Hardware Mailbox and Energy Efficient Scheduling Algorithm in Ad Hoc Wireless Sensor Area Networks

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Abstract— **Energy efficiency is the most important goal of an ad hoc wireless sensor network (AHWSN). Theoretically the most energy efficient MAC protocol would be a TDMA based protocol without the administration, control and exact timing signals that need to be conveyed in a TDMA scheme. This paper presents a hardware answer as well as a TDMA scheme and protocol for a MAC layer that is as close to the theoretical ideal as possible. The hardware solution is a low power hardware mailbox that enables nodes to catch messages destined for them while they are asleep and at the same time it affords lee-way to the exact timing of the synchronisation needed for a TDMA scheme. The protocol provides a solution to reducing the amount of non-data 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 transmissions of other nodes.**

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

I. INTRODUCTION

AN Ad Hoc Wireless Sensor Network (AHWSN) comprises a number of self-containing electronic devices which communicate with each other wirelessly, and which have a particular purpose of sensing a parameter, whether it be 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 nodes of the network. They are also the only resources of the network to other nodes. The primary goals of AHWSN are, in the order of importance, energy efficiency (to prolong the life of the network), self organising (the network must continue to exist when nodes fail), scalability and reduced cost of each node.

This paper presents a mailbox for the nodes of the network. It acts as a buffer for the signal being sent from a transmitting node to a node that is asleep, and a TDMA scheduling algorithm for the MAC layer.

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A. *THE MAILBOX*

The function of the mailbox is to store detected signals while a node is asleep. The purpose of this new design is that a node could go to sleep i.e. save battery life and still receive other nodes' messages destined for it from other nodes.

The mailbox is hardware that is integrated into each node, so there is no need for a special node which would act as a mailbox and then relay the message onto a sleeping node once it awakens.

An added benefit of the mailbox is that a sending node and a receiving node in a data transfer do not require to be synchronised with each other.

A network of nodes with mailboxes would allow the following step by step scenario:

1. An awake node has a message to send to a node that is asleep.
2. The awake node gains access to the channel.
3. The awake node requires no synchronisation with the asleep node, it just sends the message and the asleep node's mailbox catches and stores the message.
4. The asleep node awakes later. Checks it's mailbox for messages and sends acknowledgements accordingly.

A mailbox can be implemented with any MAC protocol. There are two main categories that MAC protocols fall under: CSMA and TDMA. The next section discovers which scheme works best when utilising mailboxes.

II. CSMA VERSUS TDMA

MAC protocols for AHWSNs are either contention based (CSMA) or 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.

The following Table 1 lists advantages and disadvantages of TDMA over CSMA with and without a mailbox. The advantages are marked with a star.

TABLE I
COMPARISON OF TDMA VERSUS CSMA WITH AND WITHOUT A MAILBOX

	CSMA	**CSMA/ CA with mailbox**	**TDMA**	**TDMA with mailbox**
Requires initialisation before use: (Energy consuming)	No*	No*	Yes	Yes, but Simpler
Requires time synchronisation:	No*	No*	Yes	Far Less Strict*
Requires co-ordination by certain nodes or super nodes? (Energy consuming) (Resources are very scarce in WSN).	No*	No*	Yes	No*
Has the hidden terminal or / and the exposed terminal problem:	Yes	Yes	No*	No*
Maintains a schedule to avoid collisions:	No	No	Yes*	Yes*
Requires sensing the medium before transmission: (Energy consuming)	Yes	Yes	No*	No*
Requires overhead bits for the request and the usage of the channel? (Energy consuming)	Yes	Yes	No*	No*
Requires a schedule derivation?	Yes	Yes	Yes	Yes
Latency? Dependant on … 1. Awake/ asleep cycle 2. Length and number of time slots	1	1	2	2
QoS? (This cannot be implemented in a random technique)	No	No	Yes*	Yes*
Performance in a sparse packed network?	Good*	Good*	Ave.	Ave.
Performance in a densely packed network? 1. Poor 2. Good to Excellent	1	2	2*	2*
(Number of stars)	****	****	******	********

Thus the TDMA MAC with mailboxes has the greatest number of advantages.

