing the channel in a timely fashion. This problem has been highlighted through the development of 802.11e standard, which tries to alleviate the problem within the same access point by giving higher priority to VoIP traffic. Nevertheless it fails to address the cross traffic from the interfering networks which can be significant especially in a dense environment. For this reason the inter-link effect is modeled by the following equation:

$$\vartheta_i^j = \begin{cases} 1 & if\ i's\ traffic == VoIP\ and\ j's\ traffic == FTP \\ 0 & otherwise \end{cases}$$

Note that this is a rough approximation of the effects and for example does not capture the effect of FTP links on each other or VoIP links on each other. Nevertheless it signifies the most dominant negative effects in the environment under consideration.

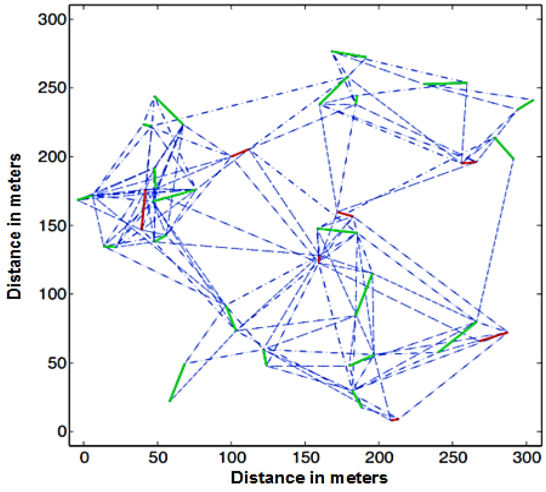


Figure 7. Randomly generated topologies of 21 FTP links (colored green) and 7 VoIP links (colored red) over an area of 300x300m^2.

Based on this simplified model, four different optimization schemes are compared. All the schemes start from random initial channel assignments.

<u>*Scheme 1:*</u> (non-cooperative) In this scheme, VoIP links which are experiencing conflicts, search for a channel with no conflict from FTP links. If this is not possible they will stop trying.

<u>*Scheme 2:*</u> (cooperative) In this scheme, FTP links detect if they are causing destructive interference with any of the VoIP links and try to avoid doing so by moving to a different channel if possible.

<u>*Scheme 3:*</u> (cooperative) In this scheme, first the VoIP links and then the FTP links try to resolve the conflicts. This is equivalent of first running scheme 1 and then scheme 2.

Scheme 4: (cooperative) In this scheme, all the VoIP links move to channel 1, and then scheme 2 is ran.

These schemes are ran over the same number of links and for varying region densities (area width changing from 100m to 300m and 20 random runs per density). Fig. 8 shows the average final number of conflicts for random channel assignment and further schemes 1-3 applied to links with initial random channels with the corresponding variances. However, designing a specific cooperative scheme is not in the scope of this work, it just demonstrates its gain through the assumption of a high quality common channel between the wireless links to collect the estimated interference ratio.

Fig. 9 shows the average gain obtained by running these three cooperative schemes compared to random channel assignment. It can be seen that at higher densities (towards 100m width) none of the first three schemes have satisfactory performance.

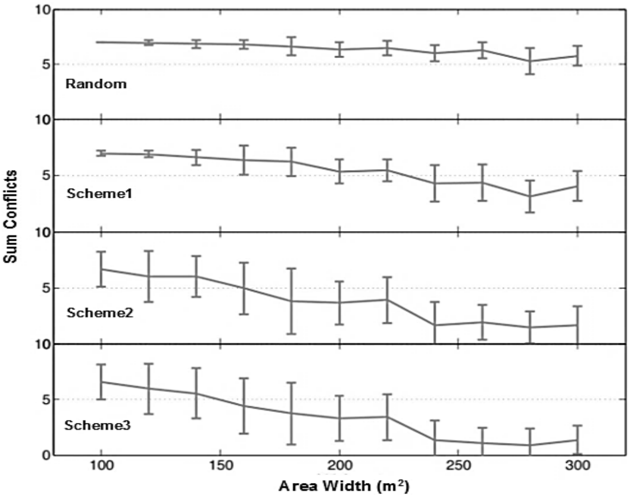


Figure 8. The average number of conflicts over different densities. A conflict exist when there is at least one FTP link interfering with a VoIP link. Max number of conflicts is 7 equal to the number of VoIP Links.

By increasing the densities to more realistic environments scheme 2 and 3 will achieve an edge in terms of performance compared to scheme 1, and they stay close to each other. The interpretation of this result is that: since there are 3 times more FTP links than VoIP links simply moving the VoIP links around will not cause much performance improvements, while moving the FTP links to another orthogonal channel is more effective.

