Co-channel Interference Modelling Between RATs in Heterogeneous Wireless Networks

Jason B. Ernst
School of Computer Science
University of Guelph
Guelph, ON, Canada
Email: jernst@uoguelph.ca

Nidal Nasser
College of Engineering
Alfaisal University, KSA
Email: nnasser@alfaisal.edu

Joel Rodrigues
Instituto de Telecomunicacoes
University of Beira Interior
Portugal
Email: joeljr@ieee.org

***Abstract*—Co-channel interference models are increasingly becoming important in wireless networking. This is especially true in heterogeneous networks where a single device may cause unintended interactions between multiple radios using difference radio access technologies, even though they are located on the same device. Currently simulation tools provide varying levels of modelling of this phenomenon. This paper tries to quantify how well popular wireless simulation tools capture these effects using qualitative techniques while providing quantitative evaulation of the effects of interference between two radio access technologies - Bluetooth and Wi-Fi. Each tool is compared according to level of interference modelling offered, the technique for interference modelling and the types of RATs which are supported. The effect of co-channel interference between Bluetooth and Wi-Fi is evaluated with respect to throughput using devices equipped with both Blutooth and Wi-Fi radios.**

***Index Terms*—Co-channel, interference, IEEE 802.11 Wi-Fi, Bluetooth, Heterogeneous Wireless Networks**

I. Introduction

Increasingly devices are equipped with multiple radio access technologies (RATs). This is due to the decreasing cost and size of radios and the increasing demand from end-users to always be connected. Typically, co-channel interference has been poorly modelled in wireless simulation software. When co-channel interference is modelled, it is usually limited to interference within a single particular RAT. For example, this means interference between Wi-Fi and Bluetooth is not modelled at all in many simulation tools. Traditionally, this was not a big problem since there were fewer wireless devices and fewer radios operating in general. However, with devices that now contain both Wi-Fi, Bluetooth and other potentially interfering technologies, co-channel interference modelling becomes more important. It is possible that a device can make use of multiple RATs concurrently in order to provide increased capacity or link fail-over, however without understanding of interactions between the RATs, performance may actually be hindered by using both RATs simultaneously. The rest of this paper is organized as follows: The next section will provide background and motivation for studying co-channel interference in simulation. Section III will outline the methodology used for comparing the popular simulation tools, and the experimental design for evaluating the models with respect to real equipment. Section IV will give a qualitative comparison of the existing simulation tools in terms of the level of interference modelling supported using the methodology defined in section III. Section V will empirically compare the simulation tools which support co-channel interference modelling with real equipment to determine the accuracy of the models. Finally, section VI will conclude the paper and give suggestions for future work.

II. Background and Motivation

The manner in which interference is modelled across simulation tools varies significantly. Some are based on bit-error rate calculations. Some only consider a single interfering source. This assumption may be extremely limiting in modern environments where there may be dense network deployments. For example consider an apartment building in an urban environment. At any given area, a particular channel may be subject to interference from multiple networks operating on the same channel, interference from microwave ovens, cordless telephones, wireless video game controllers and other devices. In order to account for the complex interactions between devices in a large simulation, some tools incorporate ray-tracing, which may be the most accurate technique. However, this technique is often costly - both in terms of computation time and in terms of money. The raytracing software packages used are often proprietary and expensive.

Previously, it has been demonstrated that partially overlapped channels is not harmful [1], however this considers overlapped channels within the same technology. This paper aims to study the effect when interference occurs within the channel from non-compatible technologies. In the case of Bluetooth and Wi-Fi, the Bluetooth channel is much smaller than a Wi-Fi channel, but given enough Bluetooth devices and poor interference avoidance techniques, the effect could be great. Furthermore, what is the effect of the larger interfering Wi-Fi channel on the small Bluetooth channel. In this case, if frequency hopping is not used, or it is for some reason restricted to the same range as Wi-Fi channel, it may not be possible for Bluetooth to function at all. In a whitepaper by Hewlett-Packet, it is suggested that interference with ACL Bluetooth links throughput will be degraded because the lack of automatic repeat requests (ARQ). At the same time, some types of Wi-Fi links may behave like Ethernet technologies and slow down to reduce bit error rates (BER) caused by poor signal to noise ratios. [2] This may increasingly become a problem as devices such as mobile phones and netbooks may contain both technologies.

