PREDATOR: A Protocol for Ad-hoc and Brokered Dynamic Spectrum Management

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Abstract— **If technological trends are any indication, we are coming upon a future where we will have highly-cognitive transmitters and receivers capable of using many different frequencies, transmission powers, modulation schemes and MAC protocols. Future generations of mobile devices will be able to bid for the spectrum that they require from a broker, or will have ways of automatically reducing interference by negotiation with other devices. Despite the many different algorithms and policies that could be used to support this, to the best of our knowledge, there is currently a lack of a unified protocol to allow negotiation of spectrum for brokered and non-brokered environments. The proposed protocol, PREDATOR (PRotocol for Equitable, Dynamic AllocaTion of Radio spectrum), accommodates both brokered and ad hoc configurations. In this paper, we provide a detailed description of how the protocol works, as well as results from a sample application environment to show its efficacy.**

I. INTRODUCTION AND MOTIVATION

Currently, there is a proliferation of wireless devices and users. Cells phones and the wireless Internet have made it clear that people want to be connected to each other and to the information they need, no matter where they go. As a rapidly increasing number of mobile devices employ wireless communications for transmitting data and voice signals, the conflict for available wireless spectrum is becoming more fierce. Traditionally, the Federal Communications Commission has established strict divisions across the entire spectrum, from 3 KHz up through 300 GHz [1], and either reserved segments for public use or licensed segments to private companies at very high prices. However, certain segments such as the 5 GHz U-NII band remain unlicensed and freely available for public use. The FCC intends this band to be used in a free-for-all manner by private individuals and has not established requirements for access methods [2]. The aforementioned spectrum conflict is quickly saturating these open bands, leading to degradation in signal quality and throughput, even though the majority of the spectrum below 3 GHz is underutilized [3]. This varying degree of spectrum utilization is a challenge in both licensed and unlicensed bands. One of the solutions that have been proposed for this problem is the dynamic and automatic allocation of spectrum to devices. Devices with software defined radio components, capable of switching frequency and modulation could use schemes that modify their transmission characteristics to reduce interference or increase bandwidth.

The research in dynamic spectrum allocation has been bifurcated. On one hand, the XG project [4] by the Department of Defense proposes an architecture by which nodes opportunistically use the entire available spectrum, without consulting a central authority. On the other hand, the DIMSUMnet architecture [5] argues that completely ad hoc, opportunistic network access is the most optimistic situation, and that in between the current state of wireless technology and that ideal there exists Coordinated Dynamic Spectrum Access Networks. In this network architecture, all clients wishing to use a portion of the spectrum communicate with authoritative brokers. A detailed survey of the area can be found in [6], [7].

We propose a protocol, called PREDATOR (PRotocol for Equitable, Dynamic AllocaTion of Radio spectrum), that accommodates both brokered and ad hoc configurations. We assume a paradigm where, in licensed bands, nodes must talk to a coordinating central authority, while in unlicensed bands, a node can make an effort to negotiate with other nodes to achieve a mutually beneficial network configuration. While devices operate in the unlicensed portion of the spectrum, they may also voluntarily use a local, non-authoritative broker, to better optimize or prioritize access. In this paradigm, certain nodes may be capable of communicating in both unlicensed and licensed bands, potentially seeking to reduce cost or increase bandwidth.

The rest of the paper is organized as follows. Related work is presented in Section II. Section III presents PREDATOR protocol in every aspects. Section IV describes the simulation environment and presents the results of the simulation study. We conclude in Section V.

II. RELATED WORK

Due to the increased number of mobile devices, the spectrum tends to be very busy in certain spots and underutilized in others. What is needed is a method not only to more efficiently distribute spectrum in the free bands among localized users, but also to leverage unused spectrum throughout the wide range of radio frequencies available.

Current methods proposed by others include simple localized bandwidth-portioning [2], [3], [8]–[10] and also schemes for dynamic spectrum allocation using an authoritative broker [5]. The proposed protocol combines both the ad hoc operation of the former with the brokered structure of the latter, allowing it to be very flexible.

