MAC and Physical Layer Energy Efficiency for Ad Hoc Wireless Sensor Networks

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Abstract— **Ad hoc wireless sensor network's (AHWSN) primary goal is energy efficiency. Theoretically, the most energy efficient MAC protocol for a mesh network would be a TDMA based protocol without the administration, control and exact timing signals that need to be conveyed. This paper presents a TDMA MAC protocol with a PicoRadio that is as close to that ideal as possible. The proposal is Colour TDMA MAC. It allows lee-way to the exact timing of the synchronisation needed for a TDMA scheme. In addition the protocol reduces the amount of control messages that needs to be transmitted between nodes and also defines how the nodes need not change their function and role periodically, to co-ordinate the TDMA scheme and transmissions of data of other nodes.**

Index Terms—**AHWSN, WSN, TDMA, CSMA, MAC, PicoRadio**

I. INTRODUCTION

An Ad Hoc Wireless Sensor Network (AHWSN) comprises of a number of self-containing electronic devices communicating wirelessly, with the particular purpose of sensing a parameter, be it machine vibrations or temperature changes or many other measurable properties of the environment. The acquired data is then fed to an information sink.

The network is called ad hoc because there is no infrastructure. The devices themselves are the resources of the network to each other.

The primary goals of AHWSN in order of importance are:

1. Energy efficiency (Prolong the life of the network),
2. Self organising (if individual failure occurs the network still exists or it can repair itself),
3. Scalability
4. Reduced cost of each node.

Nodes employ a duty cycle to ensure that their average power consumption stays low. The duty cycle consists of an awake time (where they are active) and a sleep time.

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II. CSMA/CA VERSUS TDMA

MAC protocols for AHWSNs are either:

1. Contention based (CSMA/CA) , or
2. Non-contention based (TDMA).

Contention based MAC protocols such as S-MAC [1], T-MAC [2], B-MAC [3], PAMAS [5], sense the channel for activity and if no activity is detected they place a request to use the channel, to which they receive an acknowledgement. If they are granted access to the channel then all other nodes are required to 'keep quiet' during the transmission. Non-contention based MAC protocols such as Bit-Map-Assisted MAC [4], ER-MAC [6], LEACH (with regards to cluster-head transmissions) [7], GANGS [8], TRAMA [9] and E-MAC [10], use a time division scheme to schedule nodes when they may use the channel for transmission.

III. TOPOLOGY

Topology is closely related to which MAC approach is used. Being an infrastructure-less network the nodes can either:

1. All be equal (called a flat-top), or
2. Certain nodes have authority over other nodes (hierarchical).

Generally, the nature of the MAC protocol determines the topology. Contention based protocols utilise flat-top because they are of an "equal chance for all" type. Hierarchy nodes are used in non-contention based MAC protocols because of the need to co-ordinate nodes or cluster heads.

The advantages of each:

- Flat-top topology – If any node fails in the network, it is not detrimental. (Most scalable)
- Hierarchical topology – A backbone exists where messages can be collated, compressed and sent down a trusty higher data rate path to the destination.

The upcoming proposal (Colour TDMA MAC) consists of a flat-top, TDMA scheme and the assumption is made that AHWSN are a stationary node network. (Mesh network)

IV. Colour TDMA MAC Proposal

Colour TDMA MAC's aims are:

1. To reduce to a minimum the internal collisions in a CSMA/CA scheme.
2. To remove the need for employing administration nodes to co-ordinate TDMA and data transfers.
3. To receive data utilising the smallest amount of power in the process.

It achieves its aims by:

1. Utilising TMDA over CSMA/CA.
2. All nodes know the TDMA scheme indefinitely, and they are synchronised to their neighbours. Data transfer is not synchronous.
3. If the nodes are not utilising the channel, they go to sleep. If they are required to receive data, their PicoRadio awakens them.

The protocol utilises a simple algorithm because complicated ones are avoided.

