

DELAY EFFICIENT MAC PROTOCOL FOR DIFFUSION BASED ROUTING IN WIRELESS SENSOR NETWORKS

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Abstract: In this paper we present DESMAC a contention based Medium Access Control protocol for Diffusion based routing in Wireless Sensor Networks. One of the main challenges in WSNs is to balance delay efficiency and energy consumption. Surveillance and monitoring application as well as many other need low latency data delivery; but, since sensor nodes have a small source of energy usually Active/Sleep cycles are used to reduce the energy consumption which causes higher delay. We use routing information to adaptively change the duty cycle for different loads. In our Cross Layer Design the Routing Layer can manipulate the duty cycle of underlying MAC protocol. The diffusion control messages are used to adapt the duty cycle to variation in the load. Also extensive use of some nodes can damage the connectivity of network. Therefore we provide a mechanism to balance the load between several possible paths. We discuss DESMAC design and compare our simulation results to S-MAC and IEEE 802.11 standard. DESMAC achieves significant latency reduction (up to 50 times better delay than S-MAC) while ensuring energy efficiency and load balanced delivery.

1 INTRODUCTION

A wireless sensor network is a distributed system which contains a large number of low-power, short-lived, unreliable sensors that use a low-bandwidth wireless radio for communication. (Akyildiz et al., 2002) They can be used for a number of applications from target tracking and habitat sensing to fire detection. (Werner-Allen et al., 2006), (Mainwaring, et al., 2002).

The goal of a wireless sensor network is reliable data reporting and minimum energy consumption. Sensor nodes have a small supply of energy which makes power management a great criterion in protocol design for this kind of networks. Motes (Cross Bow, 2004) can last approximately around 100-120 hours on a pair of AA batteries in active mode (Kumar et al., 2006) and battery capabilities only double every 35 years. (Ye, et al., 2002) Several methods have been proposed to put sensor nodes to inactive mode when the application of the sensor network is able to tolerate the effects (Ye, Heidemann and Estrin, 2004) (van Dam and Langendoen, 2003) (Wang and Xiao, 2005). Putting nodes to inactive mode reduces

the idle listening time which is one of the major sources of energy wastage. On the other hand it causes higher delay, lower coverage & lower connectivity in exchange for energy efficiency. Since many applications have delay or coverage criterion, use of many sleep scheduling schemes can be limited (Lu et al., 2005), (Kumar et al., 2006), (Akyildiz et al., 2002).

Medium Access Control protocols in wireless sensor networks need to be energy efficient since it is usually impossible to replace or recharge the batteries. Moreover many applications have latency and rate requirements. Balancing the trade-off between energy efficiency and delay efficiency has been subject of great deal of research. Adaptive adjustment of MAC layer's duty cycle based on current load and situation is one of the possible solutions. MAC layer information about the network is usually not sufficient and vague. MAC layer is usually does not have the information necessary to determine if degradation of data transmission is due to a neighbor's failure or a temporary distortion, etc. One of the ways to meet both the energy and delay criterion of applications is by using the help of

Routing and Application layer information to optimize the duty cycle of the MAC layer based on the current load and situation. Use of application specific information and routing data can help better adjust the duty cycle of the MAC layer.

Diffusion based routing algorithms are very popular in wireless sensor networks (Intanagonwiwat et al., 2003), (Ganesan, et al., 2001), (Al-Karaki, and Kamal, 2004). Routes are created on demand when an event occurs and are not maintained by all sensors all the time. All nodes in diffusion based routing are application-aware. Directed Diffusion's messages can be used for adjustment of MAC layer's duty cycle to provide delay efficient data transfer.

In this paper we present a delay efficient MAC protocol with adaptive duty cycle to minimize the delay in diffusion based routing algorithms. We also provide means to balance the load in dense sensor networks. Load balancing allows efficient use of different nodes that can be used for routing data. This cross layer design uses the routing and application layer information to adjust the MAC layer duty cycle to provide delay efficient and load balanced data delivery.

The rest of paper is as follows. In Section 2 we review some of related works. Several MAC protocols designed specifically for wireless sensor networks are discussed and their features are presented. We also present why we chose directed diffusion as our routing protocol and give quick introduction on how diffusion routing works. In section 3 we present DESMAC, a delay efficient MAC protocol with load balancing features designed specifically for diffusion based routing. We use SMAC and Directed Diffusion as the basis for our design. In section 4 we present our simulation results. Section 5 presents our conclusions.

