Spatial Reuse and Interference-Aware Slot Scheduling in a Distributed TDMA MANET System

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Abstract— **One of the goals pursued by this work is to gain a better understanding of the conditions for which spatial reuse in distributed TDMA ad-hoc networks is possible. Such understanding becomes particularly important when considering modern ad hoc networking. With the emergence of software programmable radios that support multiple modes of operations, the effects incurred by operating in low vs high spectral-efficiency mode should be well understood and ideally addressed by the protocol layers if system efficiency is to be preserved. A distributed TDMA system presented in [1] is re-visited to make use of an extended interference model. The extended interference model combines the graph-based interference model with the SINR-based interference model. A description of the cross-layering communication developed between the MAC and the PHY layers to support the model is given. The performance of the TDMA system is evaluated in simulation for both, the graph-based model and the extended model. The effect of the propagation environment (path loss exponent) and of the modulation requirement on spatial slot reuse is studied. Results show that network performance of the graph-based model rapidly degrades as the spectral-efficiency mode increases. The impact is even greater with decreasing values of the path loss exponent. In comparison, the extended model produces good performance results in all operating conditions.**

Keywords- spatial reuse, interference, slot scheduling, distributed TDMA Ad Hoc Network.

I. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) have a continued growth in bandwidth demand mainly driven by the introduction of new user services and applications. A solution to providing increased capacity of wireless systems is to operate over wider bands so that more information can be sent. But because spectrum resources are limited and its usage restricted, this solution is not always possible and certainly not sustainable in the long term. An alternative approach in delivering increased capacity has been the development of high spectral-efficiency radios. High spectral-efficiency radios make use of advanced modulation techniques to transmit a higher capacity of bearer data without increasing the assigned channel bandwidth. The approach, however, is not without tradeoffs. The most important one being range. Operations at high spectral-efficiency modes will invariably reduce the achievable communication range. A strategy to compensate for the loss of range is to employ multi-hop network relaying. This approach of sacrificing range to the benefit of capacity (transmitting at high spectral-efficiency modes) while relying on relays to extend the coverage seems to be establishing in MANETs. This is the case in military tactical networks, for example, where there is an increasing need for more bandwidth to support the explosion of IP-centric operations and where multi-hop relay capability is very desirable to connect nodes that are temporarily out of range under terrain impediments or node movements.

In the past two decades, many protocols that address multi-hop capabilities in MANETs have been proposed. Amongst them, TDMA-based protocols have received much attention mainly because of their ability to provide QoS guarantees. An interesting characteristic of TDMA-based media access control (MAC) protocols is their potential for achieving higher network capacity through spatial reuse of the time slots [2]. Spatial reuse allows geographically separated nodes to schedule concurrent transmissions. The challenge of spatial reuse lies with the capability of generating an efficient scheduling algorithm that takes interference into account to prevent unnecessary message losses. Hence, an accurate modeling of interference is fundamental.

A large majority of the slot schedule designs (and thus of the slot reuse schemes) described in the literature have assumed a simple disk signal coverage model also known as the graph-based interference model [3-7]. In the recent years, the poor validity of the graph-based interference model and its unrealistic propagation representation has received much attention [8-14]. In all of those works, a more accurate physical interference model that uses the signal-to-interference-and-noise ratio (SINR) to describe the aggregate interference in the network is instead proposed. A comparison between the two interference models and their impact on network performance is presented in [8]. The simulation results show that in some cases, graph-based scheduling performance suffers when compared to interference-based scheduling. The study, however, does not consider various propagation models. The performance evaluations are presented for a specific path loss exponent value and for fixed communication and interference thresholds only. In [11-14], heuristic algorithms that build TDMA link schedules by taking into account the more accurate physical interference model are proposed. Most, if not all, lack presenting their work within the context of an actual protocol (i.e., as an integrated component). This leaves open important aspects of ad hoc networking such as

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information distribution and conflict resolution. The problem is then formulated under simplified and/or unrealistic assumptions that undermine the practical relevance of the work.

In this paper, spatial reuse for distributed TDMA-based ad hoc networks is investigated. Several papers that consider both interference models present their work assuming a particular communication model in which the propagation parameters (e.g., radio power, SNR, path loss exponent) are set to the specific environment under study. Different from those, we take a generic approach to the characterization of spatial reuse. Our characterization tries to establish the conditions of operation for which a given interference model is valid. This is achieved by defining the set of parameters that have the greater impact on the interference models. Once identified, the conditions under which spatial reuse is deemed possible are derived for each model.

Based on the results obtained from the spatial reuse characterization, we present an extended interference model that combines the graph-based model with the SINR-based model. We validate the approach by integrating the proposed extended model into an actual prototype implementation of a TDMA-based MAC protocol [1]. An overview of the MAC-PHY cross layering approach used in support of the integration is provided along with the enhancements made to the distributed dynamic slot scheduling scheme. Using network simulation, we evaluate the performance of the TDMA system for various conditions of operation. In particular, we study the effects of operating the radios in low vs high spectral-efficiency modes. We also verify the impact of varying the path loss model. Performance results are presented for both the original protocol design (which was based on the graph interference model only) and the re-visited design (which is now based on the combined interference model).

