Green Network
- Power Efficient Network for Rural Areas -

Aram Melkoumian, Veljko Pejovic, Elizabeth Belding

{twinkie, veljko, ebelding} @ cs.ucsb.edu

Abstract - The bridging of the digital divide, when it comes to wireless networking, implies providing inexpensive and on the long term cost effective solutions. To lay down the technological infrastructure such as telephone lines, Ethernet, cable, or even fiber, in rural areas of the developing world, areas which are of the primary interest here, would come at an outrageous cost.

We provide a low cost solution in the way of a power efficient wireless network. Additionally, our solution is based on the existing 802.11 hardware. We achieve our goals through the MAC, protocol developed specifically for rural network settings, that introduces the idea of powering-down when there is no active traffic and the efficient way of providing loose node synchronization, so the communication performance does not suffer.

The results of the tests we performed on the protocol simulation are promising and show significant improvement over the existing implementations.

Categories and Subject Descriptors

C.2.2 [**Computer Communication Networks**]: Network Protocols; C.4 [**Performance of Systems**]: Performance Attributes

General Terms

Performance, Measurement, Design, Theory

Keywords

Media Access Protocols, Energy Efficient Operation, Wireless Mesh Networking

1. Introduction

There is a huge gap between the level of technology around the world, known as the digital divide. The digital divide is growing between the rural underdeveloped areas around the world and the technologically advanced areas. The main issues which cements this gap into place is the lack of technological infrastructure in rural areas of the developing world.

In order to bring these areas up to speed, there would be a need to connect them to the other side of the divide. This requires a great deal of work, which comes at a great cost. Laying down telephone lines out to rural areas is a huge undertaking, let alone Ethernet, cable or fiber.

With cost in mind we turn to wireless solutions. This helps avoid the cost that comes with laying down the infrastructure necessary for wired communication. All problems are not avoided by choosing a wireless solution.

With wireless come the issues of power consumption and cost. Our solution addresses all of these. The aim is to create a MAC layer protocol, which will solve these issues.

To take care of the power consumption problem we introduce the idea of powering nodes down, where nodes are switched off during certain intervals to conserve power. Next, address the issue of cost by basing our solution off of the low cost 802.11 radio. The aim of our solution is to provide a green network which is power efficient in rural underdeveloped areas. Our prediction is that these areas will be using the network for predominately VoIP traffic.

The rest of the paper is divided in the following manner. Section 2 provides background work and related protocols. Section 3 presents design details of the protocol, with detailed explanation of the preambling and the negotiation algorithm concepts. Section 4 explains the simulation setup and Section 5 explains the experiment setup. Section 6 provides the performance results. Finally, Section 7 provides the conclusion and notes about future work.

2. Related work

Since the rural mesh network represents a relatively new paradigm, no solution is de-facto standard in the field. Several MAC protocols have been proposed in order to achieve connectivity over long distance, lossy links [8] [9] in wireless rural networks. Nevertheless, power efficiency did not get substantial attention from the research community. Some solutions [2] that are implemented and tested on high node density, infrastructure networks are not applicable in the case of sparse, wireless mesh networks due to lack of centralized controller and the existence of different routing paths.

The way rural mesh networking problem is defined, node sleeping is the key for power savings, while the end-to-end performance should not suffer under extreme delay.

The most intuitive approach is probably the one taken by the Wake-on-WLAN [7], where the receiving nodes are waken up when needed, the solution mimics the Wake-on-LAN [1], leveraging the fact that 802.15.4 based sensors can detect 802.11 traffic. Besides the standard 802.11 equipment, the nodes carry an additional sensor each, used for on-demand powering up when the incoming traffic is sensed. Clearly, the solution offers almost optimal power saving capabilities, yet it suffers from occasional "false positives" ,when a node detects signal sent to another receiver, and the delay introduced by on-demand powering up. However, having in mind the economic environment where the network is suppose to be deployed, the price of the sensor (U.S.$70 for the one used in the authors' implementation) is seen as the main flaw of Wake-on-WLAN approach.