A higher level abstraction of 'Colour TDMA MAC' is now presented without the nitty-gritty. First the higher level properties are stated and then the protocols workings.

Assumptions and Properties:

- Each node is "loosely" synchronised with its neighbour. (With the allowance of an error).
- Nodes do not form clusters but have a fixed maximum number of neighbours 'x'[1]. (Else reduce radio connectivity).
- One TDMA definition exists over the network with all nodes aware being aware of it.
- Channel is divided by a TDMA scheme.
- Number of time slots is 'x'.
- Receiving data requires no synchronisation.
- Data is transmitted in fixed packet sizes.
- Data transmission has a fixed maximum length.

Protocol:

- Each node chooses 1 number between 1 and 'z' ('z' is less than 'x') which none of its neighbours or its neighbour's neighbour may posses (Also known as "The Colouring Problem" in Graph Theory). The unique number ('z') chosen by each node is the node's time slot.
- Nodes are only awake when it is their turn to utilise the channel. Nodes have PicoRadios to wake them up when they are to receive data.
- Each node's time slot is further divided to when a node may send data to each neighbour. This enables the neighbour's PicoRadio to be enabled only for a short time. (Only the one correct neighbour is awakened for whom the data is destined), as illustrated by the following example figure …

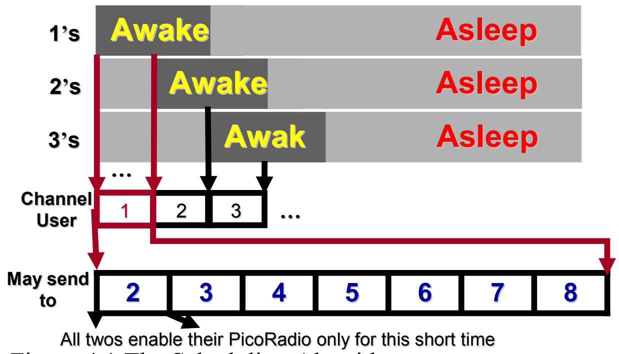

Figure 4.1 The Scheduling Algorithm

V. Issues And Implementing

Colour TDMA MAC does not suffer from the exposed terminal problem due to each node having a time slot in which to transfer data. The hidden terminal problem is also easily solved: The maximum number of neighbours a node may have is less than the number of time slots there are. This will ensure that if a node has two neighbours which are not in radio range of each other and have chosen the same time slot, the node that hears them both will request the one neighbour to change. Subsequently there will be no great complications or energy consumptions in the change which will occur quickly and efficiently due to there always being some time slots available.

The TDMA cycle of this proposal has one definition which exists across the entire network, i.e.

- the number of timeslots in a TDMA cycle.
- the length of the timeslots.
- the beginning of the TDMA cycle

is the same throughout the network and every node is aware of this information. Multiple nodes across the network may use the same timeslot in the TDMA cycle only if the radio connectivity of one node using timeslot "x" does not overlap with that of any neighbour also using this same timeslot "x" with a node in that common region. *If **any** node consumes all of its available energy it will not stop the TDMA scheme from continuously cycling through.* The nodes will only need to check that their neighbours are there every so many cycles. *This is the only TDMA MAC protocol for AHWSN that can claim such a feature.*

Some of the time slots can become contention based, so if there are mobile nodes in the network they can transmit data without asking the current TDMA cycle to reconfigure itself.

A. Synchronisation

The synchronisation technique: 'If each and every node in the network is synchronised with its neighbours then for any

[1] Many MAC protocols [4], [6], [7], [8], [9], [10] enforce the nodes in set clusters. Colour TDMA MAC does not form set clusters but each node with its neighbours composes 'its own cluster'.

given node's radio range the network is synchronised; though the entire network may not be synchronised end-to-end.' The nodes communicate only with their neighbours. There is no need for direct communication from one end of the network to the other end of the network. Perfect synchronisation is not required. Colour TDMA MAC still performs well even if the nodes are out of synchronisation by 1mS. This has to do with the time it takes to send one packet (low data rate) and is explained in Section VI "Results", subsection C "Energy Efficiency."