II. NETWORK CONNECTIVITY MODELS

A. The Graph-based Interference Model

Most scheduling algorithms proposed for distributed TDMA-based multi-hop networks use a simplified binary propagation model. This model assumes a radio transmission range that stops at a finite border i.e., it assumes no or negligible residual energy beyond that border. Direct node-to-node connectivity (1-hop neighborhood) is possible for all nodes located inside a transmitterôs disk coverage.

In the graph model (such as shown in Figure 1), the interference from direct neighbors of a receiver is considered while cumulative interferences from nodes beyond 1-hop from the receiver are ignored.

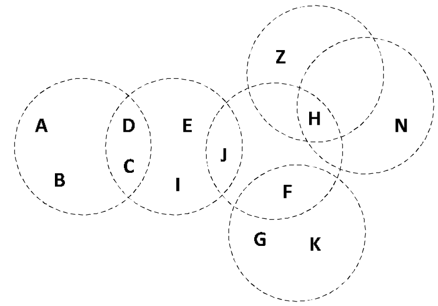

Figure 1: Simple disk-based network connectivity model

The MAC protocols elaborated under this model will typically try to maintain collision-free slot allocations by respecting the following conditions:

When traffic is intended for all neighbors (typically referred to as node scheduling), a communication from node I to all 1-hop neighbors is successful if no other node within node Iôs 2-hop neighborhood (in this case, nodes A, B, C, D,E, F, H and J) is transmitting in the same time slot as transmitter node I.

When traffic is intended for an individual neighbor (typically referred to as link scheduling), a communication from node J to receiver node I is successful if:

- Receiver node I and its 1-hop neighbors (in this case, nodes C, D and E) are not transmitting in the same time slot as transmitter node J;
- node Jôs neighbors (in this case, nodes C, D, E, F, H and I) are not receiving in the same time slot as transmitter node J.

Based on the above, a slot reuse schedule can be obtained for nodes that are geographically separated. For example, slot reuse for node-scheduled transmissions will be possible when transmitter nodes are separated by a distance of at least 3 hops. Similarly, slot reuse for link-scheduled transmissions will be possible between 1-hop transmitter nodes if their respective intended receivers are at least 3-hops apart. Such spatial slot reuse scheduling has been used by many distributed multi-hop TDMA MAC protocols to increase the capacity of the network and maximize the throughput [3, 5]. The drawback of this network connectivity representation is the over-simplification of the radio model by assuming that the signal of a transmitter node has no or negligible interference effect beyond a fixed propagation radius/range. This assumption may be valid under some specific conditions, as will be discussed further, but in many cases, this unrealistic representation of the propagation model may seriously impact the slot reuse scheme (and thus the overall capacity of the network).

B. The Physical Interference Model

An alternative and more accurate approach for achieving efficient spatial slot reuse is to consider the full interference environment i.e., to include in the connectivity model the

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contributions of all received signals, namely the ones that are too weak to provide reliable communication but yet, can still cause a non-negligible interference. This model is known as the physical interference model [8, 9]. The physical interference model is based on signal propagation properties and the distance between the nodes. The SINR is used as a measure of the perceived network interference at a receiver node. A transmission is successfully received if the SINR at the receiver is higher than a given threshold.

To establish the conditions under which spatial reuse will be possible in the SINR interference model, we derive the minimal distance separation that must be respected between the main transmitter node and an interfering node (simultaneous tx) as a function of SINR values at the receiver. Figure 2 illustrates a possible node-scheduled slot reuse scenario valid under the graph-based interference model (since the transmitting nodes T and I are separated by a 3-hop distance).

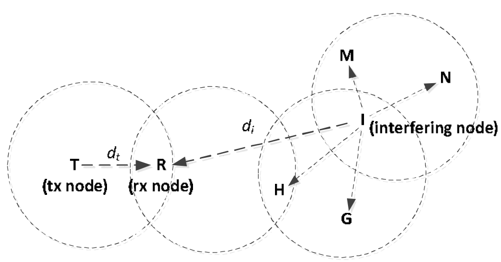

Figure 2: Interfering node scenario

Letôs assume that a signal transmission is going from a transmitting source node T to a receiver node R. The source node T is located at a distance d_t of the receiver node R. At the same time, an interfering node I located at a distance d_i from the receiver node R starts another transmission (intended for its own neighbors nodes G, H, M and N). Let P_t denote the power of the signal from the transmitter node T. In the absence of interference, it is generally accepted that the received power of a signal at the receiver is obtained as the ratio of the transmit power to the path loss. The path loss models the signal attenuation over the distance. Path loss is caused by the dissipation of power radiated by the transmitter as well as the effects of the channel propagation. The complexity of signal propagation makes it difficult to obtain a single model that characterizes path loss accurately across a range of different environments. We choose to use a simple model that captures the essence of signal propagation without resorting to complicated path loss models which are, in the end, only approximations of the real channel. Possible channel impediments such as multipath fading and shadowing effects are ignored. The formulation is derived based on the classical model for radio signal propagation in wireless networks. According to [15], the received power is modeled as:

$$P_r = P_t \left[\frac{\sqrt{G\lambda}}{4\pi d} \right]^{\alpha} \tag{1}$$

where P_r is the received power, P_t is the transmitted power, G is the gain of Tx and Rx antennas, ɚ is the wave length, d is the distance between the transmitter and the receiver and Ŭ is the path loss exponent. A path loss value Ŭ = 2 corresponds to the open space environment. The open space environment models an ideal environment for signal propagation. To account for attenuation due to ground or terrain effects, a path loss exponent value greater than 2 is generally used (typically 2 < Ŭ < 4). The higher the path loss exponent value, the greater the signal attenuation will be relative to the distance.