One scheme for portioning localized bandwidth (e.g. the 2.4 GHz ISM band) is to use graphs to select channel assignments resulting in the lowest interference and highest bandwidth, given a reasonable amount of time to calculate the graph [3], [8]. By considering each node in the wireless network to be a vertex in a graph, an iterative method can be employed to color the vertices of the graph, i.e. assign a discrete spectrum channel to that node. A greedy algorithm will assign colors (channels) starting with the vertices (nodes) with the most unassigned partners and work through in order until either all of the vertices are colored, or there are no more colors to assign [8]. A refinement of this method is to apply a fair algorithm, which instead assigns colors based on need but also assuring that each node will end up with a relatively even amount of usable bandwidth. If a coloring solution is found to be unfair, available colors all utilized before bandwidth is evenly distributed and the process is restarted. Because this process can take many iterations before an optimally fair solution is chosen, the Randomized Distributed Algorithm was devised. This behaves like a raffle, assigning the colors in random order so that each node has an equal chance to win a channel. Each time a node loses a raffle, it picks a higher random number to increase its chance of winning [3]. Calculating the optimum distribution of colors for a given graph is an NP-complete problem, and thus not possible to compute in real time. However, simulations have shown that the Randomized Distributed Algorithm can result in a spectrum distribution nearly as efficient as the optimum distribution, in a fraction of the time and with low overhead [3].

Instead of a central managing unit applying graph theory to assign channels from unlicensed spectrum to nodes in a network, it is possible for the nodes themselves to self-organized through competitive or cooperative processes. The nodes can greedily acquire bandwidth, based on game theory [9] or democratically acquire bandwidth using negotiations based on each nodes available protocols and abilities [2]. Applying game theory to a non-cooperative method of spectrum utilization results in a zero-sum game (i.e. for any one node to own a particular channel, another node must lose it, thus the total ownership is zero). In this greedy method, nodes freely interfere with other nodes competing for their spectrum, punishing them until they stop infringing on the bandwidth. Eventually, the overall spectrum use will stabilize as the nodes seek an optimal balance between owning spectrum and being unable to use a desired channel because of interference. Simulation has shown that this method can result in an efficient configuration even with little or no inter-node communication or central authority [9].

Conversely, a cooperative method of self-organization can be applied using a Common Spectrum Coordination Channel. Each node in the network broadcasts onto the CSCC its particular abilities (e.g. available frequencies, powers, modulation schemes), and then as a group the nodes allocate spectrum equally. Because this data is made up of small bursts and nodes only utilize the CSCC when requesting spectrum, the channel can be narrow and use low bandwidth. For example, a 1 Mbps 802.11 channel has enough bandwidth and range to cover an indoor or outdoor region of $50-100m$. Experiments have shown that an ISM band with conflicting 802.11b and Bluetooth networks had improved throughput and lower delay when the CSCC scheme was applied [2].

Although these methods work well for ad hoc networks, it is difficult to assimilate them into existing infrastructure-based networks. The concept of equitably distributing unlicensed bandwidth is important, and this can be realized by using Dynamic Spectrum Allocation Protocol [10]. DSAP introduces the concept of a lease, a short-term allocation of a wireless channel to a particular node. Using a radio manager, DSAP tracks the nodes in a local network, including attributes such as available frequencies, transmission power, modulation protocols, and (optionally) location. Client nodes send a ChannelDiscover message, to which a DSAP server node responds with a ChannelOffer message, which includes a suggested spectrum and transmission power to utilize. A negotiation process can take place if the initial offer is unacceptable, and eventually both parties agree on a configuration. When client nodes misbehave, causing interference, the DSAP server can send a ChannelReclaim to force it off of the network. Unresponsive or malicious nodes can be routed around by instructing the client nodes to choose different channels. When a node's lease has expired, it is expected to stop operating on that channel and request a new lease. Initial experiments show that DSAP-enabled clients outperform non-DSAP-enabled clients [10].