III. THE TDMA MAC WITH MAILBOXES PROPOSAL

TDMA requires initialisation with or without the mailbox, but with a mailbox the process is simplified. Initialisation within a TDMA scheme requires synchronisation of the nodes to a timing schedule for data transfer and for choosing a time slot. Utilising a mailbox the nodes can transfer data asynchronously thus during initialisation the nodes only require to choose a time slot and know the length and number of time slots there are in the scheme to know when next their turn will be to utilise the channel. Now a node may set its wake up to (length of time slots)*(number of time slots - 1). Every so often a node may stay on at least half of an entire TDMA cycle and ensure that it is roughly synchronised to the other nodes. Thus there is no need for a central point co-ordinating and synchronising the nodes or having some nodes co-ordinating data transfers of their neighbours and synchronising them as in [4], [6], [7], [8], [9], [10]. *This is the first TDMA MAC proposal for AHWSN that doesn't require some kind of central point or super nodes to conduct TDMA administration.*

There is no hidden terminal in a TDMA scheme. The nodes can assume that the channel is free during their time slot and that no internal network collisions will occur. (Though this does not guarantee that an external interference might not be present.) [11] clearly proves that Bluetooth, frequency division and orthogonal coding over the network to reduce collisions is high energy consuming. Knowing the medium is free ensures that the node need not spend energy sending requests for the medium and require sensing that no other node is sending a message. The less administration there is in sending data, the more energy is saved in not requiring all the extra overhead bits in the process.

[13] argues that a contention based MAC has a lower latency than a TDMA MAC but this is not true. Scheduling TDMA in the following manner gives the same latency as in contention based protocols.

CSMA TDMA
Awake Asleep…………… Awake Asleep……………
Awake Asleep…………… Awake Asleep……………
Awake Asleep…………… Awake Asleep……………

The latency of a data transmission in TDMA is dependant on the length and number of the time slots. Due to this and the fact that all nodes will have a chance to send data in a TDMA cycle (whereas in a contention based MAC approach it is unsure if all nodes will have a chance to do so), means that TDMA can guarantee a QoS. The QoS defines the bit rate transferring data from one node to its neighbour but when viewing the entire network the QoS changes according to where the information is headed. This is due to some nodes being inherently many more hops away, from where they are sending their information to, than other nodes, so some nodes will always take longer to pass their messages.

In small networks contention based MAC algorithms perform well but scaling up to larger networks the protocol performs very poorly. This is due to the probability of collisions rising rapidly as the number of neighbours of a node rises incrementally [Appendix]. The proposed TDMA MAC with mailboxes approach is for large scale densely packed networks where a TDMA scheme eradicates internal network collisions. 'Studies reveal that energy wastage in existing MAC protocols occur mainly from collision, overhearing, control packet overheads and idle listening.' [6]. A TDMA MAC with mailboxes focuses on minimising all of these energy wastages.

IV. THE HARDWARE DESIGN OF A MAILBOX

A logical block diagram of a hardware implementation of the mailbox:

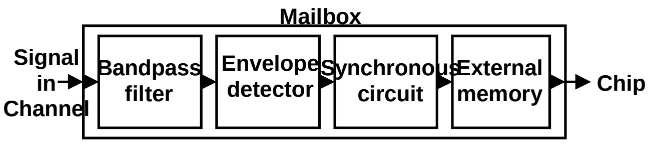

Figure 4.1 A block diagram for a mailbox

The low power external memory is exterior to the chip that is asleep.

The general transmission of data in a network (that is without a mailbox) can be summarised by the following diagram and roughly consumes the following energy:

Chip	**->Modulator**	**->Channel**	**->Demodulator**	**->Chip**
20mA	**->40mA**	**->**	**->40mA**	**->20mA**

Figure 4.2 General Transmission of data and current consumption

Subsequently if we were to add a mailbox to the hardware then the following could be noted:

- Adding the mailbox circuit in between the channel and the demodulator as a buffer would not conserve energy but deplete the battery faster!
- The synchronising logic in the mailbox design would require demodulating the signal too! So having a demodulator and mailbox is not necessary.

A better implementation would be to combine the mailbox and the demodulator, or even disregard the demodulator completely. Replace the demodulator with a low power A/D converter instead (like an eight level comparator) which is triggered by the envelope detector that plots out 2-dimensionally the incoming signal. Then later the chip can interpret / demodulate the signal via software. Thus:

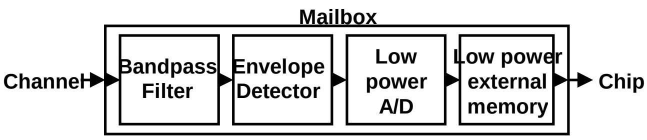

Figure 4.2 General Transmission of data

The Bandpass filter and envelope detector consumes very little energy, less than 10μA but is continuously 'on', drawing current. The low power A/D and external memory are powered up when a signal is detected by the envelope detector. Then the "shape" of the signal is stored and demodulated via software of the chip when the nodes awake.

