PERFORMANCE ANALYSIS OF POLLING MAC'S FOR EXO-ATMOSPHERIC WIRELESS SENSOR NETWORK

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ABSTRACT

In wireless sensor networks a time-variant communications channel can have adverse effects on a system's performance. Media Access Control (MAC) functionality that addresses the time-varying channel environment, in order to provide reliable data transfer within the network, is essential to ensure mission success. One such network where this becomes apparent is the "exo-atmospheric" network. The exo-atmospheric network is composed of nodes in space connected in a star topology where data transfer within the network is coordinated using a polling MAC. The outlying nodes and the center node ("access point" or "AP") may have different antenna patterns (i.e. dipole or patch), arbitrary time-variant attitudes, and different trajectories. Though the propagation loss may be R^2, the rotation of the nodes coupled with non-isotropic antenna patterns introduces a fading channel between nodes and the access point. Additionally, the network must meet certain prescribed reliability, throughput, and resource requirements. As such this paper presents a performance analysis of using two different polling MAC's for an exo-atmoshperic network. The results show the regions where proposed polling schemes – namely Channel Aware Round robin (CARR) and Channel and Congestion Aware (CCA) – will and will not successfully balance given sets of constraints for particular sets of node and network attributes (time-variant attitudes, trajectories, data rates, and antenna patterns).

INTRODUCTION

Considerable amounts of research and development have focused on improving the Quality of Service (QoS) of Wireless LANs (WLANs). The primary method discussed for improving the QoS involves managing resources, particularly the wireless channel. For example the IEEE 802.11e standard has been developed specifically to improve the QoS found in WLANs that use the 802.11 physical layer. The intended use for 802.11e is WLANs that simultaneously provide services to various applications that have inherently different QoS requirements such as Voice Over IP and streaming multimedia. 802.11e enhances the QoS of the applications it services through the use of priority based scheduling techniques - namely the Enhanced Distributed Coordination Function (Enhanced DCF) and the Hybrid Coordination Function (HCF) [1, 2]. Since the most important QoS metric is usually delay, 802.11e appropriately divides the access time of the WLAN's applications. Applications with strict QoS requirements are granted access to the wireless channel more frequently, more of the time, or both over lower priority applications.

Other proposed solutions for meeting the necessary QoS of various wireless applications is to employ mechanisms that provide interoperability (switching) between different networks [3]. Examples include Initial User Assignment (IAU) and InterSystem Handover (ISH) both of which provide switching between a WLAN and Universal Mobile Telecommunications System – High Speed Downlink Packet Access (UMTS-HSDPA) [4]. A WLAN that has access to other networks and resources, as a result of interoperability techniques, has greater bandwidth and capacity, and can hence provide better QoS to the wireless applications it services.

Clearly resource management, particularly the access to the wireless channel, is necessary for wireless network(s) to meet the QoS requirements prescribed by various wireless applications.

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APPLICATION OVERVIEW

This paper studies possible MAC layer solutions for the exo-atmospheric network. The exo-atmospheric network is composed of nodes in space that have some random trajectory away from the center node (an AP with an isotropic antenna). Additionally, the nodes have random attitudes (yaw, pitch, and roll rates) and utilize non-isotropic antennas. (Note: this situation occurs when lower-cost nodes, i.e. nodes without attitude control, are deployed instead of more complex/capable nodes. This yields a significant cost and complexity savings if the resulting network performance meets the mission requirements.) Each node generates an equal amount of equally important data that needs to be communicated to the AP. Therefore, each node has the same QoS requirement.

As discussed above, the "data generators" in a WLAN may have different QoS requirements. Hence, complex MAC protocols such as 802.11e are employed to control medium access as the means for ensuring QoS. Though, there are distinct advantages of QoS aware protocols, such as 802.11e, over non-QoS aware protocols such as 802.11. The advantages are only realized when the network must simultaneously provide service to various applications, each with possibly its own QoS requirements. The cost of implementing such QoS-aware protocols is greater complexity at the MAC layer. In contrast to WLAN behavior discussed in the previous section the exo-atmospheric application requires each node to have equal access to the channel but the channel characteristics may vary for each node-to-AP link. As such this paper considers two simpler polling MAC algorithms - namely the Channel-Aware Round Robin polling algorithm (CARR) and the Channel and Congestion Aware (CCA) polling algorithm.