B. *Initialisation of the Colour TDMA MAC scheme*

1) Discover the neighbours. Each node identifies all the other nodes within its radio range.
2) Adjust radio range if number of neighbours ≥ maximum neighbours allowed. The number of neighbours is limited.
3) Synchronize with neighbours and let the nodes know what the exact TDMA definition is and when it starts.
4) Negotiate the timeslots. Once a node has chosen a timeslot, no other nodes within its radio range or its neighbour's connectivity may choose that same timeslot.

Colour TDMA MAC's initialisation is more energy costly than a contention based MAC.

VI. RESULTS

In this section S-MAC is compared to Colour TDMA MAC with regards to energy efficiency. Comparing any two MAC protocols is difficult since one has to investigate the produced traffic. However this depends on:

- The amount of nodes,
- Position of each node,
- Density of how close they are to each other,
- And their applications.

A. *Simulation Results*

There are infinitely many possible AHWSN node configurations. One person's 30 node AHWSN will not be the same as someone else's. Hence one 30 node AHWSN simulation will not be the same as another. This is because the simulator looks at the overall network, where as the requirement is to investigate the inter-nodal communication (MAC layer). This is only affected by the amount of neighbours any given node in the network has. Thus a 30 or a 100 node AHWSN with every node only having 4 neighbours can be plotted on one graph.

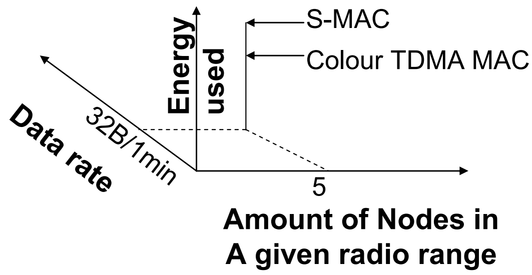

Figure 6.1 One Answer to the Comparison of S-MAC and Colour TDMA MAC

Investigating the figure 6.1 one can see the amount of nodes does not depend on the size of the network, but the amount now only affects the data rate. 100 nodes will send more than 30 with the same sensor period. The energy used is scaled by the microprocessor used by the node and distance between nodes which affects the radio receiver power utilisation. All the different simulation results can be placed together to make one 3D plane of how much more energy efficient Colour TDMA MAC is compared to S-MAC but that would take many simulations, so rather one uses a another approach to compare S-MAC to Colour TDMA MAC.

B. *The Properties of microcontroller and MAC scheme*

Depending on which microcontroller is utilised different energy graphs are obtained. The following tables present the parameters used to obtain results.

TABLE I
THE PROPERTIES OF A NORDIC SEMICONDUCTORS NRF9E5

Supply Voltage	3V
Supply current in transmit @ -10dBm	9mA
Supply current in receive mode	12.5mA
Supply current for m-controller 4MHz @ 3volt	1mA
M-controller running at	4MHz
Data rate	50Kbps
Supply current in power down mode	2.5µA

TABLE II
PARAMETERS OF THE AHWSN NODES

Node duty cycle	1150mS
S-MAC awake 10%	115mS
S-MAC 90% asleep time	1000mS
Packet size	32 bytes
S-MAC SYNC contention windows	15
S-MAC RTS and CTS contention windows	31
Colour TDMA MAC Number PicoRadio timeslots	16
Colour TDMA MAC Length PicoRadio timeslots	2mS
Colour TDMA MAC maximum neighbours	12

S-MAC is contention based. Colour TDMA MAC is non-contention based. Let us first investigate the power savings over not having internal collisions as in a contention scheme.

