Software-Defined Dynamic Power-Control and Directional-Reuse Protocol for TDMA Radios.

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Abstract — this paper presents a distributed protocol that supports power control and directional spectrum reuse for TDMA-based MANET waveforms. This protocol was developed as an add-on module to a distributed resources manager designed to provide MANET nodes with neighborhood spectrum utilization information, as well as perform dynamic negotiation of the available shared spectrum. The protocol utilizes spectrum awareness messaging that is defined per each channel and per TDMA slot. This protocol allows each node to allocate resources (channel and slot) based on demand without interfering with existing users of that channel and slot while maximally reusing spectrum resources. The proposed protocol also identifies and reacts to conflicts resulting when two disparate networks join as a result of mobility. This paper presents simulation results showing the gain in network throughput obtained in comparison to standard omni-directional antennas using an OPNET model of a tactically relevant military waveform.

Keywords—Cognitive radios, power control, directional antennas, MANET, distributed network agents, spectrum reuse.

I. INTRODUCTION

Power control and directional antennas have been shown to increase spectrum reuse leading to increased throughput of MANETs as well as reducing their electromagnetic footprint leading to increased resilience to jamming and eavesdropping [1]. With the high mobility of MANET nodes and the dynamic traffic demand, the implementation of spectrum reuse and power control techniques becomes challenging. There are many angles one needs to consider in order to develop a comprehensive solution for power control and frequency reuse. Reference [2] discusses capacity improvement with directional antennas and multiple channels, References [3] and [4] focus on the use of more realistic antennas to quantify capacity improvements. Reference [5] focused on channel access and scheduling for directional MANET emphasizing the use of two-hop neighborhood information to avoid hidden and exposed terminals. In this work, we built a heuristic communications protocol for directional reuse incorporating knowledge from the above references and others. This communications protocol was simulated in networks as large as 16 nodes and tested with a small network of 4 real military radios. This protocol gives the tactical MANET node the real-time information needed to decide if a TDMA slot can be directionally used or not.

With standard TDMA tactical radios utilizing omnidirectional antennas, techniques exist that disallow reuse of any slots that are known to be in use [6]. In most cases, slot usage information of nodes two hops away is needed to prevent interference. That is, any node within 2-hop range of any transmitter will avoid using those slots regardless of the actual location of the transmitter and receiver that are using the slots. References such as [5] emphasized the need for use of two-hop neighborhood information with directional TDMA and our implementation considers the increase of control traffic associated with propagating neighborhood information. We relied on the presence of a control plane, over which the slot usage information is proactively shared with neighbors. The control plane is also used to negotiate for available slots with a destination traffic demand to a neighbor increases. In this neighborhood usage information, we incorporated in the neighborhood usage information parameters to detect conflicts (e.g., transmitter location, antenna gain profile, transmitter power level, location, destination node) per each slot.

Our distributed protocol utilizes directional information in order to allow reuse of the slots based on the directional transmit/receive capability and using an interference level below which message decoding is feasible. At the same time, dynamic power control is utilized to increase the possibility for slot reuse. Also considered is the prioritization information such as the Type of Service (TOS) marking associated with the data of each utilized slot to allow for pre-emption of low precedence flow to accommodate high precedence flow.

The presented protocol characteristics is summarized as:

a) Transmitting power levels are based on the receiving node locations as well as the TOS marking of the transmitted flow. All packets with the same TOS marking and same next-hop are bundled into a single flow. Spectrum awareness decisions take into consideration TOS marking such that each flow can have its own power level.

b) The protocol advertises the antenna type used so that other nodes know the gain pattern associated with the antenna. It is assumed that radios in the same MANET can use different types of antennas.

1 A flow is defined as a give source, destination, and TOS value tuple.
The protocol utilizes Terrestrial Geolocation Protocol (TGP) for nodes to continuously register position updates with all nodes in the neighborhood. This allows any new potential transmitting node to know the position of its intended destination prior to having a flow with that node, and to have interference calculations per flow per node ready at all times.

