TOPOLOGICAL DEPENDENCE AND FAULT TOLERANCE IN TDMA BASED POWER CONSERVATION FOR WSNS

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Keywords: Wireless Sensor Networks, Energy Efficiency, TDMA.

Abstract: Energy conservation is a very critical issue in energy-constrained wireless sensor networks that introduces sleep-mode related delay. Since a long time delay can be harmful for either large or small wireless sensor networks, a TDMA-based scheduling scheme has been proposed, that achieves the reduction of the end-to-end delay caused by the sleep mode operation while at the same time it maximizes the energy savings. However, the performance of this system has not been studied with respect to the topology of the network, and taking into consideration node failures. In this paper, we evaluate the TDMA-based energy conservation scheme, and compare it to the S-MAC and the adaptive listening schemes, on various random topologies. In addition, we examine the performance when node failures occur, and introduce a schedule update criterion.

1 INTRODUCTION

Wireless Sensor Networks (WSNs) are increasingly used in a great number of applications nowadays. The environmental, medical and military sectors are some of the most important areas that the recent developments have been applied in. WSNs consist of an adequate number of tiny, cheap and low-power sensor nodes, which collect and disseminate critical data (Akyildiz, Weilian, Sankarasubramaniam, & Cayirci, 2002). Each sensor node has limited power capabilities due to the various limitations arising from the need for inexpensive device, its limited size, small weight, and ad-hoc method of deployment. Various energy-efficient schemes have been proposed in the literature in order to guarantee the WSNs' survivability and to increase the network lifetime in such special-purpose environments. Significant energy savings can be accomplished by allowing the sensor nodes to enter sleep mode. However, since nodes in sleep mode cannot detect any transmissions in their vicinity, they cannot participate in packet forwarding. Thus synchronization schemes are needed, that can let the

J. Vergados D., A. Pantazis N., D. Vergados D. and Douligeris C. (2008).
TOPOLOGICAL DEPENDENCE AND FAULT TOLERANCE IN TDMA BASED POWER CONSERVATION FOR WSNS.
In *Proceedings of the International Conference on Wireless Information Networks and Systems*, pages 53-58
DOI: 10.5220/0002027600530058

sensors' transceivers remain in sleep mode as long as possible, and at the same time to keep the network from partitioning.

Several power conservation mechanisms have been proposed for WSNs (Pantazis, Vergados & Vergados, 2006; Pantazis & Vergados, 2007; Srisathapornphat & Chien-Chung, 2002; Trigoni, Yao, Demers, Gehrke, & Rajaraman, 2004; Vergados, Vergados, & Douligeris, 2005; Yang & Vaidya, 2004). S-MAC (Ye, Heidemann, & Estrin, 2002) is the most well-known sleep mode synchronization scheme. It saves energy by creating a common wakeup period for the nodes in the network, followed by a sleep period. Nodes buffer their packets until the next wakeup period takes place. This strategy however increases the end-to-end delay for multihop communication paths. This happens, because each forwarder, after having received a packet, must wait for the next scheduled wakeup time and must then perform the transmission, otherwise the following node will probably be in the sleep mode, and there will be no reception. Thus, the end-to-end delay, caused by the sleep mode, is an increasing function of the intermediate forwarders.

This *Adaptive listening* (Ad_Li) provides an extension to S-MAC by trying to reduce the end-to-end delay caused by the periodic listen-and-sleep (Ye et al., 2002). The basic concept is that the node which overhears its neighbors' transmissions (ideally only the RTS or CTS packets) will wake up for a short period of time after the transmission, allowing its neighbor to immediately transmit the packet, without waiting for the next scheduled transmission time.

A TDMA scheduling scheme for energy efficiency has been proposed in (Pantazis, Vergados & Vergados, 2006; Pantazis, Vergados, Vergados & Douligeris, 2008) which constructs an appropriate transmission schedule that achieves high levels of power conservation and at the same time reduces the end-to-end transmission time delay. This is achieved by dividing the wakeup period into slots, and carefully assigning slots to nodes, in a way that transmissions from any node can be forwarded to the gateway in a single wakeup period. In case a node needs to reach the gateway, a WakeUP (WU) packet is transmitted in the appropriate slot, and repeatedly forwarded until it reaches the gateway. Nodes that receive this packet will remain active anticipating the reception of data. Assuming a target end-to-end delivery time, this strategy achieves a reduction of the power consumption, since only one wakeup period is needed for reaching the gateway.