When it comes to power saving techniques, several interesting approaches can be found in the field of wireless sensor networks. These can broadly be divided into two categories: techniques that use synchronization to assure that the communication periods coincide, and those which are not synchronized but depend on preambling and low power listening. The first group of techniques can only be used when the traffic comes with a high level of predictability, while the second group only imposes existence of short "duty cycles" so that no excessive preambling occurs. The concepts introduced by X-MAC [3] protocol for WSNs, strobed, targeted preambling, and non-interrupted sleeping are the ones that we find relevant to our problem, and based the solution on.

3. Protocol Design

When designing a MAC protocol for rural wireless mesh networks, the following goals should be achieved:

- Low energy consumption
- High network availability
- Low control overhead
- Robustness

The protocol presented here is based on X-MAC for wireless sensor networks, especially its preambling paradigm, while it is specifically crafted for mesh network setup, and traffic patterns that occur when VoIP traffic is used. Besides preambling, the protocol introduces novel sleep negotiation algorithm, aiming to provide loose synchronization of the participating nodes, reducing excessive preambling.

3.1. Preambling

When implemented, node powering down, as a power saving option, requires extra level of care since neither reliable communication nor battery lifetime should be sacrificed. Unpredictability of the incoming traffic does not allow long sleep periods, yet even if briefly awake, a node is not capable of concluding whether a transmission is about to occur soon (or perhaps, have already failed). This demands frequent power-up periods and lots of idle listening on a medium.

In order to overcome the problem we utilize preambling approach. When a sending node wants to transmit, it starts by sending a preamble, in case the receiver is awake (or wakes up during the sender's preambling period) it senses the preamble and replies with an acknowledgment packet. This signals the sender that the link between two of them is up and ready for data transmission.

One obvious drawback of the preambling approach is that node may reply to a preamble "leaked" from another link. This leads to too mush wasted energy in high density mesh networks. In order to eliminate the overhearing problem, each preamble contains the target node ID/address. Now, when a node wakes up and senses a preamble it checks the target field and either replies with an ACK (if it is the target of the preamble) or powers-down (if the intended recipient is some other node)

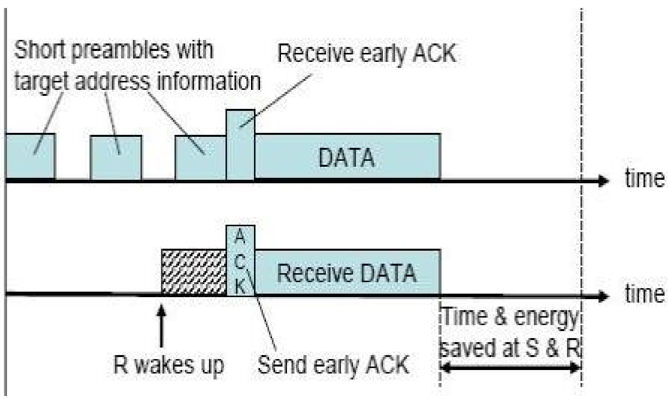


Figure 1: Strobed Preambling

One might suggest using one extended preamble packet instead of a set of preamble strobes. Although this was implemented in several existing solutions, it is not appropriate for the problem presented here. Since an ACK packet from the receiver has to follow the preamble, long preamble makes it wait in the idle state for a much longer period of time. On the other hand, minimum wake up period for a node is limited to a slot time between two consecutive strobed preambles, which is in order of hundreds of milliseconds.

Although the explained protocol works well when the degree of nodes in a network graph is low, we experience the following problem: one or more transmitters are waiting for a receiver to finish the existing transmission. If we act according to the above, preambling occurs before each "queued" session, leading to significant control overhead, and more important – unnecessary end to end delay. To cope with this the senders will not preamble if it hears an ACK from the receiver it wishes to send data to. Additionally, the receiver will not go to sleep immediately after the first transmission is over; it will wait for a minimum amount of time needed for any of the waiting nodes to send their data.