Spectrum Awareness (SA) messaging is used and includes directional information from TGP as well as power level and antenna type. These SA records are kept in an SA message database and used to calculate existing interference and signal power levels at each node. This allows spectrum reuse as long as the interference created by the new flow does not interfere with the existing transmitting or receiving nodes’ abilities to decode their intended messages.

Power associated with a flow is scaled down to the level needed to reach the receiving node, based on the mathematical antenna model plus some margin to allow for interference.

Preemption of a used TDMA slot carrying lower priority traffic is allowed to make room for higher priority traffic.

This protocol has been implemented as a software module capable of being utilized on existing military radios as well as an OPNET model. The existing implementation of the protocol relies on a distributed network agent described in [7] which is used to disseminate information between MANET nodes in the same subnet in order to disseminate the spectrum awareness information needed to implement this protocol.

II. PROTOCOL CONSIDERATIONS AND DEFINITIONS

At a high level, the problem being addressed may seem simple: A sending node is trying to determine if it can use a certain slot to communicate with a receiving node without interfering with existing communications in the network. Technically, this is a heuristic search problem that may have many approaches to solve it. In order to solve this problem per each slot and per each destination that node trying to be reached, the protocol considers the following:

1- Each distributed agent builds two neighborhood node tables specifying the hop count associated with each remote node. The first table pertains to position (latitude, longitude, and altitude) and the second table tracks all slots being use by each transmit or receive channel in the neighborhood.

2- A quantifiable pattern for each antenna type is defined. The implementation allows using different antenna models for different nodes. One simple approach is to use a cone with set of threshold powers for which the transmitter would interfere with another signal. In order to make this cone model more accurate, a small diameter circle is overlaid to define side and back lobes of the antenna.

3- Antenna characteristics for receiving can differ from antenna characteristics for transmitting.

4- Each node generates its own local coordinate system that determines the position and orientation of each node in the neighborhood. Given the antenna model used, the node can calculate if an antennas directed spectrum emission would interfere with emissions from other nodes, and hence can determine if a slot on a given frequency is available or not.

5- There are some complicated scenarios. Consider when node “a” wants to transmit to node “b”, but node (“b”) lies in the area of coverage from node “c”. The slot used by node “c” would be excluded for the omni-directional case. However, because both transmitting and receiving is directional in this case, slot reuse is possible as demonstrated in Figure 1. The protocol makes the decision to use a slot based on the estimated interference level at the receiving sector. Reference [8] explains how the angles and locations of the transmitters and receivers are considered when deciding wheather a slot is free or not. A slot is unusable for a new transmission if the topology is such that an existing scheduled receiver is the line of the new transmission. In our solution, the received-power-level of all transmitters on the same slots are added together at all existing receivers, using angles, transmit power level, and antenna characteristics to calculate the residual received power. If our proposed new transmission would result in an interference level that is still acceptable at those existing receivers (e.g. the existing scheduled messages should still be decodable at the intended endpoints), then this slot is considered available for reuse. The consideration of power level is a key differentiator of the presented work. The knowledge of transmitted power levels of all other transmitting nodes scheduled on this slot, their direction of transmission and antenna gain patterns, and the location of their intended recipient with respect to our new transmission allows us to potentially reuse slots that would otherwise be unused, especially when coupled with power control (which reduces our interference radius). This is the novelty in our design.

6- Orientation calculation differs based on where on earth nodes are located. In the implementation “North” is referenced at the equator, north pointing is not parallel. This difference is taken into consideration the algorithms orientation calculation.

7- Transforming geo-coordinates into local tangent coordinate systems can be challenging specially for airborne nodes at high latitude. The current protocol accounts for this as well as for the polar singularity.
Contrary to omni-directional cases, slots can’t be aggregated per channel. In the implementation the bandwidth associated with allocated slots per sector and frequency is referenced as a socket. Sockets are dynamically allocated per flow on demand and deallocated when there is no longer required. Defining a socket per frequency, sector and flow is needed since each socket may have different characteristics and different sectors can be assigned different powers. The implementation uses slot lists which are broken up per socket. Conveying this information to neighboring nodes can potentially result in lengthy message updates, but is needed to fully maximize frequency reuse.