V. IMPLEMENTING THE TDMA MAC WITH MAILBOXES

A general TDMA scheme shares a channel in time in round robin form for synchronous data transmission over one medium. This proposal uses the TDMA's time division technique so a node is aware of when it may utilise the channel but the data transmission is asynchronous.

In an Ad Hoc TDMA environment, nodes need to group together so that they can share the medium amongst themselves. Many other MAC protocols [4], [6], [7], [8], [9], [10] enforce the nodes in set clusters. This TDMA MAC with mailboxes proposes that *the nodes do not form set clusters but each node with its neighbours composes 'its own cluster'. Again, this is the first paper to present this idea for AHWSN.*

This can lead to the hidden terminal problem, but not the exposed terminal problem due to each node having a time slot to transfer data in. The following rule is applied to remove the hidden terminal problem: The maximum number of neighbours a node may have is less than or up to half, the number of time slots there are. This will ensure that if a node has two neighbours which are not in radio range with each other and have chosen the same time slot, the node may request one of the neighbours to change its time slot. Subsequently there will be no great complications or energy consumptions in the change. The change 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 (greatly) with that of any neighbour also using this same timeslot "x." *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. *Once more, this is the only TDMA MAC protocol for AHWSN that can claim such a feature..*

A node awakes at the beginning of its time slot and may go back to sleep when ever it wishes but may only transmit data within that time slot.

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 the entire network is (almost) synchronised.' The nodes only communicate with their neighbours; there is no need for direct communication from one end of the network to the other end of the network. Thus if the network scales and the outside corners are not in synchronisation it doesn't affect the protocol.

B. *Initialisation of the TDMA 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. The nodes are required only to synchronise their wake / sleep duty cycle, but not to align bits because data transmission is asynchronous.
4) Negotiate the timeslots. Once a node has chosen a timeslot, no other nodes within its radio range may choose the same timeslot.

C. *Scheduling*

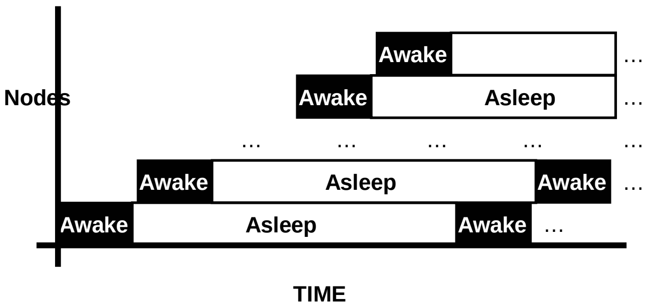

Figure 4.3 Scheduling scheme

With contention based MACs all the nodes are awake at the same time so that they can decide which nodes are sending data when. In this figure 4.3 scheduling scheme, for a TDMA MAC with mailboxes, during one time slot only one node is awake in any given radio connectivity range.

VI. RESULTS

a) Energy Efficiency

A simulator comparing a contention based S-MAC layer to the above presented TDMA MAC with mailboxes is currently in the coding process but some rough estimate results can be calculated using some simple calculations and comparing the two MAC approaches with respect to energy utilisation. This can roughly depict the MACs advantages and disadvantages.

TABLE II
ENERGY CONSUMING ATTRIBUTES

	S-MAC	**TDMA with mailbox**
Initialisation and synchronisation before use: (Energy utilised in demodulation in S-MAC is greater than the mailbox's energy consumed)	Worst case is that the node must send and receive packets that amount to the number of neighbours	Worst case is that the node must send and receive packets that amount to the number of neighbours
Demodulator	Yes	No
Hidden terminal / exposed terminal problem?	Adds to the probability of collisions	No
Collisions? (Within the network)	Yes and the probability may be calculated	No / Almost none
Requires sensing the medium before transmission?	RTS, CTS packets sent back and forth	No
Idle listening? (Waiting for data to come through)	50% - 100% of energy spent during receiving of data [14].	No
Mailbox?	No	Continual energy consumption

Both of these MAC protocols use a random technique to discover their neighbours in initialisation and in the worst case both of them will send the same amount of packets. If a fixed packet length is enforced with each different packet (RTS, CTS, data of S-MAC, data of TDMA MAC with mailboxes) when comparing these two different MAC protocols, then the TDMA MAC with mailboxes will be predominantly more energy efficient in the initialisation stage than the S-MAC protocol. This is due to the receiving of packets in the two schemes differ and the mailbox utilises less energy in receiving and decoding a message than S-MAC. A demodulator may easily use twice the energy than the chip, so moving the demodulation to software can be a great reduction is power consumption.