The SINR at receiver node R is defined as follows:

$$SINR = \frac{P_r}{P_i + N} \tag{2}$$

where P_r denotes the received power of the signal from the transmitter node T, P_i denotes the received power of the signal from the interfering node I and N represents the ambient noise at the receiver. Ignoring noise (since noise background is expected to be much lower than the interference signal) and combining (1) and (2), equation (3) is obtained:

$$SIR = \frac{P_t \left[\frac{\sqrt{G\lambda}}{4\pi d_t} \right]^{\alpha}}{P_i \left[\frac{\sqrt{G\lambda}}{4\pi d_i} \right]^{\alpha}} \tag{3}$$

We assume a homogenous ad hoc network where all nodes transmit at the same power (thus $P_t = P_i$) and at the same frequency. The successful reception of the signal sent by the transmitting node T depends on the *SIR* at node R. The signal is assumed to be valid (successful reception) if the *SIR* is above a certain threshold. After reduction, formula (3) becomes:

$$SIR = \left(\frac{d_i}{d_t} \right)^{\alpha} \quad Ó \; SIR_{threshold} \tag{4}$$

The relation of the interference range to the transmission range can thus be expressed as follows:

$$\frac{d_i}{d_t} \geq \left(\sqrt[\alpha]{SIR_{threshold}} \right) \tag{5}$$

Equation (5) was derived based on the linear path loss model. A more common way of expressing the measured

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SIR is using a dB value. Equation(5) with the *SIR* value expressed in dB becomes:

$$\frac{d_i}{d_t} \geq \left(\sqrt[\alpha]{10^{SIR_{threshold(dB)}/10}} \right) \qquad (6)$$

Equation (6) shows that for the reception to be successful, a minimum relative distance separation between simultaneous transmitting nodes must be met. This relative distance value depends on the desired SIR threshold and the particular path loss exponent of the propagation environment. The conditions for spatial reuse are thus determined by the relationship of the interference range (distance of the interfering source to the receiver node) to the transmission range (distance of the transmitting source to the receiver node). The minimum ratio requirement and thus spatial reuse conditions can be plotted for various values of $SIR_{threshold}$ and path loss exponents. Figure 3 shows the result for 4 $SIR_{threshold}$ values and 5 path loss exponent values.

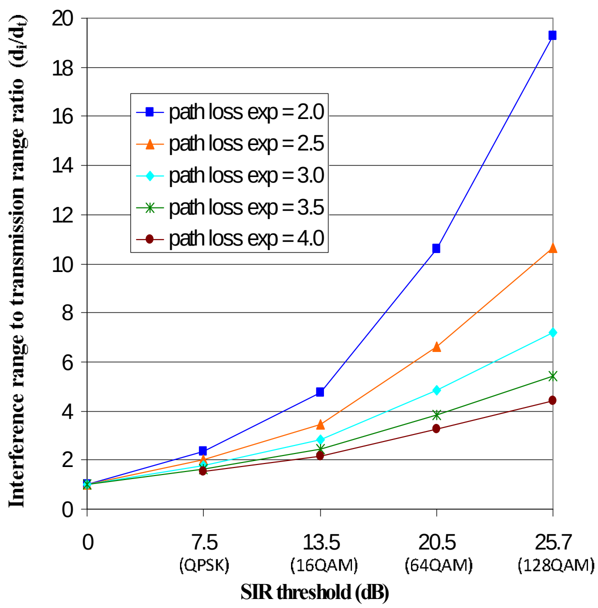

Figure 3: Min. relative distance separation vs SIR thresholds

To illustrate, the $SIR_{threshold}$ values selected for representation on the graph correspond to Signal-to-Noise (SNR) threshold values of an actual tactical VHF/UHF OFDM-based modem [1] operating at various modes over a 200 kHz bandwidth. For each mode of operation, the SNR threshold value corresponding to a Bit Error Rate (BER) of 10^{-6} was selected. A BER value of 10^{-6} is generally considered acceptable to obtain the full rate at the mode of operation. The SNR threshold values represented on the graph correspond respectively to coded modem rates of 195 kbps (QPSK), 390 kbps (16QAM), 653 kbps (64QAM) and 913 kbps (128QAM).

Figure 3 shows an interference to transmission range ratio which increases along with spectral efficiency. This relation implies that nodes transmitting with lower spectral efficiency are likely to achieve greater spatial slot reuse (since the minimum geographical relative distance requirement between simultaneous transmitting nodes is less). Consequently, the increase in network capacity gained from spatial slot reuse is expected to be higher when operating at a lower rate as opposed to higher rate modes.