Scheme 4's evaluation is not presented in Fig.9 since it will be able to resolve all the conflicts characterized by ϑ_i^j deterministically. It has an obvious superior performance. Intuitively by applying a cooperative scheme 4 with access to detailed internetwork interference information, islands of protection for VoIP traffic are generated by moving all the FTP interference to other channels. The FTP links which are not conflicting with any VoIP link are allowed to stay on the same channel as VoIP links.

Based on a forms of resource managements as channel assignment in this work, one might be interested in ensuring high aggregate throughput, or in prioritizing some devices over others (e.g., all Bluetooth headsets should get a certain bit-rate), or in ensuring that each type of network maximizes its throughput while not causing more than a certain level of interference to other networks.

5. CONCLUSION

A major finding of the investigated coexistence performance is a step toward a more broad and accurate understanding and modeling the performance of wireless networks in the face of interference and carrier sensing. As the simulation illustrates, carrier sensing scenario has a crucial role in defining SINR threshold(s), and the physical interference model should be extended to include interferer's traffic rate rather than a single SINR threshold. PRR results demonstrate that radio physical layer design with MIM support goes beyond the traditional media access control layer that cannot handle multiple packets.

To move towards improved resource utilization in wireless networks, we need to add the required mechanisms to enable cooperation and collaboration among networks. These mechanisms are needed in order to reduce the destructive relationships introduced in chaotic and uncoordinated environments. This work stated the utility optimization problem and showed its connection to the interference mitigation problem which can be further illustrated by a conflict graph. Further an application aware channel assignment scenario is studied by single link networks. The simulation concludes that non cooperative schemes have very limited ability in providing performance guarantees to the applications while cooperative schemes with access to detailed internetwork information can have significant success in resolving the conflicts as is done by scheme 4.

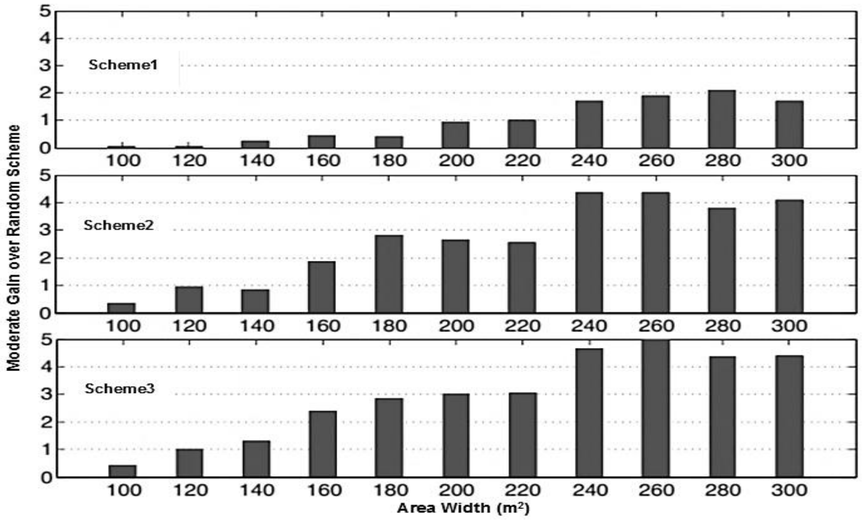


Figure 9. The average achieved gain of different schemes compared to random channel assignment (compared over different densities).

Application awareness is going to be an important factor in these types of network optimizations and it was shown that in general networks cannot guarantee a service quality and improve application experience of connectivity without the cooperation of other interfering networks.

For immediate future work, the plan is to investigate the extra needed mechanisms for estimating the interference relationships. This process should be done in the most efficient way and with minimal interference with the actual data traffic.

REFERENCES

[1] Hong Xu and Baochun Li, “XOR-Assisted cooperative diversity in OFDMA wireless networks: optimization framework and approximation algorithm, Proceeding of INFOCOM (IEEE), pp. 2141-2149, 2009.

[2] Yu Cheng, Hongkun Li and Peng-Jun Wan, “A theoretical framework for optimal cooperative networking in multiradio multichannel wireless networks,” IEEE Wireless Communications, vol.19, issue 2, pp 66-73, 2012.

[3] Qian Li, Hu, R.Q., Yi Qian and Geng Wu, “Cooperative communications for wireless networks: techniques and applications in LTE-advanced systems,” IEEE Wireless Communication, vol.19, issue 2, 2012.

[4] Douglas M. Blough, G. Resta, and P. Santi, “Approximation algorithms for wireless link scheduling with SINR-based interference,” IEEE/ACM Transactions on Networking, vol. 18, no. 6, pp 1701-1712, 2010.