Neighborhoods are decided for the local node using both distance and the set of nodes meeting the limit for hop count. The hop count limit is adjustable in the protocol. The protocol is also open to defining the neighborhood based on distance alone, where the distance is the largest interference range possible.

### III. SLOT INTERFERENCE CALCULATION ALGORITHM

The current implementation of this protocol relies on the existence of a distributed network agent described in [7] and referred to as the Organizational and Control Proxy (OCP). OCP is used to disseminate spectrum awareness information to allow channel reuse beyond the two-hop interference range of any active transmitter. A prior algorithm used with this system was simple de-confliction with incumbent transmitters. This previous algorithm used a simple scan to ensure that no nodes within an interference distance are using the slots. This simple algorithm is sub-optimal from a reuse perspective, as it does not take gain and interference rejection characteristics of the directional antennas into consideration. By expanding the interference calculation to include not only distance, but also transmit direction and antenna profile characteristics (beam width and gain pattern), the protocol is able to reuse slots more frequently, even within what would have been considered an interference radius in the omni-directional case. This reuse results in additional gain in the overall network capacity. Figure 2 shows the steps that algorithm goes through when determining the transmit availability of a proposed transmit slot.

If there are no incumbent transmissions on a slot, the slot is marked as available. If there are incumbent transmitters using the slot, then the cumulative interference power at the proposed receive node (based on all incumbent transmitter locations, antenna patterns, and incumbent flow directionality) is compared to the threshold at which the proposed link could maintain closure. If the total incumbent transmit interference is less than the threshold, the slots are potentially available. Next, the algorithm compares the proposed transmission’s potential interference at each of the incumbent receivers, to verify whether the new transmission would break an existing transmission. Again, transmit direction and antenna profiles are considered when determining the interference level. If the proposed transmit would not preclude any incumbent receivers from maintaining link closure, the slot is considered available.

![Proposed Slot Interference Calculations](image)

### IV. ANTENNA DIRECTIONAL MODEL

The slot interference model presented in the previous section relies on the antenna directional model described here to decide if a slot can be reused. Using this calculation, the total received interference power at a receiving node \( I \) is estimated as the sum of the powers received from each transmitter. Conservatively assuming the free space path loss model, the following formula is used:
\[ P_j = \sum_{j=0}^{N} P_j G_R(\delta_R) G_T(\delta_T) a^2 / R^2 \]

Where:
- \( P_j \) is transmit power
- \( G_R \) is receiver antenna gain
- \( \delta_R \) is the absolute value of the difference between the pointing angle of the receive antenna and the bearing to the transmit node.
- \( G_T \) is transmitter antenna gain
- \( \delta_T \) is the absolute value of the difference between the pointing angle of the transmit antenna and the bearing to the receive node.
- \( R \) is distance between receiver and transmitter
- \( \alpha \) is \((C/4\pi f)^2\)

Based on the antenna characteristics and the geographic location of nodes in the neighborhood, the total received interference power at the local node is calculated. It is then determined that the nodes reception is impacted if the total interference power exceeds a defined threshold value.

Figure 3 shows how “north” is used as a reference and how the angles are related.

In figure 3:
- \( \gamma \) is the antenna pointing direction, relative to north
- \( \beta \) is the bearing of the other node, relative to north
- \( \delta \) is the angle between the pointing direction and the targeted node

Note in Figure 3 that \( \beta \) of either node is equal to \( 180^\circ + \beta \) of the other node, which allows both \( \delta \) angles to be determined at either end. Also, the transmit power, antenna type, pointing angle, and location of the other nodes in the neighborhood must all be advertised.

Although the calculation can be done by either the transmitting or the receiving node, in the implementation the receiving node computes and advertises its current interference power. This is done using the same field in the message that the transmitter uses for advertising its transmit power. This allows a prospective transmitter to quickly do the required calculations.

Also note that any node proposed to become a receiver must compute its interference power for all transmitters in its neighborhood. This can be done on demand, or nodes not currently receiving can maintain their interference power to save time when a new socket is proposed.