As will be shown, in certain instances, the CARR algorithm suffers considerably due to fading in the communications channel. Therefore, the CCA polling algorithm is introduced to negate the effects of the nodes rolling in and out of antennas nulls. (Note: this effect is different from terrestrial fading channels.) This paper shows an approach for determining the conditions (data rates and number of nodes) for which the CARR algorithm is an adequate solution. It also shows where a more "QoS aware" algorithm such as the CCA algorithm becomes necessary.

Both polling techniques were simulated in OPNET®. The simulation attributes for each simulation set (data rate / number of nodes) were as follows:

- The antenna on the AP was isotropic.
- Each node in the network had the same antenna.
- All nodes generated the same amount of data at the same time.
- The number of retries was fixed at 6.
- The Roll, Pitch, and Yaw rates for the nodes were uniformly distributed random variables with minimum and maximum value of 0 and 180 deg/sec respectively.
- Each node's trajectory was away from the AP and was a uniformly distributed random variable with a minimum and maximum value of 0 and 10 m/sec respectively.

POLLING MAC SUMMARY

This section describes the CARR and CCA techniques studied in this paper. The CARR algorithm is simply the widely used Round robin technique with an additional channel aware parameter. For an *n*-node network, each "round" of the CARR algorithm went as follows.

- AP sent a Request For Data (RFD) to Node 1.
- If the Signal-to-Noise Ratio (SNR) between Node 1 and the AP was above some threshold (SNR Threshold) Node 1 responded either data or with a No Data Available (NDA) message.
- This process was then repeated for Nodes 2 through *n*.

The CCA MAC varied from the CARR MAC as it included a congestion parameter. It also polled each node according to a polling table that was based on node priorities. This table-based polling scheme is simply a "block" version of round robin. The AP polls a node *x* number of times and then moves to the next node in round robin fashion. After the AP had polled each node *x* number of times the AP would then re-build the polling table. The polling table was built by first assigning each node a priority between 1 and 4. Then, for priorities 1 through 4 a node was placed in the polling table 20, 10, 5, or 1 time respectively. (Note: the 20, 10, 5, 1 values were chosen based on preliminary simulation results. The results demonstrated that network performance improved only when the ratio between node priorities and the number of successive RFDs became somewhat significant, i.e. the difference between node priorities 1 and 4 was 20:1 as opposed to a lesser ratio of 4:1.) The following pseudo code shows how the priority of a node was determined.

```
if (SNR > SNR Threshold) && (Congestion > Congestion Threshold);
node –>priority = 1;
```

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else if (SNR > SNR Threshold) && (Congestion <= Congestion Threshold);
node –>priority = 2;

else if (SNR < SNR Threshold) && (Congestion > Congestion Threshold);
node –>priority = 3;