DSAP can be implemented at the endpoint of an infrastructure-based network, i.e. if the DSAP server is connected to an Internet gateway, however DSAP does not alleviate the problem of allocating frequencies across the entire radio spectrum or over wide geographic areas. To address this, the Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access network architecture was devised [5]. The DIMSUMnet architecture centers around the concept of coordinated access bands: sections of spectrum that are available for dynamic leasing by a central authoritative broker. Ideally, CABs would be located adjacent to existing, fixed spectrum bands (e.g. cellular, broadcast television) and thus include an overflow capability to load-balance high utilization conditions. Spectrum in the CABs would be leased over Radio Access Networks by RAN managers. Client nodes communicate with the RANMANs using SPectrum Information channels (SPIs), similar to the CSCCs of DSAP. Each RANMAN controls a specific geographic region, but fallback redundancy is built into the system by cloning the lease tables to neighbor RANMANs. By adding more CABs and RANMANs, the DIMSUMnet can be expanded across an arbitrarily large geographic and spectral area.

Ideally, at some point most or all radio spectrum will be deregulated by the FCC and a dynamic leasing architecture based on similar to DIMSUMnet will be implemented to control spectrum allocation in real time. The advantage that PREDATOR offers, and allows it to inter-operate with

DIMSUMnet, is that it can scale to work on a brokered, infrastructure-based system down to an ad hoc configuration.

III. PROPOSED PROTOCOL

A. Preliminaries and scenarios

The wireless nodes referred to in this paper are supposed to have highly agile software defined radios (SDRs). Within certain ranges specified by the capabilities of the individual nodes' hardware, they are able to modify their frequency, transmission powers, modulation scheme, and MAC layer protocols. They are capable of receiving in certain frequency ranges with certain associated receiver sensitivites. It is currently assumed that the amount of time for the node to change its operating parameters is negligable. These agile wireless nodes may potentially operate in two different scenarios.

In the first scenario, nodes are operating with the help of a broker, as specified in the DIMSUM [5] wireless access model. Here, we will have brokers, which arbitrate the process of allocating a communications channel and client nodes, which need to use that channel, either to communicate to a base station or to each other. A scenario where this would apply would be for cell phone providers or mobile Internet providers. To use the communication channel (with specified area, frequencies, power, etc), the client nodes must receive the permission of the broker. These clients nodes may (but will not necessarily) be mobile devices, and therefore may encounter several different brokers within its travels. The client node may have the ability to connect to brokers owned by different parties. It may do this, for instance, to find the best price for the channel access that it needs. In this scenario, requesting permission to access the channel may be mandatory by law (for instance, coming from the FCC or parties that are licensed on a portion of the spectrum) or mandatory by network policy (for instance, at a University level).

In the second scenario, there is no broker, but there are collections of wireless nodes which communicate. This could represent a wireless sensor network, or a collection of 802.11 devices (access points and NICs) in a University. There may be many pairs of transmitters and receivers, all of whom may be utilizing the same portions of the spectrum (for instance, the 2.4GHz ISM band for 802.11b and g). If the nodes have agile SDRs, they may negotiate with their transmitter/receiver counterpart, or even with other uninvolved nodes to try to minimize interference. Transmitter/receiver pairs may want to enter these negotiations in order to change data rates, increase ranges, or reduce their processing load (in times of high CPU load, switch to simpler communication schemes). This will typically be a scenario where nodes are communicating on the unlicensed portion of the spectrum.

In a wireless communications scenario, let there be two wireless nodes N_1 and N_2. These two nodes can communicate over a symetric wireless connection. In the non brokered-scenario, we assume that both of these nodes are peers, speaking on some non-brokered portion of the spectrum. In the brokered scenario, a node N_1 gains access to the channel from a broker, N_2.

B. Protocol design

The PREDATOR protocol works over standard 802.11 MAC layer. This is a preliminary design choice, made for ease of testing and implementation. In future implementations of the protocol, specifications for the data rate, frequencies, transmission power, and modulation schemes may need to be altered for flexibility, to make the protocol general enough to operate throughout the spectrum. The PREDATOR protocol consists of several, typically small packets sent back and fourth between nodes wanting to negotiate spectrum use.