The operation of the TDMA schemes is closely related to the network topology. Thus, the performance of the TDMA power conservation scheme needs to be investigated in various diverse configurations (number of nodes, density, and range). Also, when node failures occur, that may not be instantly reflected in the schedule, some nodes become unreachable. Thus, in this paper, we will compare the performance of the aforementioned power conservation mechanisms, on various random topologies, and for different traffic loads, in terms of delay and power conservation. Also, we will study this effect of faulty nodes, and introduce a schedule update criterion, that will be used for deciding when the TDMA schedule needs to be updated, in order to prevent degraded performance.

This paper is organized as follows: Section 2 summarizes the operation of the TDMA scheduling energy conservation scheme. The performance evaluation is presented in section 3, while section 4 concludes the paper.

2 THE TDMA SCHEDULING ALGORITHM FOR ENERGY EFFICIENCY IN WIRELESS SENSOR NETWORKS

The main goal of the algorithm is to reduce the sleep mode delay in WSNs. In order to achieve this goal, the algorithm builds the schedule using previously collected information which consists of the total number of nodes, the one-hop neighbors and the next hop of every node. This schedule assigns a number of receiving and transmitting slots to every sensor. The assignment procedure takes place in such a way so that a transmission from any sensor can be forwarded to the gateway within a single frame. Energy savings are accomplished by turning off the transceivers of every sensor in the network during the idle operation, and only periodically entering wake up periods. During these periods, the sensors wake up according to a specified schedule. In case there is no need for communication, no packets are exchanged during this phase. On the contrary, if a sensor needs to transmit information to the gateway, it uses its transmission opportunity in the WakeUP phase, and transmits a WU message. This message is repeatedly forwarded, until it reaches the gateway. The nodes that have received and forwarded the wakeup message do not turn off their transceivers during the following sleep-period, until the exchange of information has been completed. This procedure retains the amount of idle listening time at a low value, but at the same time it limits the end-to-end delivery time.

The following procedures are executed: Initially a setup phase takes place, which builds the transmission schedule, followed by an energy-saving phase. During the setup phase, the sensors do not achieve the maximum level of energy conservation, because their wireless transceivers do not enter the sleep mode. The setup phase consists of the following steps: (1) the exchange of hello and routing messages among the sensors, (2) the transmission of the needed information to the gateway, (3) the schedule calculation, and (4) the flooding of the schedule back to the sensors.

Thus, every sensor becomes aware of the other sensors (neighbors) in its communication range, and of the next node in its path towards the gateway. Afterwards, each sensor in the network transmits the above information to the gateway, which uses the algorithm described in the following sections to calculate the appropriate TDMA schedule. Finally, this schedule is distributed to the sensors, which in turn use it during the energy-saving phase for determining the sleep and wake-up periods.

The question arising is which slot should each sensor node use to transmit its WU messages (originated or forwarded) and to which slots should each sensor node listen to. Path WU requires that the first sensor nodes in the path should be assigned in earlier timeslots than the sensor nodes that follow. On the other hand, collisions can be avoided if the sensor nodes, which receive packets at the same time, are not one-hop neighbors. Moreover, transmissions to the same destination should be assigned in different time slots. Ideally, sensor nodes which are not one-hop neighbors should receive at the same time in order to achieve the reduction of the total frame length to the minimum possible (Vergados et al., 2005). Therefore, timeslot scheduling should take into account both the routing paths and the neighboring information. The proposed algorithm creates a TDMA schedule appropriate for WU transmissions in WSNs.

The TDMA scheduling algorithm assigns a transmission slot to every node in the sensor network, and a number of reception slots for every forwarding sensor node, one for each corresponding transmitting sensor node. The algorithm uses the collected information in order to calculate the TDMA schedule. Based on this information, the number of time slots, which each node has to receive prior to transmitting, is calculated.

In the Energy-saving phase the sleep and wake-up periods are determined using the schedule from the setup phase. During the energy-saving phase Path WakeUP instead of Node WakeUp and Path WU Message Aggregation techniques are used for saving energy and maintaining a low end-to-end delay. Since the reduction of the end-to-end delay is required, Path WakeUp is used instead of Node WakeUp. Node WakeUp has longer end-to-end delays than Path WakeUp, as the wakeup messages cannot reach the gateway in a single frame. Also, the application of the Path WU Message Aggregation is important, since, by requiring only one sending slot for each sensor, it reduces the number of receiving slots and, therefore, it reduces the energy spent for idle listening.