One major motivation for this research is to support devices equipped with multiple RATs such that one or more of the RATs may be active at once. There are several benefits to this type of approach. First, techniques such as [3] may be used to send portions of traffic on each link, recombining it at the destination using erasure codes. Second, increasing the number of RATs available for connection improves reliability. If neighbouring infrastructure using one particular RAT experiences problems such as congestion or downtime, another available RAT may be chosen to take on a greater load leading to greater connectivity and reliablity. Lastly, there may be the potential for increased throughput by making use of multiple RATs at once, particularly if the effects of interference between the RATs is well understood. For instance, if there is signicant enough interference within the available channels for two particular RATs it may be more beneficial to avoid using both simulatenously as the interference will be more detrimental. There are some existing attempts to formulate a general interference model for interference between wireless technologies such as [4]. The approach by [4] focuses on outages caused by interference while this work tries to focus on what throughput can be achieved inspite of interference.

III. Methodology

In order to study how well co-channel interference is modelled in simulation, several popular wireless simulation tools are evaluated both empirically and qualitatively. First, source code and available packages are examined to see if they offer any potential for interference modelling between RATs. In addition, recent publications and documentation about interference modelling are consulted for each simulation tool. The type of interference modelling level is identified and classified for each tool. For example, if the tool does not support any interference modelling, it receives the lowest ranking. If the simulation tool does not support co-channel interference modelling, it receives the low ranking. If the tool supports interference within the same RAT, it receives the middle level. Lastly, if the simulator provides interference modelling between RATs, it is given the highest level. Since only one of the surveyed simulation tools supports any type of co-channel interference modelling between RATs, it is not possible to directly compare the simulation performance with that of a real world experiment. Instead of direct comparison at this stage of research we will instead aim to quantify the effect of interference using two popular RATs, namely Bluetooth and Wi-Fi. The single simulation model which does support co-channel interference between RATs was not evaluated because it uses proprietary ray-tracing software which makes study and comparison difficult. Traditionally, simulation models for networking have been made open to allow for easy evaluation, criticism and improvement. Furthermore, the equipment available for the real-world experiment were Wi-Fi and Bluetooth enabled laptops, not Zigbee which would make a direct comparison with the raytracing tool impossible. While there have been some other works which study interference, these works take place using the physical layer perspective [5] [6]. In this case, we are concerned with the performance to the end-user and thus evaluate with respect to throughput.

In the literature, there have been several studies of the effects between Bluetooth and Wi-Fi, however in some cases the effect is only examined in one particular direction. For example [7] examines the effect of Wi-Fi interference on Bluetooth. The opposite is the case in [8] which studies the effects of Bluetooth interference on Wi-Fi. In some cases, it is related to a particular end application, such as voice [7]. None of these existing works examine the interference effects in the context of the lack of simulation models to handle interference between RATs which this paper tries to highlight. Other studies are simplistic and only examine the effects when there is a single interferer rather a more realistic scenario which this paper tries to provide. Furthermore, this paper tries to highlight some of the potential pitfalls of using multiple RATs in the context of heterogeneous wireless networking. For example, in this paper we try to isolate the extreme case of interference between Bluetooth and Wi-Fi by disabling adaptive frequency hopping in Bluetooth so that interference between the two technologies is maximized. There is only one other paper we are aware of which focuses on Bluetooth and Wi-Fi in the context of a heterogeneous wireless envioronment [9]. In this case, the authors have proposed a framework which may be used to try to detect contention and interference between Wi-Fi, Bluetooth and other non-IEEE sources. However, this work is in early stages and very little has been published relating to the throughput effects of interference between the RATs, which is what we focus on in this paper.

In [10] the authors propose ubiquitous applications which are similar to heterogeneous networks but not quite the same. However, the network architecture is quite different from the one which we study. The Bluetooth devices send data to a Wi-Fi and Bluetooth equipped laptop which then uses Wi-Fi to send data into the Internet. In our case, since we wish to avoid the dependence on data from the Bluetooth RAT before it is sent on via Wi-Fi. To accomplish this, we independently send traffic on Bluetooth and Wi-Fi at the same time. Furthermore, [10] only investigates the effects of interference on Wi-Fi with Bluetooth active, while our study looks in both directions. One interesting approach in this work is studying the effects of the interference with Bluetooth and Wi-Fi devices at various distances from one another. This is out of the scope of this paper, but could be revisited as future work. Another work which examines Bluetooth and Wi-Fi interference is [11]. The authors examined the effects of interference while the nodes were in motion in automobiles, which while related has unique challenges that make the work different from this. A similar study on wireless interference was conducted by [12] which focused on error rates and signal strengths while this work focuses on throughput when measuring the effect of interference.