The minimum relative distance requirement increases even more with decreasing path loss exponent values. For example, in the free space propagation environment (where path loss exponent value = 2), a relative distance node separation greater than 10 is required when operating at a 64QAM modulation mode. This ratio decreases to an approximate value of 4 when the path loss exponent rises to a value of 3.5. This impact of the path loss exponent is significantly reduced at lower SNR values. At QPSK for example, a path loss exponent variation of 2 to 3.5 causes only a small variation (1.5 to 2.3) of the corresponding distance ratio requirement. Lower spectral-efficiency modes are thus less affected by the propagation environment than higher spectral-efficiency modes.

It should be noted that the results presented in Figure 3 were obtained assuming only one source of interference. In a typical ad hoc network, contributions are likely to come from multiple sources of interference. In such cases, the resulting aggregation of all signals at the receiver will impact the distance required for spatial reuse which will inevitably increase. Results derived from eq (6) thus constitute a best case scenario.

C. *Limitations of the Graph-based Interference Model*

We now consider the minimum relative distance requirement in the context of the graph-based interference model. As previously stated, the graph-based interference model ignores the physical reality of RF propagation. The model imposes a static spatial separation between simultaneous transmitter nodes which does not always meet the minimal distance ratio requirement necessary to produce collision-free spatial reuse schedules. To better understand the issue, a simple case scenario is illustrated in Figure 4.

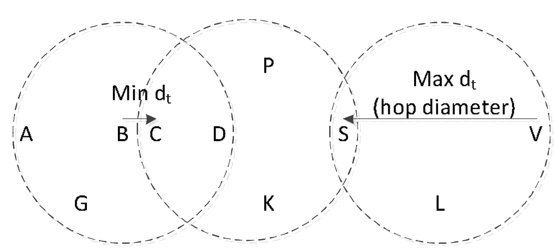

Figure 4: Relative distance separation in graph-based model

For node scheduled transmissions, the graph-based interference model imposes a spatial separation of at least 3-hops between simultaneous transmitter nodes. In Figure 4, this means that nodes A, B or G can simultaneously share slots with nodes L or V without causing any collision at C, D or S. In reality, this will be true only if the minimum relative d_i/d_t ratio is respected for the required SNR threshold value. Letôs consider the case where the d_i/d_t ratio is maximal. The d_i/d_t ratio will be at its maximum when the interference source is located as far as possible from the receiver node while the transmitter node is located as close as possible to it. In Figure 4, this takes place for example, when node B is transmitting to node C and interfering node V is transmitting to node S. The resulting ratio at node C is $(2*hop_{diameter})/\min d_t$. If the distance of the transmitter is small compared to the hop diameter, the resulting ratio value will be large enough to ensure that no collision occurs at node C (regardless of the SNR threshold value). To validate this spatial slot reuse scenario, the resulting d_i/d_t ratio must equally be measured at receiver node S. Node V is now the transmitter node while node B becomes the interfering node. The resulting ratio at node S is $(\min d_t + hop_{diameter})/ hop_{diameter}$. Keeping the assumption that $\min d_t << hop_{diameter}$, this results in a ratio of ~ 1. According to Figure 3, this low ratio value will inevitably produce a collision at receiver node S, regardless of the SNR threshold value. Thus, maximizing the ratio on one side has the effect of minimizing it on the other. This behavior seriously reduces the efficiency of the slot reuse scheme.

This simple case scenario illustrates well the limitations of the graph-based interference model. To meet the relative distance criteria, the model tends to require some sort of symmetry in the relative nodes location. This goes against the very nature of ad hoc networking. Obviously, some cases exist where the criteria will be satisfied. However, in most of those cases, the resulting d_i/d_t ratio at the receiver nodes will likely be relatively low. Based on those observations, it is reasonable to expect sub-optimal performance results from a slot reuse scheme that would strictly be based on the graph-based interference model.

Since the ratios derived in Figure 3 are relative separation distances as opposed to absolute distances, brief considerations should be made regarding the physical limitations imposed by the curvature of the earth. It is well known that the line-of-sight (LOS) communication range between two points is limited by the horizon and depends on the height of the antennas at each point. From [16], the LOS distance in kilometers can be computed as:

$$dist_{LOS} = 8.24\left(\sqrt{h}\right) \tag{7}$$

where h is the height of the antennas (assuming identical transmit and receive antennas) in meters. From (7), the maximum expected LOS distance between two nodes for antenna heights of 3m and 20m is of 14km and 37km respectively. The former corresponds to a fair estimate of the maximum LOS distances between ground-to-ground mounted vehicles while the latter is representative of ship-to-ship communications at sea. Beyond this distance the nodes cannot see each other and thus the radios cannot interfere with one another. The effect of the earthôs curvature must therefore be taken into consideration when deriving the minimum distance required for allowing slot reuse. Clearly, it can put an upper bound on the results presented in Figure 3 and in some cases, preserve the validity of the graph-based interference model.