C. *The S- MAC scheme*

All nodes awake at the same time and follow this schedule:

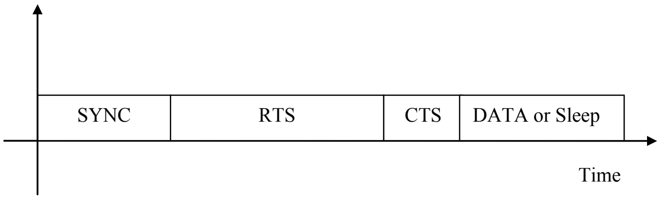

Figure 6.2 S-MAC scheduling

The SYNC section is for nodes to send a message for synchronisation. The RTS and CTS section is grouped together and is where the contention takes place. Contention happens between contenders. Contenders are a combination of the number of nodes and their number of messages they are sending. 1 node sending messages to 3 different nodes requires 3 RTS requests hence the number of contenders is 3. The following graph shows the probability of one collision among contenders:

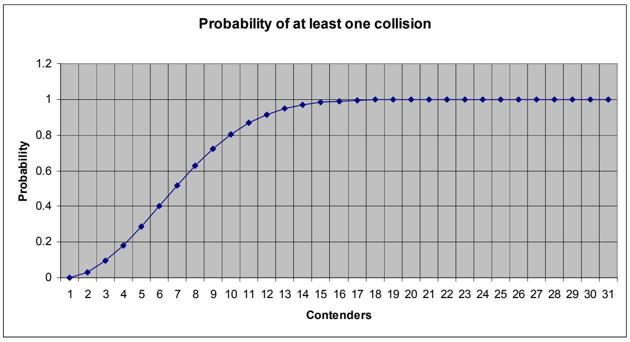

Figure 6.3 Probability of One or More Collisions

If the probability that one or more collisions occurs then how many messages will go through on average if there is between 8 and 15 contenders?

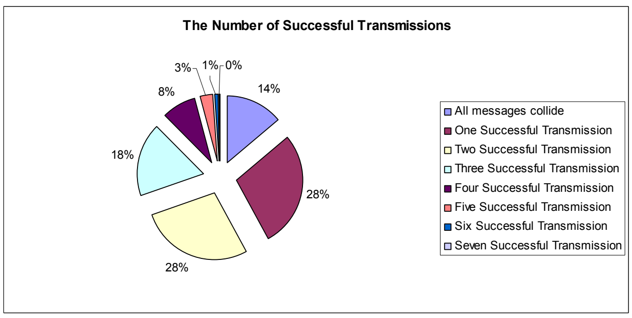

Figure 6.4 Number of Successful Transmissions if at least one collision occurs

Thus if the probability of collision does occur, there is a 56% chance that only one or two RTS or CTS will be heard. Colour TDMA MAC does not suffer from this problem.

D. Radio Usage of S-MAC compared to Colour TDMA MAC

Table I "The properties of a Nordic Semiconductor nRF9E5" shows that the microcontroller uses 9 to 12.5 time more energy than the radio transmitter. Thus it is most power hungry device. Let us compare the two protocols energy consumption when one node has two neighbours and is sending one message to one neighbour.