else if (SNR < SNR Threshold) && (Congestion <= Congestion Threshold);
node –>priority = 4;
```

The SNR Threshold was varied across simulation sets and the Congestion Threshold was set to 5 for all simulation sets. Initially the Congestion Threshold was also varied across simulation sets. However, changing the Congestion Threshold impacted the results minimally, because the polling frequency (rate between successive polls to a node) was always much greater than the data rate at each node. In contrast to CARR, the CCA algorithm considers whether or not a node has recently been in a null. For a “real” system the Received Signal Strength Indication (RSSI) of the previous communication between an AP and a node would be a reasonable replacement to the SNR metric. CARR and CCA are easily realizable since RSSI measurements are commonly available from radio hardware.

RADIO AND CHANNEL MODEL

Realistic channel model and radio behaviors are required to accurately quantify the performance of CARR and CCA. So, bit errors were calculated using the probability of a bit error for DPSK modulation which is:

$$P_b = \tfrac{1}{2} e^{-SNR} \qquad (1)$$

Any packet that incurred 1 or more bit-errors failed. Though stringent this assumption does address the worst-case scenario with respect to packet failures. SNR between the nodes and the AP were calculated for every transmission using the following equation.

$$SNR(dB) = P_{TX} + A_{TX} + A_{RX} - P_L - N \qquad (2)$$

Where:

- P_{TX} is the transmit power in.
- A_{TX} and A_{RX} are the antenna gains for the transmitter and receiver respectively.
- P_L is the path loss for free space and N is the noise.

Other parameters related to modeling the physical (802.11) and MAC layers were:

- Data Rate: 5.5 Mbps
- Center Frequency: 2.4 GHz
- Bandwidth: 22kHz
- Transmit Power: 1W
- Receiver Sensitivity: -90 dBm.
- Data Packet Sizes were fixed to 1,152 bytes.
- RFD and NDA packets were fixed to 14 bytes.
- Node antenna was either a ½ wavelength dipole or a patch.

PERFORMANCE METRICS

The two metrics of concern for this paper are goodput and average ending queue size. Goodput, as a percentage, was calculated as:

$$\mathrm{GP} = \left(\frac{\text{Received Data}}{\text{Data Rate} \cdot \text{Sim. Time} \cdot \text{Number of Nodes}} \right) \cdot 100\% \qquad (3)$$

The number of packets still queued at a node at the end of a simulation is a simple indication of how congested a node is and hence how well the MAC layer is or is not addressing network congestion. The average ending queue size was calculated as the sum of the number of packets left in each node queue at the end of the simulation, divided by the number of nodes in the network.

