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Aggregation for adaptive and energy-efficient MAC in wireless sensor networks

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ABSTRACT

Time Division Multiple Access (TDMA) protocols are considered an energy-efficient solution to prolong wireless sensor network lifetime. However, their drawbacks such as the complexity of slot assignment and schedule maintenance, clock synchronization and low channel utilization during low traffic conditions are to be overcome in a good and efficient way. In this paper we present On-demand Convergecast Sensor MACS (OCSMACS), a centralized and adaptive multihop scheduling-based TDMA protocol for Wireless Sensor Networks. OCSMACS achieves high energy efficiency by adopting a novel requests aggregation mechanism for adaptive slot assignments such that all requests generated by active nodes are aggregated in a very few small size packets. In addition, knowledge of data correlation is integrated in the design of underlying multihop scheduling schemes to improve energy efficiency and extend network lifetime. Furthermore, OCSMACS adopts an energy-efficient protocol called PROGRESSIVE for the topology discovery and setup phases. The performance of OCSMACS is compared against existing protocols based on simulations using ns-2 and the results show that OCSMACS outperforms these protocols in terms of energy efficiency and network lifetime. Also, the integration of correlation knowledge in the scheduling process improves performance and extends network lifetime.

1. Introduction

Wireless Sensor Networks (WSNs) are expected to support many real-world applications, such as event detection, target tracking, and field monitoring (Akyildiz et al., 2002). These networks are usually composed of nodes, which rely on batteries of limited energy capacity and that are hard or not feasible to replace or recharge because of the limited physical access to the network. Therefore, minimizing energy consumption is of a paramount importance. One way to satisfy this goal is by developing energy-efficient Medium Access Control (MAC) protocols due to their direct relation to energy consumption in WSNs (Cano et al., 2011).

The design of an energy-efficient MAC protocol for WSNs has to take into consideration the target application characteristics. In this paper we consider two main characteristics: first data communication is from multiple sources to a sink (*convergecast*); and second nodes collect/sample data that is spatially and temporally correlated (Li et al., 2010; Pattem et al., 2008; Vuran et al., 2004; Vuran and Akyildiz, 2006; Xue and Hu, 2012; Zhu et al., 2008). This correlation results in redundancy in the communicated data. Thus, improving energy efficiency can be done by incorporating *Data Aggregation* and *Data Fusion* techniques, which compress or eliminate the redundant data within the network and before it finally reaches the sink.

In the area of WSNs MAC design, duty cycle and on-demand wakeup protocols owe in part their performance gain to the use of Carrier Sense Multiple Access (CSMA) as the underlying access mechanism. However, for the same reason, they experience performance degradation under different network operating conditions, for example high contention and/or high traffic rates. On the other hand, a TDMA-based MAC protocol where each node is assigned specific timeslots to send, receive or sleep, inherits the advantage of energy conservation due to the existence of the built-in duty cycle. Furthermore, it can avoid the hidden terminal problem without extra messaging overhead, i.e. Request-To-Send/Clear-To-Send, by scheduling transmission of interfering nodes at different times.

Nevertheless, a conventional TDMA protocol has a number of drawbacks that make it undesirable for certain WSN applications or network and/or configurations. First, tasks of slot allocation and schedule maintenance could be complex. Second, it is difficult to change frame size and slot assignment when introducing new nodes. In addition, following a rigid transmission schedule does not allow for effective avoidance of idle listening. Third, TDMA needs clock synchronization; while it is an essential feature of many sensor applications, tight synchronization incurs high energy overhead because of its frequent message exchanges. Forth, during low contention, TDMA

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has much lower channel utilization and longer delays than CSMA. To overcome these drawbacks, we propose a TDMA solution tailored to overcome these problems such that the performance gains would outweigh the downsides.

In this paper we present a centralized adaptive multihop scheduling TDMA MAC protocol called **O**n-demand**C**onvergecast **S**ensor **MACS** (**OCSMACS**), which supports convergecast applications with the objective of increasing energy efficiency and providing bounded delay guarantees. OCSMACS adopts and integrates some concepts in our previous work in Barnawi (2012), Barnawi and Hafez (2009), Barnawi and Hafez (2008b), Barnawi and Hafez (2008a). It has a novel requests aggregation mechanism, which facilitates dynamic slot assignments to active nodes. In addition, it has the capability of adjusting the slot assignment according to the level of correlation in the collected data. Moreover, it uses low power listening (LPL) (El-Hoiydi and Decotignie, 2004; Polastre et al., 2004; Shi and Stromberg, 2007) during active time slots to achieve further reduction in energy consumption.

We advocate the use of TDMA because of the following:

1. Convergecast traffic suggests the presence of a sink, which may have an unlimited (high) power supply and is capable of reaching almost all nodes in the network. Network wide transmissions by the sink make synchronization easier compared to that of a totally ad-hoc network.
2. Many sensor applications assume static deployment.
3. An integrated LPL mechanism can be used to avoid long idle listening so that nodes use their slots only at times of network activity. In addition, nodes during receive mode have the capability to switch to sleep mode if there is no packet is received within specific duration.
4. A multihop TDMA schedule could be designed to: maximize network lifetime; route data from sensor nodes to the sink in a shorter period of time, or facilitate data aggregation and redundancy suppression; and/or a combination of any of these objectives.