TABLE I
FIELDS IN THE PREDATOR PACKET

Field	**Size (bytes)**	**Description**
Type (`TYPE`)	1	The type of PREDATOR packet (see table II)
Control (`CTL`)	1	Contains two control flags. The Broker (BRK) flag signifies whether this is a brokered or non-brokered negotiation. The Auction (AUC) flag specifies that there is an auction packet attached to the end of the PREDATOR packet
Negotiation TTL (`NEG_TTL`)	1	Limits the number of rounds that a negotiation can continue
Number of Frequency Ranges (`NFR`)	1	Specifies the number of ranges that specified in the next field
Frequency Ranges (`FR`)	0-2040	These are a series of ranges, the number of which is specified by the NFR field. For each range, there are two, 32-bit IEEE 754 floating point numbers that represent the beginning and end of the specific block of allocated spectrum (in Hertz)
Maximum Transmission Powers (`MTP`)	0-1020	A number of maximum transmission power ranges for each of the specified frequency ranges, given by a 32-bit floating point number.
Minimum Reception Powers (`MRP`)	0-1020	A number of minimum powers that the receiver is capable of receiving for each of the specified frequency ranges, given by a 32-bit floating point number.
Number of Protocols (`NP`)	1	Specifies the number of protocols that are given in the next field
Protocols (`PR`)	0-510	A number of protocol IDs (maintained in a central registry) represented by 16 bit unsigned integers.
Number of Networks (`NN`)	1	Specifies the number of networks that are given in the next field
Networks (`NETS`)	0-510	Networks to be accessed (maintained in a central registry) represented by 16 bit unsigned integers. This may represent the Internet, or any number of wireless network providers.
Number of RAV Frequency Ranges (`NFR_RAV`)	1	Specifies the number of ranges for the Resource Allocation Vector (RAV)
RAV Frequency Ranges (`FR_RAV`)	0-2040	Similar to above frequency ranges.
RAV Traffic Characterization (`TR_RAV`)	0-2040	32 bit floating point numbers specifying the amount of activity observed in certain bands.
RAV Power Characterization (`POW_RAV`)	0-2040	32 bit floating point numbers specifying the average transmission power observed in certain bands.

TABLE II

TYPES OF PREDATOR PACKETS

Type	Description
Full Beacon (`F_BEACON`)	Packet is a beacon that includes standard information specified by the packet format
Reference Beacon (`R_BEACON`)	Packet is a beacon that only includes information about how to get onto the negotiation channel
Negotiation Initiation (`NEGOT_INIT`)	Initiating the negotiation after receiving a beacon.
Negotiation Suggestion (`NEGOT_SUGGEST`)	Suggest new operating parameters for the recipient.
Negotiation Acceptance (`NEGOT_ACCEPT`)	Accept the operating parameters suggested by the sender.
Negotiation Acceptance (`NEGOT_REJECT`)	Reject the operating parameters suggested by the sender.

The PREDATOR protocol is intended to support communications channel negotiations between nodes. The reasons for performing this negotiation may vary and be governed by different algorithms and policies. Let us suppose that N_1 begins the negotiation process with a beacon packet. This may come in two different situations. In the brokered scenario, this beacon may be continually transmitted from a broker or a client node. In the non-brokered scenario, the node that decides to begin a negotiation will send this packet.

The beacon will be one of two types. The *Full Beacon* (`F_BEACON`) contains some portion of the frequency or transmission/reception power information as specified in the packet format. For nodes that are already engaged in some kind of communication, or are at least typically synchonized on a negotiation channel can use this type of beacon to shorten the negotiation process. The *Reference Beacon* (`R_BEACON`) only contains information on where to find a negotiation channel. This provides short beacons, most probably for use by brokers. The fact that the negotiation channel is specified in `R_BEACON` can provide for robustness of the negotiation channel. If, for instance, a broker had a problem with a negotiation channel, (i.e. interference or overloading) it could specify different negotiation channels for different client nodes. Tables I and II summarizes the fields in the data packet and the types of data packets of PREDATOR protocol respectively.