Collisions consume great deals of energy. If a node's duty cycle is one second then in a day eighty six thousand four hundred cycles will occur. If there is a small probability of collisions occurring, for example eight percent probability of a collision in each cycle, then clearly a great deal of energy would be wasted in one day's worth of collisions. The hidden terminal problem increases the probability of collisions. S-MAC endures these collisions but TDMA MAC with mailboxes does not.

Packet control overhead such as RTS and CTS in S-MAC is required to be sent each time a node wants to send data. In TDMA MAC with mailboxes there is no such requirement thus when inter-nodal data transmission occur the packet ratio (if all packets are of a fixed length) is three for S-MAC to one for TDMA MAC with mailboxes.

Once a node has received a confirmation to send data in S-MAC, the sender and receiver wait for the other neighbours to go to sleep and then the transfer of data may occur. The idle time where the nodes stay awake and wait consumes energy.

The mailbox continuously utilises energy in the TDMA MAC with mailboxes protocol. The complete circuit of the mailbox does not require to be powered all the time. Only the first two stages: The Bandpass filter and the envelope detector need to be powered constantly. The envelope detector may switch on the A/D and memory when a signal is detected. Thus the permanent power utilised is approximately a mere 10µA and when a signal is being stored that increases by the amount that the A/D and memory use.

B. Cost of hardware for mailbox

The Bandpass filter and envelope detector would consist of two resistors, a diode and two capacitors, which hardly amount to any added cost to the design. The eight level comparator would consist of a few resistors and op-amps and again that would hardly amount to any significant increase in cost. The low power external memory would be a low power flash memory consisting of a maximum of thirty two kilo bytes of data. This would make a significant difference in cost, but with flash memory being produced in bulk the price would be reduced as the industry produces.

VII. CONCLUSION

A. TDMA MAC with Mailboxes versus S-MAC

The TDMA MAC with mailboxes is more energy efficient than S-MAC in:

- Demodulation
- Amount of packets sent in a data transfer by 3:1
- Having no inter-nodal collisions
- Not having an idle listening stage between two nodes transferring data

The TDMA MAC with mailboxes is less energy efficient than S-MAC in:

- Requiring the mailbox to be powered at all times

B. TDMA MAC with Mailboxes versus other TDMA MACs

The TDMA MAC with mailboxes 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
- No central point or super nodes co-ordinating the TDMA scheme
- The data transfer is asynchronous
- 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. TDMA MAC with Mailboxes uniqueness in AHWSNs

The TDMA MAC with mailboxes has the following unique features that are the first of its kind in AHWSN:

- Demodulation occurs in software
- The receiving node of a data transfer does not require being awake while accepting data

D. TDMA MAC with Mailboxes' cost versus S-MAC's cost

Energy efficiency is the primary goal of AHWSN but its secondary is the cost of each node. With the addition of a mailbox costs are incurred but at the same time the node no longer requires a demodulation circuit (if it was separate to the modulating one) which would reduce costs. The two would not cancel each other out. Further investigation is required for the actual increase in cost per node.

VIII. FUTURE IMPROVEMENTS

Energy efficiency has been focused upon for each node but what has not been addressed is that each node passes on messages that are not its own. (Each node is another node's resource). One node can spend more energy passing on messages than another. This is unfair to the nodes that pass more messages on than others. A future improvement would be adding a neighbour power level table to each node thus ensuring that there is fairness among sharing the networks responsibilities.

The definition of the TDMA MAC with mailboxes cycle is that one definition exists across the entire network. Certain parts of the network could be more densely packed than others; a future improvement would be an on-the-fly reconfiguration of a certain area of the network's TDMA cycle to optimise performance.

Another improvement for QoS would be to implement a prioritised MAC layer.

Appendix

If α = the number of neighbours a node has plus itself, and

β = the time allocated for a node to send a SYNC or a RTS or a CTS, and the exponential $^{n} = \alpha / \beta$, then the probability, converted into a percentage, of a collision occurring during the SYNC or RTS or CTS stage of the S-MAC awake cycle is:

$(1- (1- (\alpha / \beta))^{n}) * 100$

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