RF CHANNEL ASYMMETRY

Both CARR and CCA are channel aware algorithms since nodes consider their link quality before transmitting data. Being aware of the channel offers distinct advantages over blindly sending data after receiving an RFD from the AP, because the communications link between AP and node is asymmetric. This asymmetric channel is an artifact of the different packet sizes. An RFD from the AP to a node is 14 bytes while a data packet from a node to the AP is 1,152 bytes. Additionally, the communications channel may be time-variant because the rotating nodes have non-isotropic antenna patterns. (Note: error-correcting codes could help solve the first problem. An adaptive error-correcting code might also be another alternative for solving the “fading” problem.) Figure 1 depicts the error rate associated with the data and RFD packets.

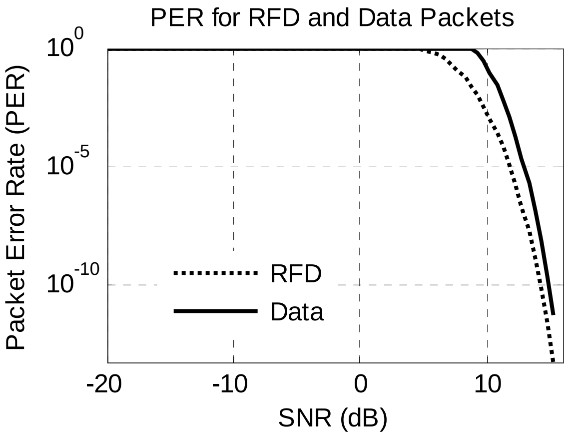

Figure 1. Packet Error Rate for RFD and Data Packets

The packet error rate varies some between message types, particularly in the region where the communications link may be considered marginal. So, an RFD sent when the link is marginal is more likely to be correctly received than a data packet. Hence, both CARR and CCA use the SNR Threshold parameter to mitigate the asymmetry problem. Upon receiving an RFD a node only sends data back if the detected SNR is greater than some SNR Threshold. Figure 2 shows the added benefit, in terms of goodput, gained by including channel awareness in a simple two node network with an AP and one node.

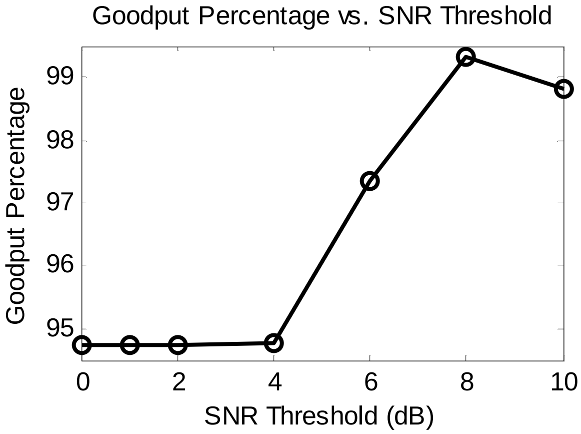

Figure 2. Goodput of 2 Node network as a function of SNR Threshold.

Notice that the goodput slightly decreased after the SNR Threshold value was set above 8 dB. This was because the node discriminated when it should not have. The node should have sent data to AP upon receiving an RFD because the link was good (SNR was above 8 dB), but it didn't because the SNR was not above the SNR Threshold.

Although not included in the simulations or this papers analysis other common physical layer conditions may also contribute to asymmetry. They include variances in receiver sensitivity, transmit power, and other physical layer variations that may occur between an AP and a node in a "real" system.

POLLING MAC RESULTS

The following section summarizes the results for utilizing CARR and CCA algorithms for 8 and 12 node exo-atmospheric networks. As Figure 3 demonstrates CARR, in terms of goodput, is adequate only over a particular region (data rate < 200 kbps and SNR Threshold > 5).