Once this beacon is received, N_2 responds with a *Negotiation Initiation* (`NEGOT_INIT`) packet. This sends along all of the information specified in the packet format. When N_1 receives this packet, both nodes will have some information about the capabilities of the other. However, these packets may not contain complete information about the capabilites of the nodes. To keep packet size down, the nodes may only put their preferred communications information into the packet. For instance, if there is a frequency range that the node currently finds optimal, it may suggest those ranges first. To send more information about capabilities, or to suggest operational parameters to the other node, the nodes will use some number of Negotiation Suggestion packets. In additional to sending information about the nodes' capabilities, the node may send spectrum usage information in the form of a Resource Allocation Vector (RAV). The RAV specifies average power and traffic observed for certain bands of the spectrum scanned by the node. The nodes can use this information to find a band to use where interference would be minimal. The ability to characterize wireless traffic or interference in different bands will be predicated on the availability of a sufficiently capable RF frontend. We assume that this exists and is available to the network node utilizing the PREDATOR protocol. The node will observe what frequency ranges are active, and what the average transmission power was over the time observed. It will then insert into the PREDATOR packets which bands it found active and the average power over that time.

The PREDATOR protocol stands independently of what algorithms or policies are used to select RF operating characteristics. In brokered situations, PREDATOR will be able to support various brokering schemes and algorithms. In the non-brokered situations, the PREDATOR protocol will be able to support algorithms for channel allocation and cooperative spectrum sensing. In the non-brokered scenario, the cycle of suggestions is simply based on the operational capabilities of the nodes. However, in the brokered scenario, packets in an as of yet unspecified auction format will be exchanged. The PREDATOR protocol may actually be used to specify many different types of auction protocols. The auction protocol will provide bids or quotes for certain parts of the spectrum.

If after this cycle of information sharing and suggestion the nodes finally reach an agreement for operational parameters, the agreeing node will send a *Negotiation Accept* (`NEGOT_ACCEPT`) packet. If on the other hand, the nodes cannot come to an agreement or the Negotiation TTL has been exceeded, the node first aware of the impasse will send a *Negotiation Reject* (`NEGOT_REJECT`) packet. This ends the current negotiation.

In the brokered scenario, the amount of time that a node is allowed to keep some set of operational characteristics is determined by the auction process. In the non-brokered environment, all negotiations are kept in time out vector (TOV). The TOV will age the negotiations until at some point, they are no longer valid. This allows the nodes to adapt to a changing environment where mobile devices could come and go.

Next, we give an illustrative example of how a simple negotiation may work in Figure 1. In this scenario, 6 nodes were used, with CBR transfers between each pair. All started out on the same channel. They were spaced in a dumbell shape with a pair of nodes on each end and one pair in the middle. In addition to having a CBR data transfer, the center pair also use the PREDATOR protocol while the other pairs do not.

To begin with, node 2, perhaps upon sensing a large number of MAC collisions begins the process of seeking another channel by scanning the radio environment for information about other transmitters and interference. This may be done with an additional receiver or by time sharing a single receiver. Node 2 scans and discovers the presence of node 0 and node 1. It inserts this information into the RAV and sends a `F_BEACON` containing the pertinent information to node 3. Node 3, upon receiving the `F_BEACON`, does its own scan of the air around it, discovering node 4 and 5. Node 3 then sends a `NEGOT_INIT` packet with this information and its own operating characteristics to node 2. Assuming that the nodes have managed to fit all of their operational parameters into this single packet, node 2 will have all of the information that it needs upon receiving the `NEGOT_INIT`. Through some mechanism, node 2 now decides what will be the best operating parameters to use. It puts this information into an `NEGOT_SUGGEST` packet sent to node 3. Node 3 looks at the suggestion and decides to accept. It sends back an `NEGOT_ACCEPT` packet. Both nodes then change their operating characteristics accordingly.