As the final preambling issue, we decided to restrict the maximum number of strobes. This decision may result in early backing off in case the preambles are not successfully acknowledged, but it alleviates some security issues and may result in lower power consumption on the sending node.

3.2. Sleep Negotiation Algorithm

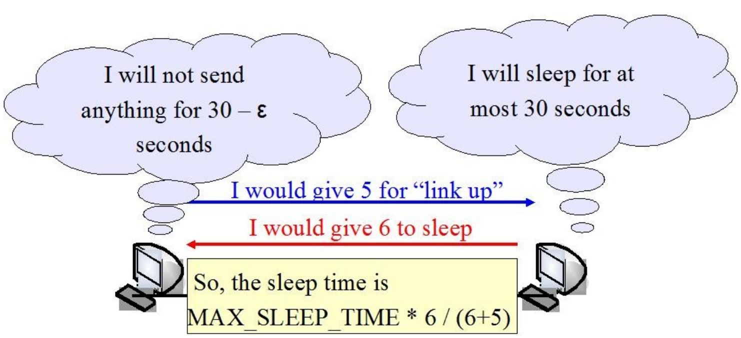
The preambling approach shows very good performance in short, strictly determined duty cycle wireless sensor networks. Unfortunately, in a rural mesh network where traffic may be sparse, allowing longer sleep periods to receiving nodes requires more preambling for the senders. Since these periods may last for minutes, even hours, preambling overhead becomes predominant over the actual data transfer. In order to allow nodes to be powered down, yet to make sure that the network performance doesn't suffer significant loss, senders and receivers should negotiate on the sleeping periods.

From the senders point of interest, a link should be up as long as there is (an will be) some data to be transferred over it. On the other hand, the receiver's reason for a link to be down is based on power saving: when link is down the node can be powered down. Having these in mind, we design the sleep negotiation algorithm, with aim to balance between the receiving and the sending node requirements.

We base the algorithm on the following assumptions: after the warm-up period, the sending node should have a somewhat clear picture of the incoming traffic patterns. So, it should be able to predict the amount of traffic to be experienced in the near future. At the same time, the receiving node should monitor it's power consumption and have a good estimation of the current power supply status.

The algorithm initiates the negotiation after a data exchange session between the two nodes is about to terminate. Each node sends the information with a level of desirability for a specific state (link up or link down) to the other one. In specific, the sending node sends a higher value if, with high probability, it expects data packet which will require the link to be up. Similarly, the receiving node sends a higher value if its power supplies are low. In the beginning, both nodes should have their levels set at the same initial value. After the exchange, the receiving node should be allowed to sleep for the time determined by the balance of the levels announced by each of the participants, while the sending node should not try to send any data before the arranged time interval ends. When the interval is over, the receiving node must wake up and stay awake for long enough to sens a preamble which may be emitted by the sender. If a preamble is not sensed, it may return and sleep for the same period it did in the previous iteration.

Although this solution implies high level of synchronization, it may not be optimal from the receiver's point of view, since possible clock skews may result in the receiver being awake earlier than actually needed. As we perceive power saving on the receiver side to be our most important goal, we make sender preamble ε before the arranged wake up time, getting sure that no idle listening happens.



The example of one negotiation round is shown on *Figure 2*, where the arrangement ii made upon the value which corresponds to a certain portion of the MAX_SLEEP_TIME (in this example 55 seconds) , that is slightly biased on the receivers side, since the desired value for “link down” (6) is grater than the desired value for “link up” (5) state.