The analysis presented in this section has shown the limitations of representing network connectivity based on the simplified disk signal coverage model. The analysis has revealed that the model can be used in support of spatial slot reuse but only under some specific conditions of operation. In particular, the model is expected to provide some throughput increase when the radios are operated in low spectral-efficient modes (because of the lower distance ratio requirement). It is also expected to perform well when the transmission range is large (in which case, the physical limitation due to the earth curvature comes into play and preserves the validity of the interference model). When operating outside of these conditions, the model starts to suffer significantly from distant node interference (border effects), affecting network performance and the ability to perform efficient slot reuse.

III. THE EXTENDED INTERFERENCE MODEL

Previous work carried out by the authors in the area of distributed TDMA ad hoc networking, has led to the design and development of an experimental prototype system called the *MATRIQS* [1]. *MATRIQS* is a distributed TDMA-based multi-hop system developed to provide enhanced tactical IP networking capabilities within battle group units. Designed to be flexible and adaptive, the *MATRIQS* system supports programmable VHF/UHF waveforms with multiple modes of operation. Various degrees of spectral-efficiency modes are offered with data rates ranging from 9600 bps (low efficiency, low bandwidth, high robustness mode) to 1.0 Mbps (high efficiency, high bandwidth, low robustness mode). Currently supported bandwidths are 25, 50, 100, 200 and 350 kHz.

The *MATRIQS* MAC developed initially and presented in [1] automatically achieved spatial slot reuse based on the traditional graph interference model only. When characterizing the system in various operating conditions, the limitations of the interference model and its impact on the system performance were observed. A more realistic network connectivity model was needed. The approach adopted to address the problem was to extend the graph model to include physical interference considerations. Essentially, the approach that we propose is a combination of the two interference models. The concept is to keep the simplified disk coverage model to establish the first level of interference knowledge. Then, the more accurate physical (SINR) interference model is applied to the slots that are identified as potentially available for reuse by the protocol (as an outcome of the first level). The slot scheduling/slot reuse scheme resulting from this combined two-step approach has the benefit of remaining efficient and accurate through a wide range of operating conditions while keeping the implementation complexity at an acceptable level.

Conceptually, the approach is similar to the hybrid solution presented in [17]. However the two methodologies differ greatly. The algorithm proposed in [17] uses an iterative scheme based on a fixed interference range value. The interference range is increased adaptively and new squared conflicted graphs are re-generated until an interference-free schedule is found. No distribution aspects are discussed and the algorithm implies global network connectivity knowledge. Our scheme, instead, relies on the distribution of slot information to dynamically guide the slot allocation decisions. While the reported slot information makes use of the graph-based interference model to ensure distance-2 non-conflicting node scheduling, it also includes physical interference information that ensures interference-free slot reuse scheduling. This solution not only maintains the increased capacity provided by spatial slot reuse but it also preserves the flexibility of the protocol in terms of dynamic slot allocations.

An overview of the modifications that were performed to the *MATRIQS* MAC protocol to support the extended interference model is provided next.

A. The Cross-Layering Approach

The physical interference model makes use of the SINR to evaluate the perceived network interference at a receiver node. Since this specific channel information can only be obtained by the physical layer (modem), a cross-layering communication approach was developed between the MATRIQS MAC layer and its underlying modem.

The cross-layering exchange between the two layers occurs via abstract generic interfaces that conform to Software Defined Radio (SDR) principles. The communication enables the MATRIQS protocol to derive a ñper slotò channel quality value which is used in the protocolôs slot scheduling and allocation algorithm.

The ñper slotò channel quality is expressed as a binary value. The value is either 0 or 1, where 0 indicates a ñgoodò slot with low rx interference level and 1 indicates a ñbadò slot suffering from high rx interference level. To derive this channel quality, the MAC obtains, at the end of each slot, two parameters from the modem: the rx signal power (S) and the noise + interference power (N), as measured and estimated by the modem for the slot period. The rx signal power can only be measured by the radio frequency receiver. Receivers contain an automatic gain control (AGC) device used to normalize the output signal level. The control voltage (V_G) of the amplifier is derived from the input signal level and follows a known transfer function. This signal can be supplied in digital form and be used to derive the absolute incoming signal power. The RF input signal power (S + N) is calculated as follows:

$$P_{RF} = P_D / f(V_G) \tag{8}$$

where P_{RF} is the incoming RF power (S + N), P_D is the power of the digitized signal after AGC (measured by demodulator) and $f(V_G)$ is the AGC transfer function and represents absolute gain. Since the MAC requires S and N to be separate values, the burden falls onto the demodulator to measure the noise (N) and therefore provide both S and N separately. In the event where the demodulator is unable to detect an incoming signal, it declares N = (S+N) where S = 0.