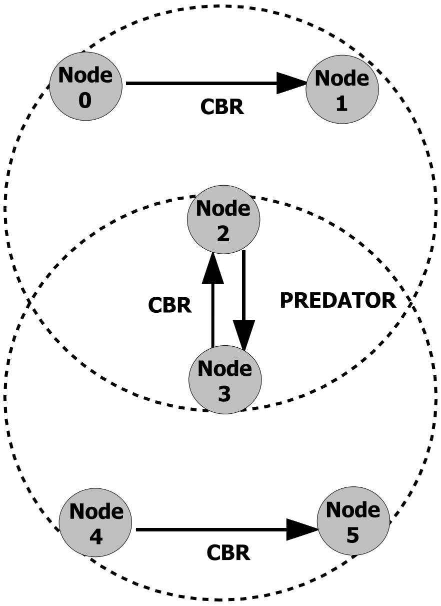

Fig. 1. Illustration of Scenario 1

IV. Simulation Study

A. Simulation environment and setup

For the simulation, a simplified version of the protocol is utilized to illustrate its efficiacy in dealing with the simpler problem of channel allocation. The nodes in the simulation only exchange information about their available channels and observed channel usage, ignoring power, modulation and more complex frequency issues. These issues will be more extensively evaluated in future work.

The protocol was implemented as an extension to the ns-2 simulator. The main portion of the protocol was done in C++. Some extensions were made to the ns-2 source code itself to make it more stable for allowing nodes to switch channels. Unfortunately, ns-2 currently has only limited support for advanced testing of software defined radio and 3G/4G concepts. More robust extensions to support this type of research may, in the future, be incorporated into ns-2 or another simulator package.

The scenario used to evaluate the PREDATOR protocol is a $500mx500m$ square grid with 100 nodes. The nodes are all arranged in pairs within $200m$ from each other. The pairs are placed randomly and are at random angles to each other. The nodes can hear and be heard by other nodes within a $250m$ radius. Each pair of nodes is randomly selected to start out on one of the three available channels. The channels are assumed to be non-interfering. Each pair participated once in a PREDATOR negotation cycle, at a random time during the first 50 seconds of the simulation. Each pair of nodes runs both a CBR source at 448 Kbps. The 802.11 operating speed is set to 1 Mbps.

The negotiations in this scenario took place very similar to the simple scenario described in Section III-B. The nodes gather a RAV vector of channel usage that is within their sensing range. The data in the RAV is represented in a simplified manner. There are three elements in the vector, one for each of the available channels, indicating how many nodes it can hear transmitting within the specified range of 250 meters. To pick a new channel, the nodes simply add together these usage vectors, and choose the channel with the lowest usage. In future implementations, this selection mechanism may be replaced by more sophisticated processes, and may involve engaging in recursive negotiations to achieve a better overall channel allocation.

Using an identical scenario with regard to node placement and channel allocation, the simulation is run with and without using the PREDATOR protocol. The simulation time is $100s$, but in the experiments, the first 5 seconds are ommitted to allow the network time to calm down from the initial ARP traffic. Finally, collisions and packet throughput over time are extracted from the log files.

The scenario used is shown in Figure 2. This was produced by the Network Animator (NAM) extension to ns-2.

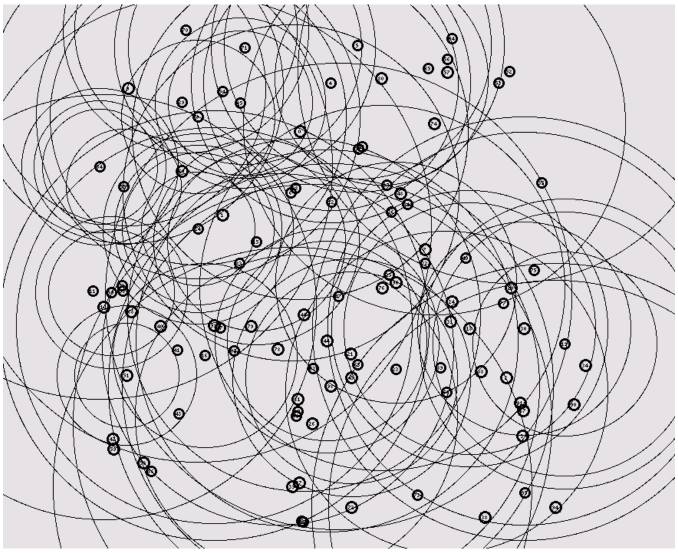

Fig. 2. 100 nodes with CBR and PREDATOR connections.