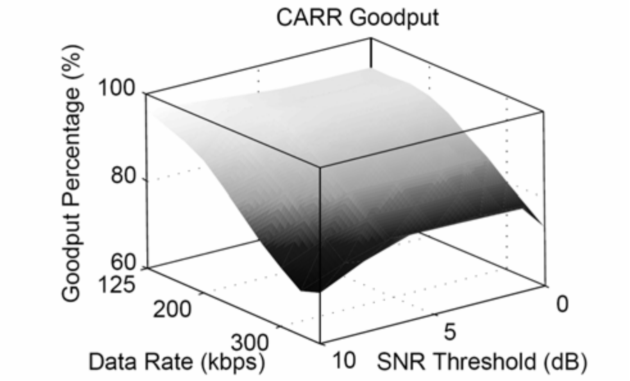

Figure 3. Goodput of 8 node network using the CARR algorithm and patch antenna's at the nodes.

The ending queue size for CARR, as Figure 4 demonstrates, varied considerably with respect to data rate.

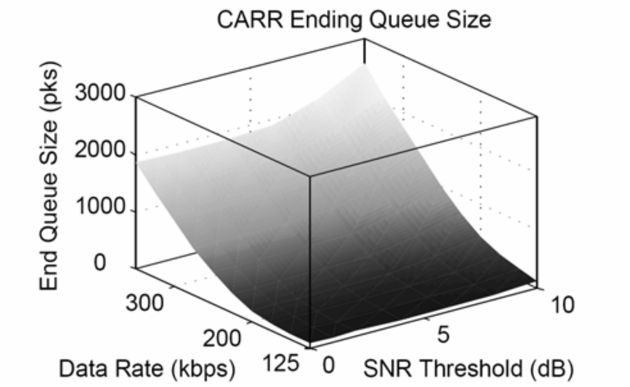

Figure 4. The average ending queue size for 8 node network using the CARR algorithm and patch antennas.

The number of packets in the nodes' queues at the end of the simulation became larger as the data rate was increased, further indicating the inadequacy of CARR above certain data rates.

In contrast, as Figure 5 and 6 demonstrate, CCA was much better suited for the 8 node exo-Atmospheric application.

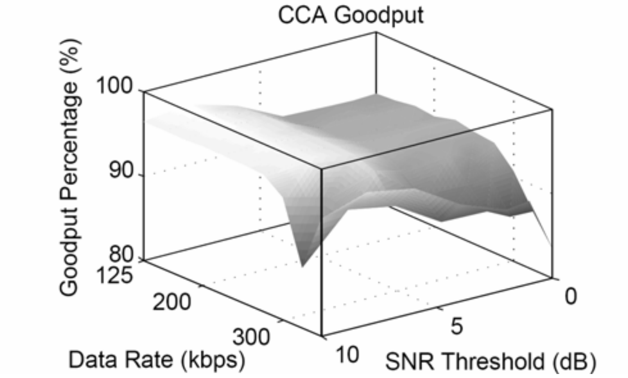

Figure 5. Goodput of 8 node network using the CCA algorithm and patch antenna's at the nodes.

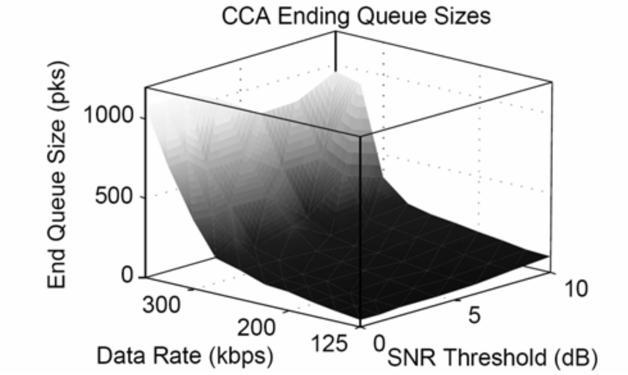

Figure 6. The average ending queue size for 8 node network using the CCA algorithm and patch antennas.

It provided sufficient goodput over a broader range of data rates (assuming that the SNR Threshold was set appropriately, e.g., between 5 and 8) and was able to recover quicker then CARR when a node came out of a null, as indicated by the ending queue sizes.

CCA performs better than CARR because it is aware of the present congestion at each node. As such, when a node becomes congested the AP will query it more often then nodes which are not congested.

In the simulation sets for which the nodes used dipole antennas both algorithms performed well, when the SNR Threshold was set appropriately (5 < SNR Threshold < 8), since the communications links between the nodes and the AP was better more of time. This was only true so long as the antenna gains associated with the dipoles' "good" regions were sufficiently large enough. The use of dipole antennae, as opposed to patch antennae, improved the performance of the exo-atmospheric network.

Four nodes were added to the exo-atmospheric network and the simulations sets were performed again for a 12 node exo-atmospheric network. As Figures 7 and 8 demonstrate, both algorithms performed considerably better.

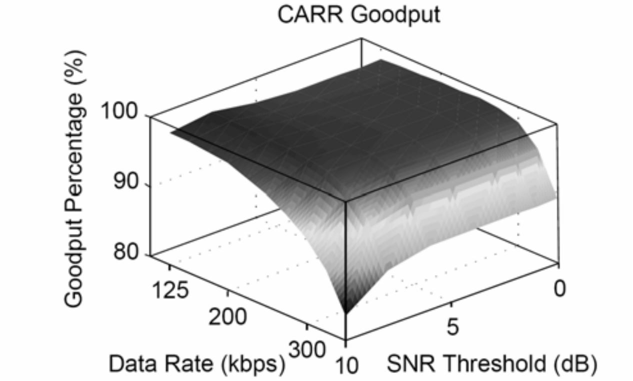

Figure 7. Goodput of 12 node network using the CARR algorithm and dipole antennas.

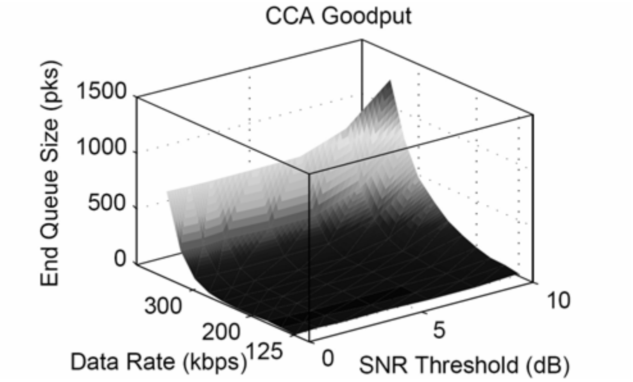

Figure 8. Goodput of 12 node network using the CCA algorithm and dipole antennas.

The added benefit of using dipole antennas, as opposed to patch antennas, was significant as more nodes were added. Figures 9 and 10 show that the average queue sizes also saw significant improvement.