Using the rx signal power (S) value obtained from the modem, the MAC protocol maintains a run-time table of received power for each of the nodeôs 1-hop neighbors. The rx power value is averaged over a time window to smooth out the effect of possible transient conditions. The MAC then combines this information with its knowledge of slot status and ownership to compute an SINR value for each slot. The SINR value is calculated as follows: if the slot status is *rx*, the MAC first determines the slot ownership (i.e., which neighbor the slot belongs to). The MAC then extracts from the table the latest recorded rx signal power for that neighbor node and derives the SINR by using the ratio formula (S/N). If the slot is available (i.e., the slot does not belong to anyone), then no corresponding rx signal power value will be found in the table. The calculation of the SINR value cannot be performed at this point since it requires a relative comparison of a neighborôs rx signal level to the measured interference. In this particular situation, the worst-case approach is adopted. The MAC identifies from the table the node for which it has the weakest signal (lowest recorded rx signal power). The MAC then uses this value to compute the SINR for the slot.

For each slot, the channel quality is obtained by comparing the computed SINR value with the SINR threshold (typically set to correspond to a BER of 10^{-6}) for the modulation and error correction code in use. This channel quality estimate is provided by the physical layerôs demodulator. Here, the implication is that a matching good/bad signal threshold value must be pre-established and included in the programming. The channel quality for the slot is declared good if the computed SINR value is greater than the SINR threshold. It is declared bad otherwise.

The cross-layering communication enables the MATRIQS protocol to obtain and maintain a run-time per slot channel quality value that takes into considerations the full interference environment. The MATRIQS slot scheduling and allocation scheme was modified to take advantage of this channel quality information. The enhancements done to the scheme are described next.

B. The Distributed Dynamic Slot Allocation Scheme

The *MATRIQS* protocol supports a fully dynamic slot scheduling and allocation scheme [1]. The scheme is based on slot request and release. As for most distributed-based schemes, it combines two approaches: a pro-active approach and a re-active approach.

The pro-active approach makes use of the information readily available to guide decisions on selecting/requesting the slots that have the highest probability of producing error-free transmissions. The idea is to pick non-conflicting transmission allocations in the first place. Nodes request slots based on the distributed slot information they maintain. Each node reports slot ownership information at minimum once per cycle. The reported slot status information ensures that nodes request non-conflicting node-scheduled transmission allocations over a 2-hop neighborhood while taking advantage of simultaneous link-scheduled transmissions whenever possible. Spatial slot reuse based on the graph interference model is thus inherently supported by the protocol and may take place when transmitters (in the case of node-scheduling) or receivers (in the case of link-scheduling) are separated by a distance of at least 3 hops. As neighborhood slot information is collected, a node derives and maintains a set of slots it considers available for request. Essentially, this set includes all the slots that have been reported with the *available* status by the neighbors. A node selects the slots to request from that set.

The protocol also supports a re-active approach. The re-active approach offers a mean to bring corrections when problems or conflicts are detected. Conflicts may rise from sudden changes in conditions due, for example, to node mobility. The protocol implements the re-active approach by specifying a comprehensive conflict detection and resolution scheme. Actions/decisions resulting from this scheme typically translate into nodes issuing slot preemptions or objections to slot requests.

Because these design approaches were originally based on the graph interference model, the slots considered available by the protocol were often unusable due to the interference coming from remote nodes. Consequently, in many situations, decisions taken by the protocol to perform slot reuse led to an increase in the number of collisions and yielded sub-optimal performance. The channel quality information obtained from the cross-layering was included in both approaches (pro-active and re-active) to improve the slot allocation and scheduling scheme.

B.1 Extended Pro-active Approach

The pro-active approach is extended by including the channel quality value in a nodeôs periodic slot status report for slots that are advertised as *available*. To keep the overhead low, each slot status is expressed using a 3-bit code. Originally, only 2 of the 3 bits were used to indicate slots status *available*. The third bit is now used to report the slot channel quality value where a bit value of 0 indicates a ñgoodò slot (slot is considered interference-free) while a bit value of 1 indicates a ñbadò slot (a strong enough interfering signal has been detected in the slot).

This supplementary information is now used to refine the *available for request* slots set maintained by a node. The set now only includes the slots reported as *available good* by each neighbor. As a result, when making a request, a node will pro-actively select slots that are truly interference-free at that time. It is important to note that no penalty is paid in additional overhead cost. The cost lies with the increased complexity in the structure of the cross-layering solution.

B.2 Extended Re-active Approach

Because operating conditions of ad hoc networks vary over time (e.g., topology changes, propagation characteristics changes), slot schedules that were collision/interference free may suddenly not be anymore. The reactive approach is extended by considering the channel quality in the conflict resolution scheme. The parameter is integrated to guide slot preemption decisions. Originally, the slot preemption mechanism was strictly used as a means to resolve slot scheduling (ownership) conflicts. The mechanism is now also used to notify a sending node of bad slot receptions. A node will now also issue a preemption message to a neighbor for which signal reception on specific slot(s) has fallen below the SNR threshold. On reception of a preemption message, those ñbadò slots are immediately released by the transmitting node.

In the same manner, the channel quality value is now also considered within the slot approval process. Nodes now verify their latest slot channel quality values before approving or objecting to a request. This is because the interference conditions may change between the time the original slot selection is done and the time a neighbor makes its approval or objection decision. An approval is sent if no slot ownership conflict is found and the slot channel quality is good. An objection is sent otherwise.