B. *Simulation results*

The number of collisions and throughput have been shown with and without PREDATOR protocol with respect to time in Figures 3 and 4 respectively. It is observed that there is a decrease in collisions and increase in the throughput in the early stages of the simulation experiment with PREDATOR protocol.

In a situation with even a moderate rate of traffic, the PREDATOR protocol managed to provide reduced collisions and increased throughput. In terms of applying to a real situation, the protocol may act even more favorably. Increased data rates may lead to more interference, which would be better handled by the PREDATOR protocol. The initial channel allocations were made from a uniform random distribution. If for instance, this were a collection of Wi-Fi base stations and cards, the channel allocation would likely be heavily weighted toward whatever comes as the default channel. Finally, in more sophisticated scenarios, the nodes may be able to make additional choices to reduce interference, such as changing modulation schemes and MAC layers. For instance, the reduced interference negotiation by the PREDATOR protocol may have allowed the nodes to turn off their `RTS-CTS` mechanisms for increased throughput.

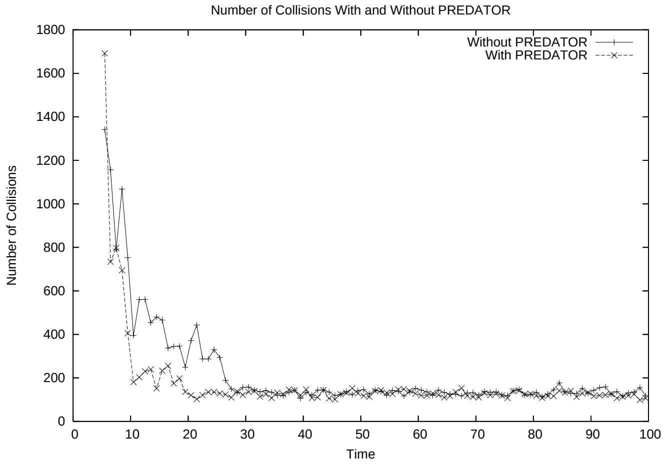

Fig. 3. Number of collisions over time with and without PREDATOR.

V. CONCLUSIONS AND FUTURE WORK

The PREDATOR protocol, in the preliminary results available, has shown itself able to both perform negotiations and to some degree, reduce interference between peer nodes. The future work include the need for the simulation tools to be greatly enhanced to allow realistic evaluation of agile switching of operational parameters. Perhaps a current SDR device should be modeled and validated to provide the opportunity for actual test runs. When more sophisticated simulation tools are available for SDR research, we can then evaluate more of the protocol's effectiveness including situations for changing transmission power, modulation schemes, MAC layers, and so on. Finally, the PREDATOR protocol needs a more sophisticated base than standard IEEE 802.11, in order to facilitate operation across a wide area of the spectrum.

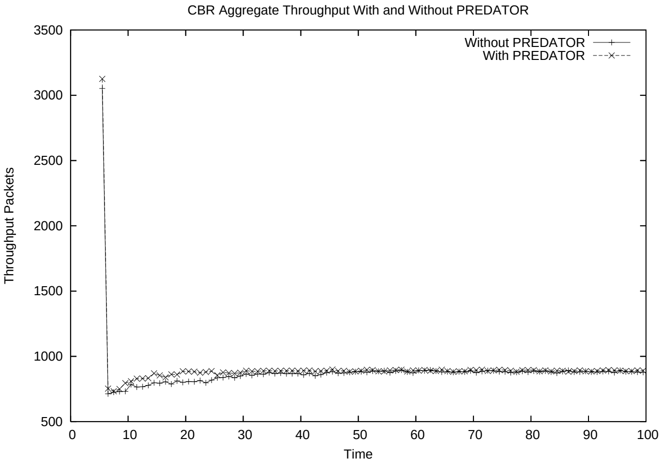

Fig. 4. Aggregate packets throughput over time with and without PREDATOR.

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