2 RELATED WORKS

Several approaches for the design of a MAC protocol for wireless networks have been used. Contention based methods (CSMA) focus on maximizing throughput and minimizing the latency. Although IEEE 802.11 allows putting node to a *power-save* mode, it is optional for each node and usually happens when the nodes has been idle for a long period. Nodes are most of the time active in IEEE 802.11; which dramatically increases the *idle listening* (sometimes up to 99% of the time) in

nodes. Idle listening consumes almost the same energy as receiving data. (Ye, et al., 2002) Keeping nodes active all time on the other hand minimizes the latency.

TDMA methods on the other hand have a built in duty cycle and usually have lower energy consumption in comparison to CSMA methods. The main problem of these schemes is that obtaining and keeping the neighbors schedules takes up too much memory and is very complex. Also they need very tight time synchronization between the nodes. Although several methods have been proposed to provide microsecond level time synchronization (Gelyan, et al., 2007) (Elson, Girod, and Estrin, 2002) dividing time to small slots can be dramatically affected by clock drifts. Developing and efficient schedules with a high degree of concurrency is very hard (*NP Hard*) (Rhee, et al., 2005).

S-MAC (Ye, Heidemann and Estrin, D., 2002) (Ye, Heidemann and Estrin, 2004) is specifically designed for sensor networks. Each node periodically sleeps, wakes up and listens to channel. In this contention based method time is divided into two parts: In the active period first neighbor nodes exchange their sleep schedules (the SYNCH period) and then they contend to reserve the media for data transmission using an RTS/CTS scheme. The active period is fixed (115 ms). The sleep period determines the duty cycle of S-MAC. S-MAC inspired by PAMAS tries to avoid overhearing by putting the interfering nodes to sleep after hearing an RTS or CTS message. Data transmission is done via fragmentation of long packets into small messages. In (Ye, Heidemann and Estrin, 2004) *Adaptive listening* in which an immediate neighbor wakes up after the end of a transmission to check if it is the next hop of the message, is proposed to reduce the *sleep delay*.

T-MAC (van Dam and Langendoen, 2003) introduces the *adaptive* duty cycle by dynamically ending the active period of it. It uses a very short listening period at the beginning of the active period. It is able to achieve higher energy efficiency in comparison to S-MAC under different workloads.

B-MAC (Polastre, Hill and Culler, 2004) is a CSMA protocol that provides a flexible interface to achieve low power operation. B-MAC uses clear channel assessment and packet backoffs for channel arbitration, link layer acknowledgments for reliability and low power listening (LPL) for low power communication. It achieves higher data

delivery and power efficiency than S-MAC and T-MAC. B-MAC is a link protocol, with network services like organization, synchronization, and routing built above its implementation. S-MAC and T-MAC may be implemented as services that use B-MAC as underlying link protocol.

Z-MAC (Rhee, et al., 2005) presents a hybrid MAC for wireless sensor networks that try to combine the strengths of both TDMA and CSMA. It uses a distributed implementation of RAND to assign time slots to nodes. Nodes can send at their own time slots and other nodes time slots but the owner has priority over other nodes. Experiments show that it can achieve higher throughput than B-MAC.

D-MAC (Lu, Krishnamachari, and Raghavendra, 2004) proposes an energy and delay efficient MAC protocol for unidirectional trees in wireless sensor networks in which data is collected from several source nodes and is sent to the sink through the tree. It proposes staggered active/sleep schedule to reduce the sleep latency. It needs local time synchronization among the nodes.

P-MAC (Zheng, Radhakrishnan, and Sarangan, 2005) presents another method to dynamically change the duty cycle. The schedules are determined based on the node's own traffic and that of its neighbors. In P-MAC the node get information about activity in its neighborhood through *patterns*.

These MAC protocols that try to adaptively adjust the duty cycle using information available in the MAC layer.