4. Simulation Setup

To test the solution we developed a Qualnet v4.0 implementation of the protocol, relying on the existing mac_dot11.* build provided by default. Preambling and negotiation control messages are directly implemented in the MAC layer, while the negotiation algorithm itself requires some cross-layer information (power consumption, data packets sent). To avoid this, we used power up/down times and data traffic analysis from the MAC layer itself. The reasoning behind this decision is that sleeping time on the MAC layer is exactly the same as sleeping time on the Physical layer, while for the data transfer we take information on data packets sent through the MAC layer as well as the packets forwarded from the Network layer, but buffered on the MAC layer.

In order to effectively evaluate power consumption, we discarded QualNet's power model which does not keep track of power consumption in node idle, sensing and receiving state. Instead, we introduced a power model derived from C. B. Margi et. Al [6] and implemented it on PHY layer of the Qualnet protocol stack. This model accurately represents power consumption in all states that can be found in the original QualNet model, as well as for new states provided by it. For the default energy consumption model values, we referred to WaveLAN specifications [12] The model was later verified through testing.

5. Testing Specification

The aforementioned Qualnet implementation of the protocol is evaluated to provide a clear picture of how well our solution would perform, both in a simple point-to-point topology as well as in a more complex topology reassembling the actual village-like implementation.

We see the following as the most important properties of a MAC protocol aimed at power efficient packet delivery in rural area settings: average wait time for a user to associate with a network, average delay for data packet delivery, power consumption and power consumption distribution, algorithm control overhead, number of nodes supported, sleep period negotiation/exchange performance, security and robustness in the real world application.

For all tests we use environment of static nodes with omnidirectional antennas, since we presume that only mesh network nodes participate. For testing purposes we use static routing although we are well aware that future tests should examine the behavior under more flexible AODV and DSR routing protocols or their derivatives. CBR traffic is generated to mimic VoIP application behavior, as we see it as the primary application in this type of a network.

6. Protocol Performance

The first set of tests is aimed at the protocol tuning in order to optimize end to end delay and power consumption. A simple node to node topology and bursty CBR traffic are used. We variated the level of node synchronization (parameter ε) and measured total energy consumed, as well as end-to-end delay experienced. As expected, we found that the delay grows linearly when the nodes desynchronized and the sender starts emitting preamble before the receiver is awake. Fortunately, the delay introduced by preambling and acknowledging is insignificant. On the other hand, total power consumption does not record its minimum when nodes are completely synchronized, rather, the case when the sender wakes up right after the receiver show the best performance. The explanation lies in the fact that the receiver is not capable of sensing and transmitting a preamble ACK to the first strobed preamble packet sent, so it gets lost in any case.

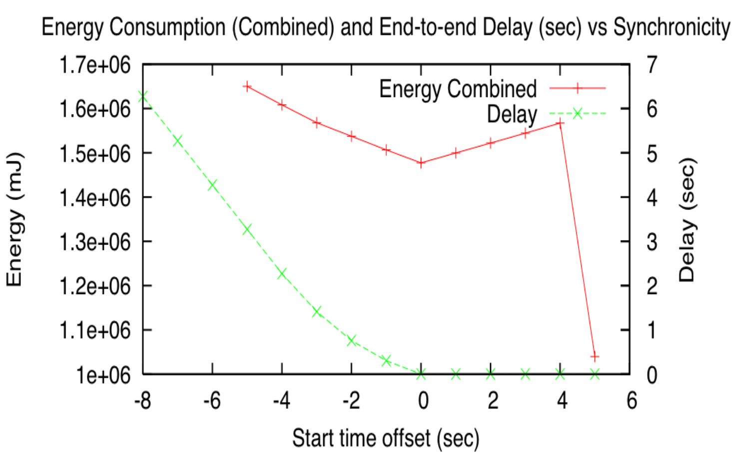


Figure 3: Energy consumption and End-to-end delay

Although the graph suggests that ε delay does not result in total energy savings, we still believe that in the real world scenarios savings on the receiver side should be valued more. However, we are well aware that higher ε value results in increased end-to-end delay, therefore in the experiments to follow we used ε = 0.1 second

To evaluate power consumption we tested the solution on a sparse village-like topology, with a varying number of nodes and a traffic pattern we found the most appropriate to the actual network usage.