Closely related to multihop scheduling is *network topology discovery*. Distributed scheduling and topology discovery algorithms, like DRAND (Rhee et al., 2006), used in Z-MAC (Rhee et al., 2008), rely solely on CSMA to exchange large number of control messages. In dense sensor networks, high contention, and subsequently large number of collisions, may happen. If the discovery/scheduling phase runs for a short period, then some nodes may end up being unassigned transmission timeslots. On the other hand, having a very long discovery phase is not desirable for two reasons. First, longer period means more control messages; hence more energy is wasted in transmission and reception. Second, nodes that are able to obtain transmission timeslots early in the setup phase must remain active, mostly idle listening, to share their current status with other requesting nodes. Therefore, having an efficient TDMA-based MAC protocol requires an efficient topology discovery phase. In this work, we have adopted PROGRESSIVE (Barnawi and Hafez, 2009) - an energy-efficient progressive topology construction protocol during which gradual topology information reach the sink and at the same time TDMA slots are assigned to the already discovered nodes.

The main contributions of this work are:

1. We have proposed a TDMA-based MAC protocol which integrates the knowledge of data correlation into the scheduling algorithm such that overall energy efficiency is maximized. In doing so, we have considered three correlation models based on existing literature. In addition, we have provided new expressions for these models based on the concept of entropy. We have also presented a correlation-aware scheduling algorithm.
2. We have analytically derived expressions to find the best frame size for a specific performance objective; minimizing energy consumption or delay.
3. We have analytically derived expressions for the total energy consumed by the radio and micro-controller.
4. We have conducted extensive simulations and comparisons with the different variations of OCSMACS and also with other prominent MAC protocols, i.e. Z-MAC and SMAC (Ye et al., 2004). Results show that the adaptive on-demand timeslot assignment is efficient in handling the varying traffic load and network size. Also, the integration of data correlation in the scheduling algorithm provides further reduction in energy consumption, hence increasing network lifetime.

The rest of the paper is organized as follows: Section 2 reviews state of the art related to MAC protocols in WSNs while focusing on TDMA and scheduling-based protocols. In addition, it discusses protocols and algorithms that address data correlation and aggregation. Section 3 presents the network model and other design assumptions. Section 4 briefly describe PROGRESSIVE protocol. Then, details about OCSMACS operation is given in Section 5. Correlation-aware OCSMACS is discussed in Section 6. Analytical models for total energy consumption are presented in Section 7 followed by simulation evaluation of the proposed protocols in Section 8. Finally, Section 9 concludes the paper and highlight future research directions.

2. Related work

Duty cycle MAC protocols, such as S-MAC (Ye et al., 2004) , T-MAC (van Dam. and Langendoen, 2003) and DMAC (Lu et al., 2004) rely mainly on CSMA in their operation. They allow nodes to alternate between two periods: *active period* and *sleep period*. During the active period, nodes listen to the channel for possible traffic from neighbors and go back into sleep mode when that period expires. A potential transmitting node must acquire knowledge about active periods of targeted receiving nodes and send its packet at the right time. An entire cycle consisting of a sleep and an active period is called *wakeup period*. The ratio of the active period length to the wakeup period length is called *duty cycle*. Compared to S-MAC, T-MAC reduces idle listening by allowing nodes to end the active period prematurely if there is no activity in the channel for a specified duration of time. DMAC, on the other hand, assigns wakeup periods to nodes based on a data gathering tree so that nodes on the multihop path wake up sequentially according to their hop count from the sink. Using this mechanism, nodes wakeup at the appropriate time during the data gathering interval hence, minimize energy and latency.

Distributed TDMA MAC protocols provide a multi-hop scheduling for data collection from sensors to sink. However, unlike centralized protocols, the slot assignment is performed in a distributed fashion. For example, Advertisement-based Time-division Multiple Access (ATMA) (Ray et al., 2010) utilizes the bursty or periodic nature of the traffic in WSNs to prevent energy waste through advertisements and reservations for data slots. ATMA is based on ADV-MAC (Ray and Heinzelman, 2009), which is considered to be an improvement to T-MAC (van Dam. and Langendoen, 2003). As discussed previously, in T-MAC, the listen period ends when no data is exchanged among neighbors for a specific timeout period. This timeout makes the active period in T-MAC adaptive to variable traffic loads. Despite this, all nodes that overhear the data exchange renew their timeout timers even if they are not a part of that data transmission. As a result, nodes still end up wasting valuable energy. ADV-MAC prevents this energy waste by using an advertisement period instead of a timeout period to alert intended receivers of packets waiting for transmission. Nodes that are not part of the following data exchange go to sleep, hence save energy. ATMA eliminates contention-based transmission of ADV-MAC by converting it to a slotted TDMA protocol. During the advertisement period nodes utilize TDMA to advertise for packets and reserve data slots.