In order to adapt the duty cycle of sensor nodes to variations in the network load and meeting latency requirements efficiently, having information about traffic characteristics and application needs is necessary. Since the sensor nodes have extremely small memory and processing power a simple yet efficient design is required. The best way to acquire necessary information required to effectively adjust the duty cycle is using the application and routing layer information. A cross layer design allows better use of information available to different layers to optimize the overall performance.

Several approaches to solve the routing problem in wireless sensor networks have been proposed (Al-Karaki, and Kamal, 2004). Directed Diffusion is one of the most popular approaches that has become a breakthrough in routing. Many other protocols have been proposed based on directed diffusion (Handziski, et al., 2004), (Al-Karaki, and Kamal, 2004).

Directed Diffusion (Intanagonwiwat et al., 2003) presents a data-centric approach to routing problem in wireless sensor networks. All the nodes in a directed diffusion based network are application aware. Directed diffusion uses several elements: interests, data messages, gradients, and reinforcements. Interest messages contain named attributes and specify what user wants. Interest messages consist of Attribute-Value pairs that altogether define a task. The node that injects this packet to the network is called *sink*. Sink periodically broadcasts Interest Messages.

Each node maintains an *interest cache* which contains distinct received interests. Nodes that receive new interest messages add them to their interest cache and re-broadcast the messages to their neighbors. This interest message appears to originate from the sending node. Every pair of neighboring nodes establishes a gradient toward each other.

If an event which matches one of the items in the interest cache is found, node starts sending data messages. This node is called the *source*.

Upon reception of data messages in *sink*, sink sends a positive reinforcement message to selected neighbor node(s). Positive reinforcement message causes neighbor nodes to set a higher gradient toward the sender. This sequence of local interactions establishes a path from source to sink. Several paths can be established based on this method which is why the sink sends *negative* reinforcement messages to reinforce a single path.

Directed Diffusion is very energy efficient since it presents on demand routing and also there is no need to maintain a global network topology. Only local interactions are used to route the packets toward the destination. Moreover since the communication is only between neighbors, and nodes are application aware each node can perform caching and aggregation. (Handziski, et al., 2004)

Most works on Directed Diffusion have used IEEE802.11 as the underlying MAC protocol. (Intanagonwiwat et al., 2003), (Ganesan, et al., 2001), (Handziski, et al., 2004). S-MAC poses high data transmission delay and high jitter which can mess with routing operations.

3 DESMAC, OUR APPROACH

We introduce a novel cross layer design to reduce latency caused by periodic sleeping of the nodes. Routing and application are used to help the MAC protocol better adjust itself. We use S-MAC as the basic framework for our design and adaptively change its duty cycle.

In this approach we use routing layer control messages to adaptively reduce the sleep period of the MAC layer of the nodes that take part in the routing process. We decrease the sleep period of the nodes that are reinforced by Directed Diffusion for routing purposes. Nodes that are not reinforced preserve their current sleep schedule. This results in lower latency in exchange for higher energy consumption in the nodes involved in routing but doesn't have any impact on the nodes not involved.

In Directed Diffusion sink periodically sends interest messages to all nodes in the network. When a node detects an event which matches the diffused interests it becomes a data source and starts sending exploratory data messages. These messages are forwarded towards the sink. When the sink receives a positive reinforcement it issues a *positive reinforcement*.

Positive reinforcements are similar to interest messages but have lower interval. Each node compares this interest message with the fields in its own cache and if a lower interval is detected, it updates its gradient toward that node to the new value. In our approach positive reinforcements also trigger a sleep period reduction in the MAC layer.

Negative Reinforcements have the exact opposite effect on the sleep period. Negative reinforcements in Directed Diffusion are used to reduce the number of reinforced paths and path repairs. Several mechanisms for negative reinforcement are introduced in directed diffusion (timeouts, gradient reductions, etc). Any mechanism for negative reinforcement used by Directed Diffusion also triggers an increase in the sleep period of the MAC layer.

The goal is to benefit from energy saving features of S-MAC and have much lower latency in comparison to it. Nodes that are not reinforced by the Directed Diffusion have the same duty cycle as S-MAC, But nodes that are reinforced increase their active period exponentially therefore upon path establishment nodes on the path are almost always active which

results in very low latency that is comparable to IEEE802.11.

Nodes that are not part of routing preserve their original duty cycle and have similar energy consumption to S-MAC. But routing nodes have high duty cycle which provide very low latency and can meet the application criteria.