This energy conservation scheme is designed for static sensor deployments, where the majority of the traffic is directed to the gateway. The centralized nature of the scheduling algorithm makes it suitable for static deployments with no or very infrequent topological changes.

Most Sleep–WakeUp schemes operate in a per-hop basis. Thus, the transmitting sensor node should wait for the arrival of the appropriate wakeup time of its next-hop destination before it transmits the data. Then, the forwarding sensor node should wait for the wakeup time of the next sensor node in the path, before it transmits the data, and so on, until the message reaches the sensor gateway. This strategy leads to end-to-end time delays that are related to the product of the number of intermediate forwarders times the length of the wakeup interval (Ye et al., 2002).

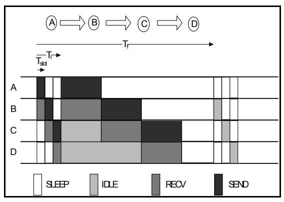

Figure 1: The path WakeUp.

If the source sensor node transmits a short WU packet to the next hop in the transmission path, and this WU packet is forwarded until it reaches the final destination, then all the related sensor nodes will be in the ACTIVE mode, anticipating the reception of the information. Thus, the intermediate sensor nodes can forward the message immediately. Through this technique, the Path WakeUp strategy can allow longer wakeup intervals for the forwarding sensor nodes while keeping the end-to-end delay as short as possible.

In order to take advantage of the Path WakeUp mechanism, TDMA scheduling should be performed in such a way as to ensure that the transmitting timeslot of each intermediate sensor be scheduled before the transmitting timeslots of the next forwarder in the path. Fig. 1 illustrates the power mode transitions of Path WakeUp for a simple 3-hop network. In Fig. 1, A, B, and C are the nodes in a simple 3-hop network, with node D being the gateway. The length of the total period is T_f , the WakeUp frame duration is T_i and the slot length is T_{slot} .

3 PERFORMANCE ANALYSIS AND EVALUATION OF THE TDMA SCHEDULING ALGORITHM

The performance of power-aware MAC protocols depends on many different parameters, such as the traffic arrival rates, the channel congestion, the topology of the sensor network and the routing algorithms. In this section, we quantify the power savings achieved by the proposed protocol, under various network and traffic conditions and the obtained results are compared to other power-saving approaches in the literature. Thus, a simulation tool was developed, that allowed an accurate estimation of the sensors' variables that helped to calculate the values for the entire WSN. Repeated executions on random networks produced the required mean values and the intervals.

The network topology (number and location of sensors) may become a conclusive factor to affect the effectiveness of the power conservation scheme, especially during the TDMA scheduling phase which is the one most heavily influenced by the sensor nodes' topology. This section highlights the effect of the topology on the power conservation mechanisms, both in terms of end-to-end delay and of average power consumption.

In order to accurately determine the behavior of each energy conservation scheme, we must examine various types of network topologies. An object-oriented simulator has been created, which implements a random topology generator, a scheduler and a trace analysis module. Their values are used to calculate the average value of the end-to-end delay for each sensor transmission to the gateway, and the average power consumption of the network, both in standby modes and under various traffic conditions, according to the following equations:

$$\overline{P}_{S-MAC} = (\lambda_o + \overline{\lambda}_T)LP_{send} + \overline{\lambda}_T LP_{recv} + (T_i / T_f)(1 - \lambda_o L - 2\overline{\lambda}_T L)P_{idle} \quad (1)$$

$$\overline{P}_{adaptive} = (\lambda_o + \overline{\lambda}_T)LP_{send} + \overline{\lambda}_T LP_{recv} + (T_i / T_f)(1 - \lambda_o L - 2\overline{\lambda}_T L)P_{idle} \quad (2)$$

$$\overline{P}_{TDMA} = (\lambda_o + \overline{\lambda}_T)LP_{send} + \overline{\lambda}_T LP_{recv} + \overline{n}(T_{slot} / T_f)P_{idle} + \overline{L_{Wt}L_{Wait}}P_{idle} \quad (3)$$

$$E\{D_{S-MAC}(N)\} = \overline{N}T_f - T_f / 2 + t_{cs} + t_{tx} \quad (4)$$

$$E\{D_{adaptive}(N)\} = \overline{N}T_f / 2 + 2t_{cs} + 2t_{tx} - T_f / 2 \quad (5)$$

$$E\{D_{TDMA}(N)\} = \overline{N}(t_{cs} + t_{tx}) + T_f / 2 \quad (6)$$

Where: λ_T is the arrival rate of the through traffic, *n* is the number of TDMA slots each sensor listens to, and $\overline{N}$ is the average number of times node packets are retransmitted, until they reach the gateway.