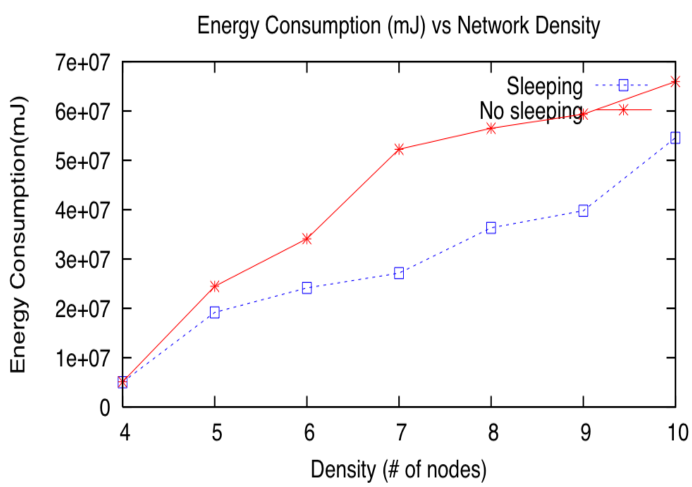


Figure 4: Energy consumption in a complex setting

The results (Figure 4) show substantial improvement when the protocol is used, no matter how many nodes are present. We believe that the tested scenario is also the worst case scenario since any additional predictability or periodicity in the traffic pattern should result in longer sleeping periods when the algorithm is implemented.

Additional tests that we ran in order to evaluate power consumption for each of the nodes showed that the power consumption on the nodes which didn't sleep in both cases does not differ significantly. Clearly, the fact that we restricted number of preamble strobes sent resulted in additional savings.

To conclude if the performance benefits from the negotiation algorithm we used the topology similar to the previous one, and added nodes and traffic incrementally. This time we limited the buffer space on the MAC layer, so no more than 5 packets could be buffered at the same time. The result is that packets had to be dropped if the receiving and sleeping node are not responding to the actual network state (i.e. Traffic patterns, power consumption). We ran tests with the negotiation algorithm in place and with the default sleep periods set for the receiving nodes (one half of MAX_SLEEP_TIME).

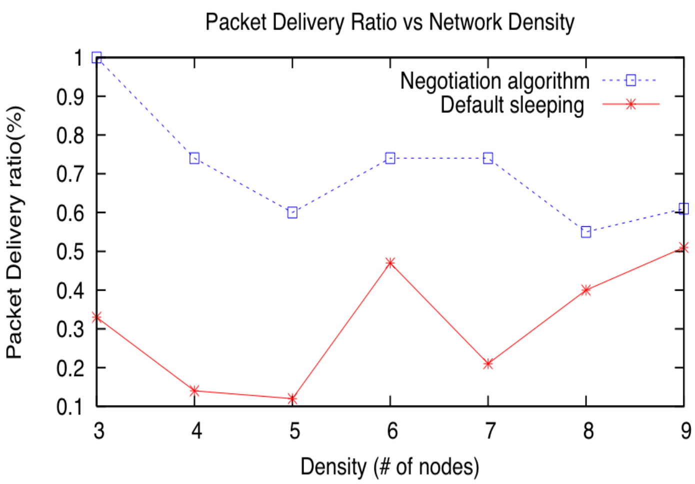


Figure 5: Packet delivery ratio

It can be observed that the delivery ratio falls drastically when the powering down is blindly forced regardless of the conditions. Despite solid performance of the negotiation algorithm, we feel there is still room for major improvements.

Finally we examined the security issues in the protocol. The most obvious attack where a node constantly preambles clogging the network is made impossible by restricting the number of strobes sent from the same node. The other concern is preamble SYN attack where a malicious node can preamble, get an ACK and defer from the transmission leaving the connection "hanging". In the current implementation of the protocol, this is quite possible, yet a simple timing out and/or subsequent sender identification implemented on the receiver should make the attack ineffective.