In case a path failure or degradation occurs, the path is negatively reinforced by Directed Diffusion which will reduce the duty cycle of the nodes previously involved in the routing. Therefore nodes that are no longer involved in routing have low duty cycle and energy saving is maximized.

S-MAC works on the basis that neighbor nodes wake up at the same time therefore they can hear each other's broadcast messages (SYNC, RTS/CTS). If neighbor nodes don't have synchronous schedules, communication between them becomes impossible.

Dynamic reduction of sleep period can disrupt the synchronization done in the SYNC period of S-MAC.

To address this problem we reduce the sleep period in a manner that the SYNC and listen period of the new schedule is still synchronized with that of neighbor nodes. In order to achieve synchronized wakeups we increase the duty cycle exponentially. The sleep period in S-MAC is much longer than the listen period therefore it is possible to reduce it so that the frame size is divided in half. Each frame turns into two frames with SYNC, RTS/CTS, and sleep period. For example if the duty cycle is 10% (default for S-MAC) the duty cycle after positive reinforcement is 20%. Each positive reinforcement message doubles the duty cycle of the node until it achieves maximum possible duty cycle (in this case 80%). This is shown in Figure 1.

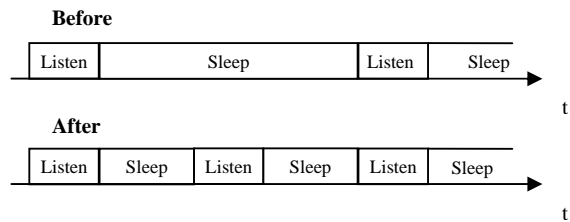


Figure 1, Change in Duty Cycle as a node receives a reinforcement message. Beginning of Listen periods is still synchronized.

Increasing the duty cycle in this fashion does not disrupt the synchronized wakeup of the neighbor nodes. Nodes that are on the same path have the same duty cycle. These nodes wakeup more often

and have more time for transmitting data therefore provide lower latency and higher throughput. These nodes are still able to communicate with the nodes that have different duty cycles. Since the duty cycle is increased exponentially the neighbor nodes still have the synchronized wakeup. After a positive reinforcement is received each two wakeup of the node is synchronized with one wakeup of its neighbors with the normal duty cycle, Therefore the node is able to normally communicate with its neighbors.

Nodes active in the routing process have very small sleep periods and show similar behavior to 802.11. But nodes not involved behave similar to S-MAC.

Since the control messages of Directed Diffusion are used to dynamically adjust the duty cycle of the nodes no messaging overhead is caused.

3.2 Load Balancing

Nodes that are involved in routing for a long period will fail faster than other nodes in the network.

These nodes have higher energy consumption as a result of higher duty cycle. Failure of these nodes can cause the network to be partitioned. This can endanger the connectivity of the network and has several other unwanted effects such as reduced coverage, etc.

In dense sensor network multiple paths may exist between a source and destination; therefore, it is desirable to use all these paths in order to efficiently use the energy in a distributed manner. (Ganesan, et al., 2001) is an example of a diffusion based multipath routing algorithm. Directed Diffusion's nature makes it a good candidate for multipath routing. In fact Directed Diffusion initially reinforces several paths and then tries to reduce the number of paths by using negative reinforcements.

In our cross layer design we use this multipath potential of Directed Diffusion to use MAC layer duty cycle to balance the network load based on remaining routing nodes' energy. We define a critical remaining energy limit for the nodes. When a node hits this critical limits it will dramatically reduce its duty cycle which will degrade the data delivery rate to the sink node. This degradation is detected by Directed Diffusion and triggers the local path repair mechanism. In local repair mechanism when a node detects degradation (either by noticing that event reporting rate from its upstream neighbor is now lower, or by realizing that other nodes are

transmitting previously unseen reports) it applies reinforcement rules to discover another path.

This chain of local interactions results in another path establishment that does not contain the node that has reached the critical energy limit. In a dense network where there are several neighbor nodes that can replace a node with low energy level this mechanism can be used to efficiently distribute energy consumption on neighboring nodes.