The above equations were used by the analysis module of the simulator tool. The T_f value for the S-MAC scheme was given by the following equations:

$$T_{f\_SMAC} = N \cdot (D - t_{tx} - t_{cs}) / \sum (n_i - 0.5) \quad (7)$$

$$T_{f\_adaptive} = 2N \cdot (D - 2t_{tx} - 2t_{cs}) / \sum (n_i - 1) \quad (8)$$

where D is the desired delay, and n_i is the number of retransmissions required for sensor *i*'s packets to reach the gateway. For the rest of the parameters, the following values were used: P_{send} = 1.5, P_{recv} = 1.3, P_{idle} = 1, λ = 0.0000 (or otherwise stated), T_{cs} = 0.001, T_{tx} = 0.5, T_f = 10 (or otherwise stated), T_i = 0.001. We generated a 1000 node network and varied the originating arrival rate (λ_o) from 10^{-9} packets/second/sensor, to 1 packet/second /sensor. Fig. 2 illustrates the average power consumption of each energy conservation scheme, for a single 1000 node topology. We observe that the TDMA power conservation scheme has a lower idle power conservation, but when the traffic increases S-MAC becomes better. This is due to the fact that in the TDMA scheme, all forwarding sensor nodes must be awaken as soon as the packet is transmitted from the originating node, resulting in an increased idle listening time, when the arrivals are more frequent.

Nevertheless, the ability to use a large interval for the same delay, results in lower idle power consumption. For the comparison of the performance of the three schemes, under different network topologies, we generated topologies ranging from 198 nodes to 1500 nodes. For each number of nodes, a = 0.02 confidence intervals were produced by generating 50 different topologies. Fig. 3(a) and

3(b) illustrate the resulting performance. The TDMA scheme consumes much less power under all circumstances (with no traffic), when the system is tuned to give the same delay for the three schemes.

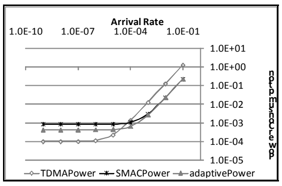

Figure 2: Power Consumption for the S-MAC, Ad_Li, and the TDMA schemes, as a function of packet arrival rate for a random 1000 node topology.

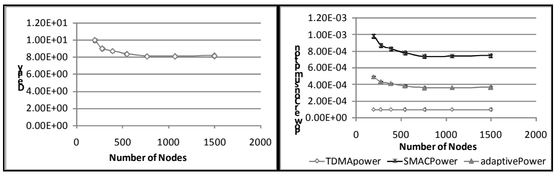

Figure 3: Delay (a) and power consumption (b) for the S-MAC, Ad_Li and TDMA schemes, for topologies with increasing nodes, and no traffic.

Figure 4 was produced using the same configuration, but keeping the total traffic constant, at N λo = 0.005. In this configuration, the TDMA scheme is always better than the S-MAC, when the system is tuned to give the same delay for the three schemes.

Since all the previous results were produced assuming there are no sensor failures, in this section we study how the performance of the proposed algorithm is affected by sudden topological changes, if the computed schedule has not been updated in a timely manner. Even when no sensor movement takes place, the topology will probably change as a result of node failures cased by various reasons (i.e. exhaust of battery, DoS etc). These nodes, referred to as dead nodes, cannot participate in communication and therefore in the network. In such a case, the network may become partitioned and some nodes or groups of nodes may become isolated and therefore, they cannot reach the gateway, since the required forwarding nodes have become dead. These nodes, together with the dead nodes, are referred to as disconnected nodes. Moreover, the non-disconnected nodes that their transmissions cannot reach the gateway, because at least one of the nodes in the scheduled path towards the gateway is dead, are referred as unreachable. The transmissions of these nodes will not be able to reach the gateway until the schedule is updated. The nodes that don't require rescheduling to transmit to the gateway are referred to as *active*.