IV. PERFORMANCE EVALUATION

To evaluate the performance of the system and to measure the impact of the enhanced scheme on slot reuse, the MATRIQS experimental system was ported into the QualNet (QN) simulation framework [18]. Most of the MATRIQS protocol stack (i.e., the MAC and link layers) was preserved during the porting process. Consequently, discrepancies between the actual system implementation and the simulated version are minimal. The QN physical abstract layer was used in place of the actual modem. It was modified to support the SINR-based interference model as well as the cross layering communication scheme.

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A. *Simulation Setup*

In section 2, it was determined that spatial reuse is mainly affected by the propagation path loss and the modulation requirement (SINR threshold). Hence, a multi-hop network topology was constructed to which we applied various combinations of path loss exponent values and modulation modes (SINR thresholds).

To be consistent with the analysis presented in section 2, the QN radio signal propagation model was set to the classical log-distance path loss model. Scenarios were run for three path loss exponent values of 2.5, 3.0 and 3.5 respectively. Those values were selected to be representative of various types of propagation environments with a degree of attenuation ranging from mild to severe. For each path loss exponent value, the impact of the modulation was evaluated by varying the SNR threshold values. The SNR thresholds were 7.5 dB, 13.5 dB and 20.5 dB each corresponding to modulation modes QPSK, 16QAM and 64QAM respectively. The channel bandwidth was 200 kHz. The operating frequency was set to 300 MHz which is representative of low band UHF tactical operations. The resulting raw channel rates were 195 kbps (QPSK), 390 kbps (16QAM) and 653 kbps (64QAM).

The network topology was composed of 20 nodes deployed using the random uniform distribution. In order to evaluate the effect of both the propagation path loss and the modulation mode on spatial reuse, it was required that the d_i/d_t ratio values remained the same in all scenarios. This meant keeping the node layout and the relative distance between the nodes the same for all scenarios. This was achieved by scaling the size of the grid and by adjusting the transmission power level accordingly. For each scenario, once fixed, the transmission power was kept uniform and configured the same for all nodes. The resulting topology had a network connectivity diameter of up to 8 hops.

The network was fully connected at all time (there was always a path between any pair of nodes). To ensure worst-case interference, the network was saturated i.e., each node always had traffic to send. The traffic was UDP/CBR and sent by the MAC protocol using the node-scheduled transmission mode.

B. *Results and Discussions*

For each scenario, the following performance metrics were collected:

- reception collision ratio (%): total number of rx collisions over the total number of rx signals (locked signals)

- successful slot usage ratio (%): total number of successful slot tx (i.e., no neighbor rx collision) over the total number of slots

- network throughput (kbps): total number of bits successfully received in the entire network over the time period.

The results are presented in Figures 5, 6 and 7 respectively. The results refer to metrics averaged over 10 runs, each initiated with a different simulation seed. The simulated time was long enough to ensure that steady-state conditions had been reached. For each simulation run, data collection began only after the network was ñupò to avoid transient effects due, for example, to initial empty neighbor tables. For comparison purposes, the performance results are presented for both, the original protocol design (which was based on the graph interference model only) and the re-visited design (which is now based on the combined interference model).