In order to provide more control over different energy levels we define several duty cycle reduction levels. When a node reaches the predetermined critical energy level it reduces its duty cycle to half the original duty cycle in the deployment time. This will cause a dramatic change in duty cycle of node that has been involved in routing and has a high duty cycle. To maintain the synchronization between sensor nodes duty cycle reduction is exponential (similar to path reinforcements). Every time a node reaches a new energy level it will trigger a duty cycle reduction in the same manner. For example if three energy levels are defined the duty will be reduced up to one eighth of the original duty cycle.

The critical energy limit and different energy levels can be defined based on the network, traffic, and application characteristics. If high data delivery rate is the most important criterion in the application a low critical energy limit can be used to allow maximum delivery rate in exchange for high energy consumption. But if network longevity is the ultimate goal a high critical energy limit should be used to avoid early node failures. These levels can also be dynamically changed based on current network situation and application needs.

4 SIMULATION RESULTS

We compare our MAC protocol to 802.11 and S-MAC. We used NS-2 for our simulations. Latency and energy consumption of a Directed Diffusion application on three MAC protocols: 802.11, S-MAC, Delay Efficient S-MAC (DESMAC) will be compared. The initial energy of the nodes is 3000 joules. To compare the energy consumption of each protocol we use the power consumption model of Cabletron 802.11 network interface card in Transmit, Receive, Idle, and Sleeping modes (Chen, et al., 2002). Energy consumption in different modes is shown in Table 1.

Table 1, Energy consumption of Cabletron network interface card in different modes.

Transmit	Receive	Idle	Sleeping
1400mW	1000mW	830mW	130mW

Nodes' deployment is grid and source and sink are at the ends of grid's diagonal.

In 802.11 all nodes are active all the time therefore it has highest energy consumption and lowest latency. S-MAC on the other hand has fixed long sleep periods therefore has the highest latency and lowest energy consumption. In DESMAC nodes involved in routing have high duty cycle to provide low latency data transmission and therefore have higher energy consumption. Nodes not involved in routing have low duty cycle and have similar energy consumption to S-MAC. Since the number of nodes involved in routing is a small fraction of deployed nodes overall energy consumption is comparable to S-MAC. Also since the sleep period in the routing nodes is very short the latency is comparable to 802.11.

Before the path establishment, delay of S-MAC and DESMAC is similar because no positive reinforcements are sent but as the path is reinforced data transmission delay between source and sink is dramatically decreased. In the path establishment phase some nodes may be falsely reinforced which makes them to increase their duty cycle. These nodes will return to their normal duty cycle when the path establishment phase is finished and these nodes are negatively reinforced.

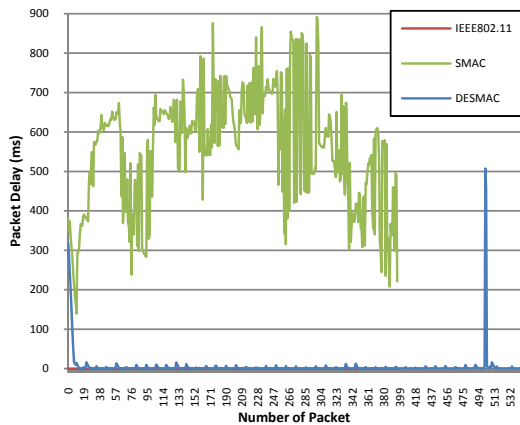


Figure 2: Comparison of Packet delivery delay in different MAC protocols for 6×2 grid deployment

Figure 2 compares the latency between S-MAC and DESMAC and IEEE802.11. As shown average delay in DESMAC is much lower than S-MAC. Since S-MAC is not able to transfer data message with the required rate, queuing delay makes the behavior of S-MAC unpredictable. It can also trigger unwanted path changes in Directed Diffusion since it may falsely detect degradation in the current path because of high jitter. DESMAC on the other hand shows a much more stable behavior. Small path changes because of load balancing mechanism create a small variation in DESMAC's delay. As expected delay of IEEE802.11 is lower than DESMAC (always near zero).

Figure 3 compares average delay of these MAC protocols as the network size increases. S-MAC shows an unpredictable behavior in packet delivery and IEEE802.11's delay always remains near zero. DESMAC's delay is much lower than S-MAC and shows a much more stable behavior than it. Since nodes are not always active in DESMAC, each hop poses a delay on the data transmission. Therefore, delay in data transmission is slightly higher as the number of hops increases.