IV. Qualitiative Comparison of Interference Models in Simulation

In this section, we compare the simulation tools using the method described previously in the methodology. This comparison allows for a starting point to perform further experiments and evaluate which tools are perhaps the most accurate in terms of simulating co-channel interference between RATs.

TABLE I
COMPARISON OF CO-CHANNEL INTERFERENCE MODELS IN CURRENT SIMULATION TOOLS

Tool	Int. Level	Method	RATs
OMNET++, INET Framework [13]	Lowest	Within Wi-Fi Only	Wi-Fi
NS2,UCBT Module [14]	Low	Within Particular RAT, Several Techniques	Wi-Fi, Bluetooth, UWB
OMNET++, MiXiM Framework [15]	Low	Within Wi-Fi Only	Wi-Fi
NS3 [5]	Medium	Within Wi-Fi Only, Tables, BER, Other	Wi-Fi, WiMAX
OMNET++, Raytracing [16]	High	Raytracing and 3d environment mapping	Wi-Fi, Zigbee

First, the NS2 simulation tool with the UCBT module was examined. According to the authors, "Radio Channel/PHY is not modelled explicitly" [14]. Because of this limitation, it makes it impossible to model co-channel interference between Wi-Fi and Bluetooth using this module. Other modules such as HSBT for NS2 are also based on UCBT and so are likely to suffer from the same limitation. Interference in these modules is only support within the Bluetooth RAT itself using a configurable loss model, interpiconet interference detection model or a table driven loss model. The OMNET++ tool is also evaluated. In this case, the tool website only lists IEEE 802.11 as the only supported wireless technology [13]. Since only one wireless technology is supported, it is not possible for co-channel interference between RATs to be modelled at all using this environment. Similarly, OMNET++ with the MiXiM extension does not provide interference between different RATs, but does support interference within RATs according to the developer documentation. [15] While NS3 does not yet support co-channel interference modelling completely between RATs, is in the process of developing a model where RATs can cause additive interference in a channel, however it is still under development at this time. NS3 current supports basic interference between devices such as microwave ovens and Wi-Fi, which is why it receive a medium ranking for co-channel interference modelling. NS3 has perhaps one of the most complete set of interference models, allowing for several different techniques for modelling interference within RATs including using tables, bit error rate, and others [5]. Finally, OMNET++ combined with a Raytracing tool [16] is the only known work where co-channel interference is modelled between two RATs. It currently support interference modelling between Wi-Fi and Zigbee. This type of simulation model could be potentially applied to some of the other popular tools to create more realistic wireless simulations for heterogeneous wireless networks. As can be seen in the qualitative comparison of the popular simulation tools, only one of the currently available tools have a high level of support for co-channel interference between RATs in wireless networks. The rest of this paper will show why this is a problem by trying to quantify the effects of co-channel interference in real wireless equipment.

V. Performance Evaluation of Bluetooth and Wi-Fi with Interference

Since all of the simulation tools except one ignore co-channel interference between RATs we will attempt to quantify the effects of interference between two popular RATs. In this case, Bluetooth and Wi-Fi was chosen since both of these technologies are commonly available and are commonly included in many popular consumer devices such as smartphones, netbooks and tablets. In this experiment, laptops equipped with both devices were used. The experiment was conducted at the University of Guelph in the PERWiN lab during the late evening when it was unlikely students were using the campus network. This time was chosen to avoid any interference from existing wireless networks in the area which could not be disabled or avoided.