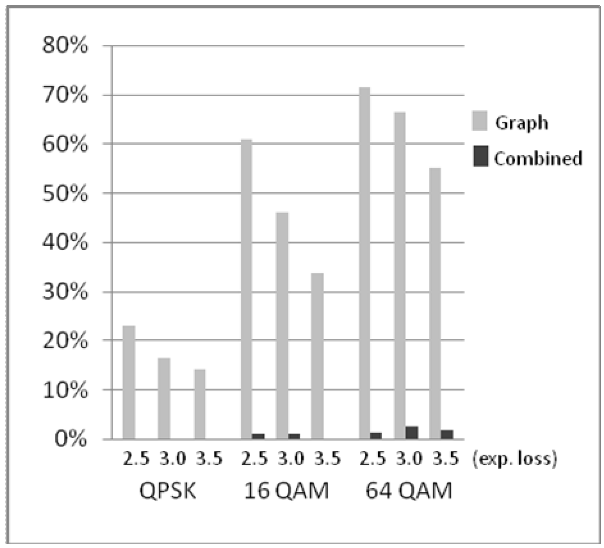

Figure 5: Rx collision ratio

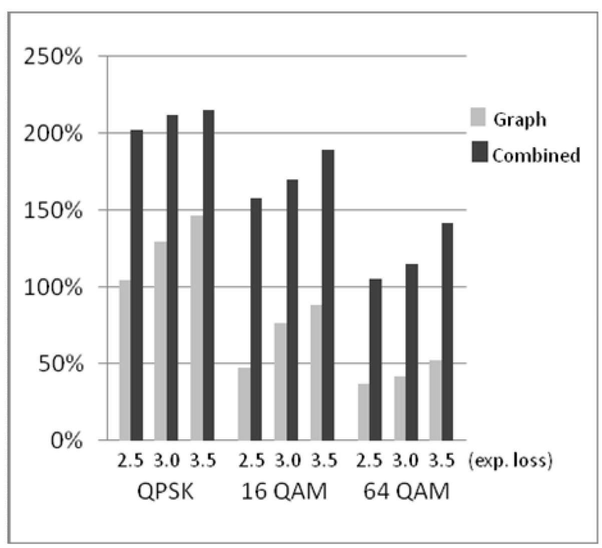

Figure 6: Successful slot usage ratio

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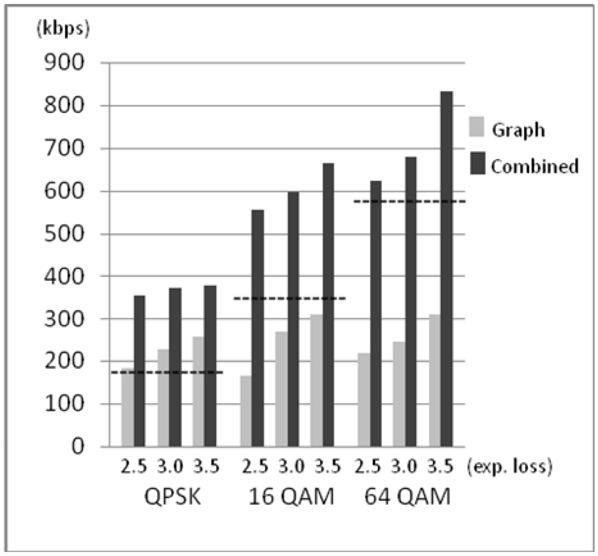

Figure 7: Network throughput

As expected, the performance results obtained with the combined interference model are better than the results obtained with the graph interference model only. A significant difference is seen with the measured reception collision ratios (Figure 5). While the protocol based on the combined interference model achieves quasi collision-free schedules, the graph-based protocol exhibits rx collision ratios between ~15% to ~70%. Figure 6 shows that the successful slot usage ratios obtained with the combined model surpass by as much as 70% to 110% the ratios measured with the graph-based model. For example, in the case of 64QAM+exp. loss 3.5, the graph-based model achieves successful transmissions in only half (50%) of the slots. In contrast, the combined model displays a successful transmission rate of 140%. In addition to achieving successful transmissions in all (100%) of the slots, an additional 40% is gained through the occurrence of simultaneous transmissions due to slot reuse (slot reuse ratios are represented by the portions in excess of 100% in Figure 6). Slot reuse translates into a direct increase in network capacity. This can be observed in Figure 7. Whenever slot reuse is present in Figure 6, Figure 7 shows corresponding network throughput values above the 100% user data capacity limit (indicated by the dotted line for each modulation mode). Thus any value in excess of the displayed thresholds represents a gain in network throughput resulting from the slot reuse scheme. Due to the success of the slot reuse scheme, the network throughput values (displayed in Figure 7) are consistently higher for the combined interference model. In some cases, a network capacity up to 3 times that of the graph-based model is obtained.

The performance results obtained for both approaches closely match the predicted behaviors of section 2. As expected, a higher ratio of spatial slot reuse and thus a greater increase in network capacity is achieved when operating at low spectral- efficiency modes (e.g., QPSK) than when operating at high spectral-efficiency modes (e.g., 64QAM). This is because the minimum distance ratio requirement is less for lower rate modes. It is thus more easily satisfied in the MANET (ref. Figure 3: min d_i/d_t = ~2 for QPSK vs min d_i/d_t values between 3 and 11 for 64QAM). It should be noted that for the graph model, slot reuse occurs in the QPSK modulation mode only. It takes place however, in all scenarios for the combined model.

While the results obtained with the combined interference model remain quite acceptable in all cases, the performance of the graph-based approach quickly degrades as the spectral- efficiency mode becomes higher. The impact is even greater with decreasing values of the path loss exponent. Clearly, as the minimum distance ratio requirement becomes greater, the graph-based model fails at meeting the criteria and its performance seriously starts to suffer. The amount of rx collisions increases drastically and the network throughput collapses as the successful slot usage ratios fall below 100%.

V. CONCLUSION

In this work, spatial reuse for distributed TDMA-based ad hoc networks is investigated. The simulation results confirm that the accuracy of the interference model is essential to fully benefit from a maximum network capacity. The simple graph-based interference model, for example, shows sub-optimal but yet acceptable performances when tested with low spectral- efficiency modes (e.g., QPSK). However, the validity of the model rapidly degrades as the spectral-efficiency mode increases. The reception collision ratio increases drastically and seriously impacts the network throughput.

The extended interference model proposed in this work clearly outperforms the simple graph-based approach. More importantly, it produces good performance results in all operating conditions. The approach requires the support of cross-layering communication between the MAC and the PHY layers but the resulting improvements are sufficient to justify the increase in complexity.

One of the goals pursued by this effort was to gain a better understanding of the conditions for which spatial reuse in distributed TDMA ad-hoc networks is possible. Such understanding becomes particularly important when considering modern ad hoc networking. With the emergence of software programmable radios that support multiple modes of operation, the effects incurred by operating in low vs high spectral-efficiency mode need to be well understood and ideally addressed by the protocol layers if system efficiency is to be maximized.

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