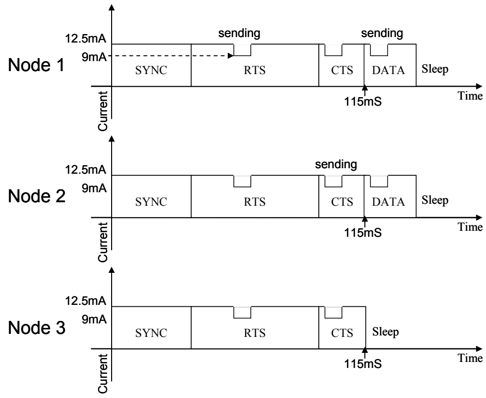

Figure 6.5 S-MAC Three Node Network, One Node is Sending Data to Another Node

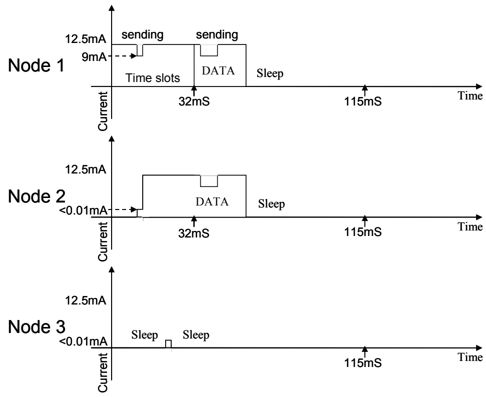

Figure 6.6 Colour TDMA MAC Three Node Network, One Node is Sending Data to Another

As one can see, the radio is placed in to receive mode (when idle) which consumes 12,5mA. This is the radio listening to the channel. (An idle radio is energy wasted). When the node sends a signal that idle figure goes down to 9mA. Upon receiving a signal there is an auto gain control (AGC) that adjusts according to the incoming signal and if the node is far away more energy is required to magnify the signal, and less if the node is near by. In the diagrams of figures 6.5 and 6.6 the receiving current value is assumed to be 9mA. The total energy consumed in figure 6.5 is 13.08174mJ and the total energy consumed in figure 6.6 is 2.19918mJ. That is an 83% increase in power savings. Of course this just one example and that figure changes. But AHWSN are made to be low data rate and a low node number network, which acts in the favour of both MAC protocols and keeps that power saving percentage high.

E. Colour TDMA MAC compared to other TDMA MACs

Other TDMA MAC protocols do not suffer from the collision issue of S-MAC. They do however employ some kind of administration nodes to co-ordinate a strict TDMA scheme while Colour TDMA MAC does not. Colour TDMA MAC does not require such a strict scheme. The function of the administration node changes in each TDMA scheme but only by a function or two. All of them require one node to keep strict timings of the TDMA scheme. Such stringent timings are not required when "large" time slots are provided. Other functions of the administration node vary from one TDMA MAC protocol to another. Some employ a synchronous data transfer [11] where the node "in charge" synchronises the sender and the receiver. This is very costly with respect to energy utilisation.

VII. CONCLUSION

A. Colour TDMA MAC versus S-MAC

Colour TDMA MAC is more energy efficient than S-MAC:

- There is no idle time waiting for a data transfer.
- Maximum sleep time, minimum awake time.
- There is no inter-nodal collisions.

Colour TDMA MAC is less energy efficient than S-MAC:

- During initialisation.

B. Colour TDMA MAC versus other TDMA MACs

Colour TDMA MAC offers a better TDMA scheme and energy utilisation than other TDMA MACs [4], [6], [7], [8], [9], [10], [14] for AHWSNs due to its unique features:

- It does not require strict timing for the TDMA scheme.
- There is no central point or super node(s) co-ordinating the TDMA scheme.
- The data transfer is not synchronous.
- The nodes with their neighbours do not form clusters.
- If any node leaves the TDMA sequence, it does not stop the continuous cycle.
- The receiving node does not need to be awake to obtain data.

C. Colour TDMA MAC uniqueness in AHWSNs

Colour TDMA MAC has the following unique features that are the first of its kind for TDMA MAC protocols in AHWSN:

- If any node fails the TDMA cycle continues uninterrupted.
- There is no need for nodes to form clusters.

D. Extra Hardware and costs in Colour TDMA MAC

Colour TDMA MAC requires a PicoRadio with a timer which is an additional hardware and increases the cost of the node. It is a simple device that awakens the node to receive data. Its simple structure consists of a few components which are not costly items to add to the node. A few cents more is the maximum that is required by each node.

VIII. FUTURE IMPROVEMENTS

If one could move away from the PicoRadio and use the concept of a mailbox system, where a message destined for an asleep node does not require it to be awakened and turned on to receive a message but that such a message can be stored in a "mailbox" elsewhere while the node remains asleep. Later when the node awakens for its time slot it would check its mailbox and retrieve "any mail".

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