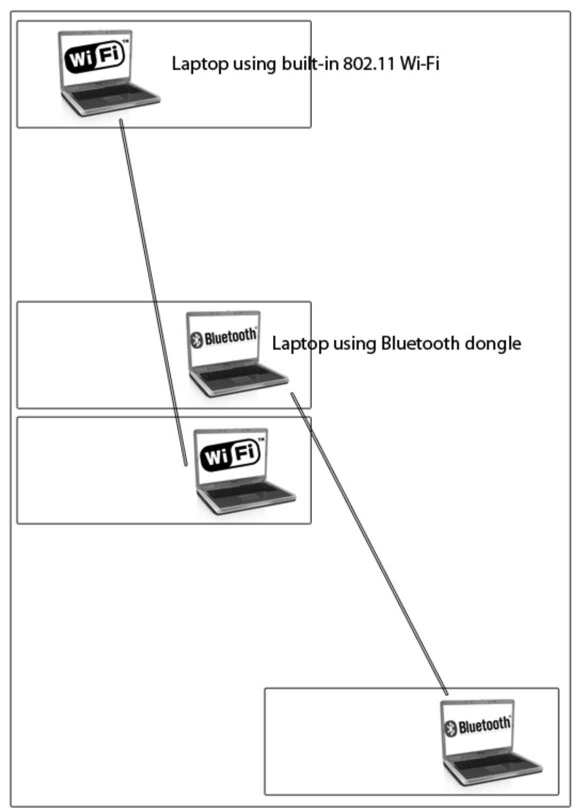

Fig. 1. Experimental Layout of Bluetooth and Wi-Fi Laptops

The laptops were arranged as can be seen in Figure 1 for the experiment run with four laptops. This experiment used two Bluetooth and two Wi-Fi laptops. The laptops are arranged in such a way that the Bluetooth and Wi-Fi enabled laptops should interfere with one another due to their close proximity and the overlapping communication paths. As more laptops with Bluetooth and Wi-Fi are added, they are spread out around the room in a similar pattern. In each case, the same laptop is used to measure the throughput. This gives each experiment a constant frame of reference so that the effects of interference on one particular device can be studied. Similarly, all of the source laptops send their traffic to one destination device. This way the traffic pattern remains the same across all experiments. Repeatedly, the laptops sent a 100 megabyte file to each other using FTP for the Wi-Fi devices and a 10 megabyte file for the Bluetooth devices. The reason for this difference is due to the bandwidth differences in the two RATs. The time taken to send the complete file was measured which was then used to determine the throughput. The Bluetooth and Wifi devices were set to use the same channel, and adaptive frequency hopping on the Bluetooth devices was turned off. More specifically, the Wi-Fi devices were forced to use IEEE 802.11 B/G channel 1, while the Bluetooth devices used Bluetooth channel 10. This put both devices within the same frequency range. While this may not necessarily be realistic in a real-world environment, it aims to model environments with a high number of users making use of Bluetooth and Wi-Fi simultaneously since the chance of interference increases with more users.

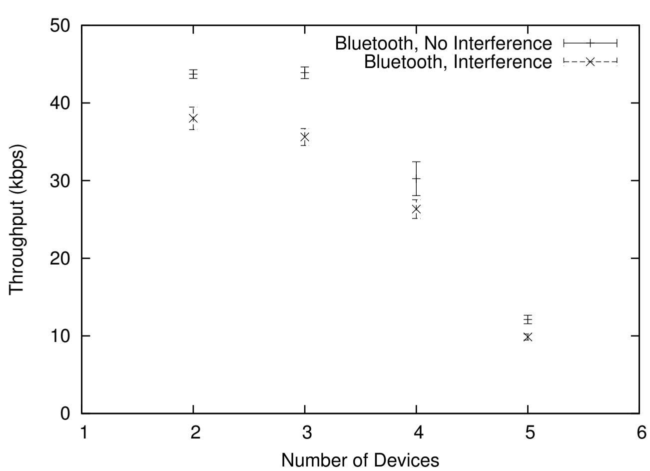

Fig. 2. Bluetooth throughput with and without interference

In Figure 2 the effects of Wi-Fi interference on Bluetooth can be seen as the number of Bluetooth and Wi-Fi devices in the network grows. It should be noted that the number of devices represents the number of Wi-Fi and Bluetooth devices. So the experiment with two devices has two Wi-Fi and two Bluetooth devices, making a total of four devices in the experiment. The error bars show the standard deviation from the mean for each of the results. For each result, the experiment was repeated 30 times. In all cases, regardless of the number of Bluetooth devices the network throughput is much higher without interference from Wi-Fi nodes. The reason for this behaviour is likely due to the higher powered Wi-Fi devices overpowering the weaker signal from the Bluetooth devices. In addition, the Bluetooth devices use a narrow portion of the spectrum leaving compared with Wi-Fi. This means that the entire frequency range used by Bluetooth is also covered by Wi-Fi interference. Contrast this with the opposite where only a portion of the frequency range used by a Wi-Fi channel is taken by the Bluetooth interference. This result is particularly important when considering devices such as smartphones and netbooks which often include both Wi-Fi and Bluetooth radios. If efforts are not made to avoid interference with nearby Wi-Fi devices, Bluetooth performance significantly drops. The effect is most pronounced with fewer Bluetooth devices present in the immediate area. While there is some effect present from Wi-Fi to Bluetooth interference, the throughput is dominated most by the number of Bluetooth devices present. Depsite this, the results show some room for improvement if Wi-Fi to Bluetooth interference is avoided.