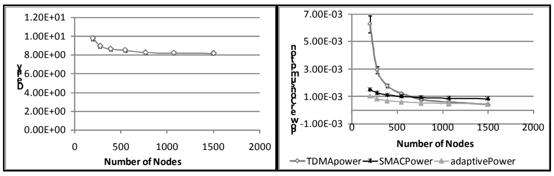

Figure 4: Delay (a) and power consumption (b) for the S-MAC, Ad_Li, and TDMA schemes, for topologies with increasing nodes, and some traffic (N λo = 0.005).

As the WSN operation evolves, and nodes gradually become dead, an increasing number of nodes will become either disconnected or unreachable, leaving a reduced number of active nodes, causing the network performance to degrade. In order to quantify the above observation, simulation runs were carried out on a 1000 node network, for various numbers of dead nodes, and the number of unreachable and disconnected nodes was calculated, and depicted in Fig. 5(a). Statistical significance was obtained by averaging 50 different simulation runs for every number of dead nodes, on the same topology. The number of disconnected nodes is close to the number of dead ones for most numbers of dead nodes, but the number of unreachable ones reaches significant levels even when the number of dead nodes is relatively low. Thus, the network performance will be decreased drastically, even when only limited nodes become dead.

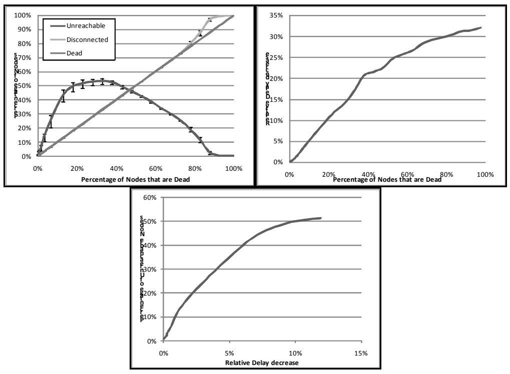

Figure 5: (a) The percentage of disconnected and unreachable nodes in the networks for varying numbers of dead nodes (1000 node topologies, 98% confidence interval). (b) The relative decrease of the end-to-end sensor to gateway delay (of the active nodes) in the networks for varying numbers of dead nodes (1000 node topologies). (c) The percentage of unreachable nodes in the network versus the relative decrease of the end-to-end delay (1000 node topologies).

Since the disconnected nodes cannot become active again, while the unreachable ones can, the performance of the network will be improved by using a timely rescheduling, that will increase the number of active nodes in the network. Depending on the percentage of unreachable nodes that can be tolerated by the specific application, a schedule update criterion can be defined as the percentage of the dead nodes in the network. Fig. 5(b) illustrates the end-to-end delay of the previous simulation, for different numbers of dead nodes. This is more obvious in Fig. 5(c), where the percentage of unreachable nodes in the network is plotted against the relative decrease of the end-to-end delay. Therefore, in case sensor failures occur in our network, which will cause significant nodes to become unreachable, the rapid decrease in delay will be detected by the gateway, triggering a schedule update. This procedure retains the number of active nodes which are close to the highest possible value, by removing the dead nodes from the schedule, and thus improving the network performance.

4 CONCLUSIONS

Power control and Energy efficiency are major issues in WSNs, since they determine the network lifetime. Several energy-efficient schemes have been proposed in the literature to prolong the lifetime of sensor networks, by periodically putting the sensor nodes to sleep mode. This introduces a sleep-related access delay that increases with the achieved power saving. The *Path-WakeUp* and the wakeup message aggregation strategies presented in this paper can be used for minimizing the sleep-related end-to-end delay and for minimizing the idle listening time, in order to decrease the power consumed for given delay levels. Simple analytic models were developed for quantifying the power consumption of several schemes. The performance evaluation showed that the TDMA scheme achieves higher power conservation than other relevant schemes, when the traffic generation rate is low, and thus it can be used for WSNs that monitor rare events and are expected to operate for a long period of time, maximizing the energy conservation.

ACKNOWLEDGEMENTS

This paper is part of the 03ED485 - "Design and Development Models for QoS Provisioning in Wireless Broadband Networks" research project, implemented within the framework of the "Reinforcement Programme of Human Research Manpower" (PENED) and co-financed by National and Community Funds (25% from the Greek Ministry of Development-General Secretariat of Research and Technology and 75% from E.U.-European Social Fund).

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