This approach involves more computation than simply checking whether a node is in a simple cone area, however, is able to handle all cases (i.e., directional, omni-directional, and a mix of directional and omni-directional simultaneous transmission). To be viable, the protocol only requires a reasonable model of the antenna gain pattern.

In computing the antenna gain pattern, the following three models have been considered [9].

1. The modified Gaussian model using the function:
   \[ G(\delta) = a * e^{-(\delta^2 + \gamma^2) / c} \]
   Where \( a \) is the maximum gain, \( \gamma \) widens the maximum band, and \( c \) controls the width.

2. The Lorentzian model using the function:
   \[ G(\delta) = a * d / ((\delta - 2)^2 + d) \]
   Where \( a \) is the maximum gain, \( \gamma \) widens the maximum band, and \( d \) controls the width.

3. Finally to shape corners, the “modified Lorentzian” model using the function:
   \[ G(\delta) = a * d / ((\delta - 2)^4 + d) \]
   Where \( a \) is the maximum gain, \( \gamma \) widens the maximum band, and \( d \) controls the width.

Note that in all cases, it is implied that the gain is equal to \( a \) when \( \delta \) is less than or equal to \( \gamma \).
Of these models, the Gaussian model gives the poorest fit and is also computationally expensive. The Lorentzian model provides an acceptable fit, in that the actual measured gain patterns are fully enclosed. The current implementation uses the regular Lorentzian second order model.

Note that these patterns are symmetric about the pointing angle, so only 0 - 180° are shown.

### V. SIMULATION RESULTS

To test this protocol an OPNET model of a known tactical directional TDMA waveform was used to create the 16 node grid scenario shown in Figure 4. This model was used to evaluate the use of the directional antenna and power control protocol.

The two curves in Figures 5-a and 5-b summarize the gain obtained from the simulation model. The first case uses the radios omni-directional model and the results are depicted in Figure 5-a and the second case uses the described technique and the results are depicted in Figure 5-b. In both curves, the x axis is the simulation time and the y axes is the aggregate measured subnet throughput in bps (aggregate for all 12 nodes in the scenario. One can see a much higher aggregate throughput is achieved using the proposed technique (almost 4 folds). Note that with both cases, the traffic demand was increased gradually and thus the lagging in reaching the full network throughput in Figure 5-b is due to the gradual increase in traffic demand and should not be attributed to the algorithm needing time to reach a steady state (convergence of routes). The proposed approach is based on existing routes that are created with the omni-directional TDMA case. In other words, when an omni-directional link is closed based on certain slot allocations and a route is established, the system resorts to the directional case with power control to close the exact same link established with omni-directionality. As such, route conversion time is not affected while the aggregate throughput of the network is greatly increased as more spectrum is made available at each node.

![Figure 4: OPNET scenario](image)

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![Figure 5-a: Subnet throughput leveled around 13Mbps with Omni-directional antenna](image)

![Figure 5-a: Subnet throughput leveled around 13Mbps with Omni-directional antenna](image)

![Figure 5-b: Subnet throughput leveled around 50Mbps with directional and power controlled antenna](image)

![Figure 5-b: Subnet throughput leveled around 50Mbps with directional and power controlled antenna](image)
VI. Summary

This paper presented a heuristic software defined protocol for the dynamic reuse of TDMA slots in a network with directional antennas and power control capabilities. This protocol relies on estimating the interference power for each prospective slot used at each node to dynamically determine the slot allocations in real-time as network traffic demand requires.

By calculating the interference power and antenna patterns, the protocol is able to greatly increase the aggregate throughput of the network while also reducing the electromagnetic footprint. This reduction in footprint increases the networks resilience to jamming and eavesdropping. In simulation the protocol has shown a significant increase in frequency reuse over standard network wide and two hop count frequency exclusion methods.

The paper also discussed the protocol considerations and antenna directionality models used. The protocol described has been implemented as a software module within OPNET as well as existing military radios.

Future investigation plans include tying Low Probability of Intercept / Low Probability of detection (LPI/LPD) into this dynamic spectrum reuse implementation. It is anticipated that LPI/LPD may require recalculation of new routes to avoid certain routes, which may increase route conversion times.

References