In contrast, Figure 3 shows the experiment from the point of view of the Wi-Fi devices. Again, the error bars in this graph represent the standard deviation from the mean for each experimental result. Each experiment was repeated thirsty times to determine the means presented. In this case, there is often not a significant difference in performance between interference and non-interference. One exception is with three Bluetooth and three Wi-Fi devices. This result may be more related to the positioning of the devices in the experiment, and certain configurations may show more or less effect in terms of Bluetooth to Wi-Fi interference. One interesting result is the difference compared with the Wi-Fi to Bluetooth interference in Figure 2. In this case, since Wi-Fi is higher power compared with Bluetooth the difference in effect make sense. So the focus of interference avoidance, at least with these two particular technologies should be on Bluetooth avoidance channels where Wi-Fi is used. Of course, more extensive experiments could be undertaken to try to discover the conditions where Bluetooth interference with Wi-Fi is significant enough to warrant avoidance techniques. For instance, there may be a certain range where a Bluetooth devices is close enough to a Wi-Fi device that performance is affected more greatly. Particularly, this is important when a single device contains both Radios.

VI. Conclusions and Future Work

First, this work shows that many current wireless simulation tools do not support co-channel interference between RATs at this time. The only tool which does support any type of co-channel interference between RATs is proprietary and expensive, making it impractical for use in research. Many existing simulation tools have found success and acceptance

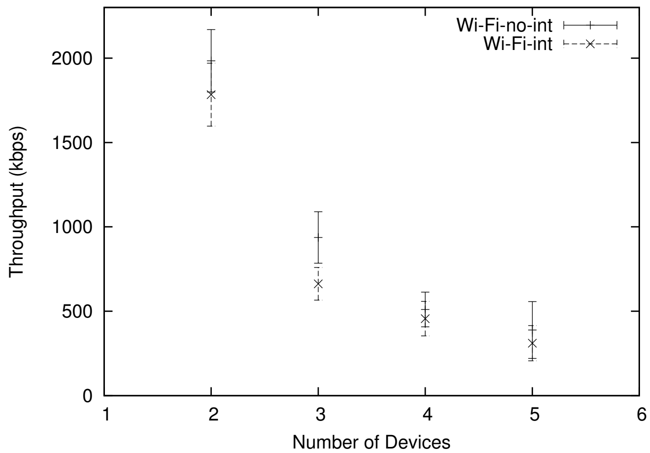

Fig. 3. Wi-Fi throughput with and without interference

in the research community from open source which allows for easy review and criticism of techniques. This approach should be extended to include interference between RATs in the future to support next generation wireless research. Furthermore, we have shown the effect of interference between Bluetooth and Wi-Fi (only two of the potential RATs) when this is not taken into account. The experiments presented in this paper showed a significant effect when Wi-Fi interferes with Bluetooth and a limited effect when Bluetooth interferes with Wi-Fi. This problem will only get worse as limited spectrum space becomes more crowded and devices contain more radio technology together.

This work may be extended in several ways. First, investigation of interference between RATs on the same device could be completed. Additionally, further scenarios, different topologies and ranges could be studied to try to establish bounds on how close competing RATs should be before interference is considered a problem, similiar to some of the methodology present in [10]. In this paper, as the number of Bluetooth nodes increased, the number of Wi-Fi nodes increased accordingly. The number of each radio could be controlled independently to gain more insight into how interference affects throughput in particular scenarios. Second, this study only examines the interactions between IEEE 802.11 Wi-Fi and Bluetooth. Further work could include other interfering technologies or devices such as Zigbee, Microwave ovens, cordless telephones or video game controllers. Some of these technologies are considered in [8]. Wider-range technologies such as WiMAX, LTE or other 4G technologies could also be studied in a similar manner. When including these types of technologies, mobility may be another issue worth studying following an approach similar to [11]. Lastly, this work forms the basis for further study in interactions between RATs in heterogeneous wireless environments. This area will become increasingly important as devices contain more radios and users try to take advantage of these extra resources by using multiple radios simultaneously without negative effects. Despite several previous studies examining the effects of interference between RATs, and Bluetooth and Wi-Fi in particular, very little effort has been put into developing simulation models that represent this phenomenon. Given that a vast amount of wireless research is produced using simulation and the growing push towards heterogeneous wireless technology, this problem is becoming more important.

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