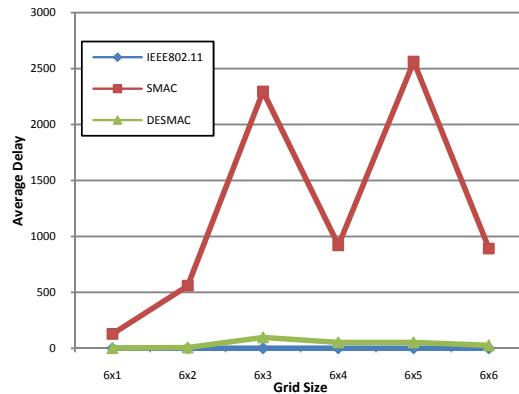


Figure 3: Average delay for different network size

Figure 4 compares the energy consumption of S-MAC, DESMAC, and IEEE802.11. IEEE802.11 has the highest energy consumption and nodes fail much sooner than other protocols (mid-way during simulation). DESMAC has higher energy consumption than S-MAC because nodes involved in routing have higher energy consumption than nodes with the normal duty cycle.

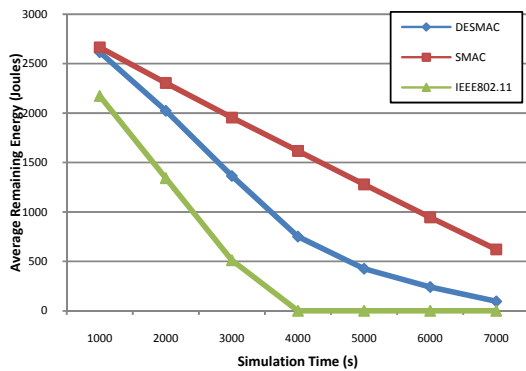


Figure 4: Comparison of energy consumption in different MAC protocols

Figure 5 compares the average remaining energy of the network. IEEE 802.11 as expected has the highest energy consumption. Nodes are always active and the number of nodes involved in routing doesn't affect the average total remaining energy of the network. S-MAC has the lowest energy consumption, and similar to IEEE 802.11 average remaining energy doesn't depend on the number of involved nodes in routing. DESMAC's total remaining energy is close to S-MAC but since nodes involved in routing have higher energy consumption total remaining energy decreases as the number of these nodes grow. The network size has another effect on the average remaining energy. As number of paths increases multiple path changes becomes possible and different nodes during simulation may become involved in routing therefore number of nodes that have very high duty cycle decreases. This results in lower energy consumption in network. But as network size grows further number of nodes involved in routing becomes a high percentage of the deployed nodes therefore total remaining energy of the network decreases.

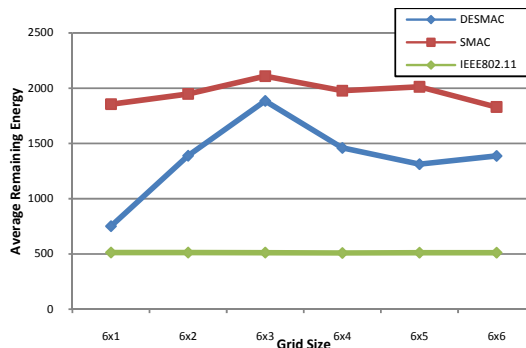


Figure 5: Average network remaining energy for different network size

2.3 Conclusion

In this paper we presented DESMAC, a delay efficient MAC protocol for diffusion based routing in wireless sensor networks. It supports power saving features and adapts to data transmission load in different situations. DESMAC does not pose any messaging overhead for its adaptive duty cycling and load balancing. It has much lower delay in data transmission in comparison to S-MAC and has much better energy consumption in comparison to IEEE 802.11.

In order to avoid failure of nodes involved in routing due to higher energy consumption in these nodes DESMAC changes the path when these nodes hit a critical energy limit. This results in higher network longevity and preserving of network connectivity.

In the future we plan to test this protocol on multipath diffusion based routing algorithms such as (Ganesan, D. et al., 2001). This approach has built in multipath capabilities in the routing layer and increases the resilience to node failures.

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