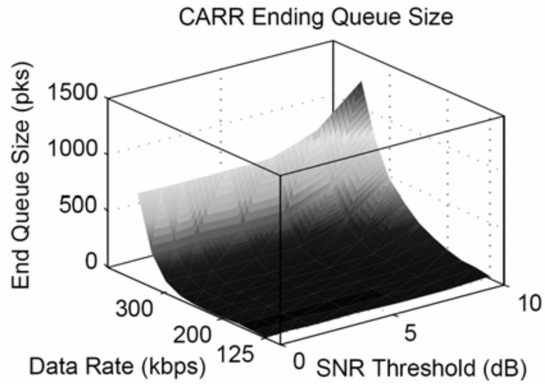

Figure 9. The average ending queue size for 12 node network using the CARR algorithm and dipole antennas.

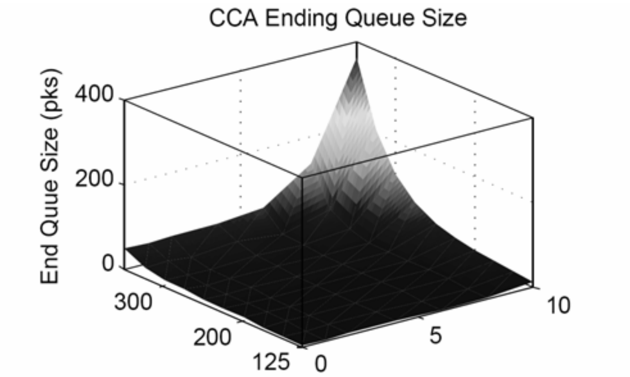

Figure 10. The average ending queue size for 12 node network using the CCA algorithm and dipole antennas.

Additionally, for the 12 node case, the CARR algorithm proved to have adequate performance for a larger region (data rates). This meant that, for certain network conditions, CARR was a good and "simple" solution to the exo-atmospheric application, as it provided acceptable performance with low complexity.

CONCLUSIONS AND FUTURE WORK

The exo-atmospheric application is unique due to the fading that is introduced by the node attitudes, node trajectories, and non-isotropic antennas. But like many other WLAN's, the QoS is still a critical measure of the exo-atmospheric network's performance. Since, the nodes in the exo-atmospheric application have the same QoS requirement; two simple polling algorithms can meet the performance objectives for the examples given in this paper. Though CCA covers a broader range of network and node conditions (antennae, data rates, and number of nodes in a network), CARR has also proven just as effective for certain regions.

Although it is not discussed formally in this paper the recovery time, or the time it takes for a node to empty its queue, could also prove to be a critical measure of network performance. This is particularly true for applications that have strict delay requirements, or ending events that may have high priority (critical data). As such, future work will focus on quantifying the recovery time of CCA and CARR algorithms as well as investigating the tradeoffs associated with implementing more complex MAC layer solutions such as 802.11e.

REFERENCES

[1] S. Mangold, S. Choi, O. Klein, G. Hiertz, and L. Stibor, "Analysis of IEEE 802.11e for QoS Support in Wireless LANs," *IEEE Wireless Communications*, pp. 40-50, Decemeber 2003.

[2] D. Gao, J. Cai, K.N. Ngan, "Admission Control in IEEE 802.11e Wireless LANs," *IEEE Network*, pp. 6-13, July/August 2005.

[3] R. Pintenet et al., "Evaluation of interoperability mechanisms for coexisting HSDPA and WLAN enhanced with MTMR techniques," *Vehicular Technology Conference*, pp. 1807-1811, October 2003.

[4] T.A. Gizawi, K. Peppas, D.I. Axiotis, F. Lazarakis, "Interoperability Criteria, Mechanisms, and Evaluation of System Performance for Transparently Interoperating WLAN and UMTS-HSDPA Networks," *IEEE Network*, pp. 66-72, July/August 2005.