7. Conclusion and Guidelines for the Future Work

In this paper we described the MAC layer protocol implementation which aims towards power efficient networking in rural wireless mesh settings.

Our protocol is based on a loose synchronization of sender and receiver nodes in a network, which is made possible by two major concepts: preambling and negotiation algorithm. Preambling suppress idle listening, while the negotiation algorithm allows longer sleeping periods which are adapting to the actual network usage.

The results show significant power saving when the protocol is implemented and tested on a village like simulation topology. In addition, network responsiveness is not seriously changed.

Despite, we believe that the protocol can be improved from several perspectives: most notably delay and delivery ratio performance and security. For the first one, we have already sketched a version of the negotiation algorithm where nodes try to achieve a global power consumption/network availability optimum through network wide bidding. However, we strongly feel that the future work on the algorithm is needed. And for the second one we are looking into better preamble-ack-data schemes.

In conclusion, we believe the protocol is a step further towards the fulfillment of the goals stated in the section 3. Designed specifically for wireless mesh networks in rural areas, this protocol can also be applied to other network settings.

References

[1] AMD White Paper on WOL. http://www.networking.ibm.com/eji/ejiwake.html.

[2] Elizabeth Belding, Green Mesh: technology for Rural Mesh Networks, proposal, March 2007

[3] Michael Buettner, Gary V. Yee, Eric Anderson, Richard Han, X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks, Proceedings of the 4th international conference on Embedded networked sensor systems, Boulder, CO, November 2006

[4] L. M. Feeney and M. Nilsson. Investigating the energy consumption of a wireless network interface in an ad hoc networking environment. In Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies.INFOCOM 2001, volume 3, pages 1548–1557. IEEE, April 2001. puter Design: VLSI in Computers and Processors, San Jose, CA, October 2003.

[5] A.Jardosh, K. Papagiannaki, E. Belding, K. Almeroth, G. Iannaccone, and B. Vinnakota. Green WLANs: On-Demand WLAN Infrastructures, Submitted for publication

[6] Cintia B. Margi, Katia Obraczka, Instrumenting Network Simulators for Evaluating Energy Consumption, in Proceedings of the IEEE/ACM MASCOTS 2004, October 5-7, 2004

[7] Nilesh Mishra, Kameswari Chebrolu, Bhaskaran Raman, Abhinav Pathak, Wake-on-WLAN, Proceedings of the 15th international conference on World Wide Web, May 23-26, 2006, Edinburgh, Scotland

[8] Rabin Patra, Sergiu Nedevschi, Sonesh Surana, Anmol Sheth, Lakshminarayanan Subramanian and Eric Brewer. WiLDNet: Design and Implementation of High-Performance Wifi-based Long Distance Networks, In ACM/USENIX NSDI, 2007.

[9] Bhaskaran Raman and Kameswari Chebrolu, ``Design and Evaluation of a new MAC Protocol for Long-Distance 802.11 Mesh Networks", 11th Annual International Conference on Mobile Computing and Networking (MOBICOM), Aug/Sep 2005, Cologne, Germany

[10] Jacob Sorber, Nilanjan Banerjee, Mark D. Corner, Sami Rollins: Turducken: hierarchical power management for mobile devices. Proceedings of the 3rd International Conference on Mobile Systems, Applications, and Services (MobiSys 2005), June 6-8, 2005, Seattle, Washington

[11] Lakshminarayanan Subramanian, Sonesh Surana, Anmol Sheth, Rabin Patra, Sergiu Nedevschi, Melissa Ho and Eric Brewer. Rethinking Wireless for the Developing World. In proceedings of Hot Topics in Networking (Hotnets-V), Irvine, CA, November 2006.

[12] X. Zeng, R. Bagrodia and M. Gerla, "GloMoSim: a Library for the Parallel Simulation of Large-scale Wireless Networks", will appear in Proceedings of PADS'1998