[5] Y. Ding, Y. Huang, G. Zeng and L. Xiao, “Channel assignment with partially overlapping channels in wireless mesh networks,” Proceeding WICON’08 (ICST), Maui, 2008.

[6] M. Garetto, T. Salonidis, and E.W. Knightly, “Modeling per-flow throughput and capturing starvation in CSMA multi-hop wireless networks,” Proceeding INFOCOM (IEEE), Barcelona, pp 1-13, 2006.

[7] A. Kumar, E. Altman, D. Miorandi, and M. Goyal, “New insights from a fixed point analysis of single cell IEEE 802.11 wireless LANs,” IEEE/ACM Transaction on Networking, vol.15, no.3, pp 588-601, 2007.

[8] G. Brar, D. Blough, and P. Santi, “The SCREAM approach for efficient distributed scheduling with physical interference in wireless mesh networks,” Proceeding ICDCS'08 (IEEE), Beijing, pp 214-224, 2008.

[9] C. Reis, R. Mahajan, M. Rodrig, D. Wetherall, and J. Zahorjan, “Measurement-based models of delivery and interference in static wireless networks,” Proceeding SIGCOMM’06 (ACM), Pisa, pp 51–62, 2006.

[10] Nouha Baccour et al, “Radio link quality estimation in low power wireless networks,” Springer, 2013.

[11] R. Maheshwari and S. R. Das, “Physical interference modeling for transmission scheduling on commodity WiFi hardware,” Proceeding INFOCOM (IEEE), Rio de Janeiro, pp 2661 – 2665, 2009.

[12] K-H. Kim and K. G. Shin, “On accurate measurement of link quality in multi-hop wireless mesh networks,” Proceeding MobiCom’06 (ACM), Los Angles, pp 38-49, 2006.

[13] J. Lee, S-J. Lee, W. Kim, D. Jo, T. Kwon and Y. Choi, “Understanding interference and carrier sensing in wireless mesh networks,” IEEE Communications Magazine, vol. 47, no.7, pp 102-109, 2009.

[14] Jim Geier, “Assigning 802.11b access point channels, WiFi-Planet, Feberuary 2002.

[15] Arunesh Mishra, Suman Banerjee and William Arbaugh, “Weighted coloring based channel assignment for wlans,” SIGMOBILE Mob. Comput. Commun. Rev., vol. 9, no.3, pp 19-31, 2005.

[16] E. Rozner, Y. Mehta, A. Akella, and Lili Qiu, “Traffic-aware channel assignment in enterprise wireless lans,” SIGMOBILE Mob. Comput. Commun. Rev., vol. 11, no. 2, pp 43–44, 2007.

[17] Xiaonan Yue, Chi-Fai Wong and S.-H.G. Chan, “CACAO: Distributed client-assisted channel assignment optimization for uncoordinated WLANs,” IEEE Transactions on Parallel and Distributed Systems, vol.22, issue 9, pp1433-1440, 2011.

[18] X. F. Shen, Z. Wang, R. Z. Lin, Y. X. Sun, “Connectivity and RSSI based localization scheme for wireless sensor networks,” Lecture Notes on Computer Science, ICIC 2005, Hefei, China, August 2005.

[19] Q. Chen, F. S. Eisenlohr, D. Jiang, M. T. Moreno, L. Delgrossi and H. Hartenstein, “Overhaul of ieee 802.11 modeling and simulation in ns-2,” Proceeding MSWiM'2007 (IEEE/ACM), Crete Island, pp 159-168, 2007.

[20] IEEE Std. 802.11-2007, Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, IEEE Std. 802.11, 2007.

[21] P. Santi, R. Maheshwari, G. Resta, Samir Das and D. Blough, “Wireless link scheduling under a graded SINR interference model,” Proceeding FOWANCE'09 (ACM), New Orleans, pp 3-12, 2009.

S. Abdulkareem Mustafa received her BSc and MSc degree in Electronic and Communication Engineering from Mosul University at 1992, 1998 respectively, and PhD degree in Electronic and Communication Engineering from Baghdad University at 2004.

Since 1999 she has been an academic staff with the Electrical Department in the College of Engineering Salahaddin University, Kurdistan-Iraq.

She was a recipient of the IWFF Award in 2009, Endeavour Research Fellowship Award in 2012 and the FTFF awards in 2013 and 2014. She was a visiting academic at the School of EECS at the University of California, Berkeley during 2009-2010, and a visiting academic at the School of ITEE at the University of Queensland during 2012-2013.

Her research interests include digital communication systems, signal processing, wireless network and microwave imaging.