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CCS-MAC: Exploiting the overheard data for compression in wireless sensor networks ☆

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ABSTRACT

Both the overhearing and overhearing avoidance in a densely distributed sensor network may inevitably incur considerable power consumption. In this paper we propose a so-called CCS-MAC (collaborative compression strategy-based MAC) MAC protocol which facilitates to exploit those overheard data that is treated useless in traditional MAC protocols for the purpose of cost and energy savings. Particularly the CCS-MAC enables different sensor nodes to perform data compression cooperatively with regard to those overheard data, so that the redundancy of data prepared for the link layer transmission can be totally eliminated at the earliest. The problem of collaborative compression is analyzed and discussed along with a corresponding linear programming model formulated. Based on it a heuristic node-selection algorithm with a time complexity of ($O(N^2)$) is proposed to the solve the linear programming problem. The node-selection algorithm is implemented in CCS-MAC at each sensor node in a distributed manner. The experiment results verify that the proposed CCS-MAC scheme can achieve a significant energy savings so as to prolong the lifetime of the sensor networks so far.

1. Introduction

In a massive distributed wireless sensor network (WSN), the sensory data redundancy is usually inevitable due to its high deployment density [1–3]. This paper presents a novel power efficient protocol named CCS-MAC which aims to early eliminate the data redundancy at source nodes. As an underlying protocol in WSN, the media access control (MAC) has attracted a plethora of research interest [4–9] such as S-MAC [4], T-MAC [5], B-MAC [6], SCP-MAC [7], RI-MAC [8], etc. However, most of these schemes still keep the root of IEEE802.11 protocol and mainly focus on the energy-latency tradeoff. In fact, the traditional MAC technology, such as 802.11 which is proven to be neither energy efficient nor ad hoc operation friendly, is not suitable to be applied in a high density wireless sensor network [10–13]. With regard to the data correlation in WSN, a new protocol CC-MAC [14] was proposed to reduce the number of packets transmitted to the sink nodes under the help of a subset of representative sensor nodes. The proposed CCS-MAC protocol is quite different from all those prior works. The key idea of CCS-MAC is that it uses a collaborative compression method to reduce the data redundancy by exploiting the overheard data, which is neglected or discarded in previous MAC protocols.

Almost all of the previous MAC protocols use the overhearing avoidance technique to reduce the energy consumption. In fact, overhearing avoidance mechanism requires the node that maybe overhear the data packets not destined to itself to perform the RTS/CTS, MAC header or a preamble check operations, which inevitably incur considerable energy consumption as well. Therefore the overhearing avoidance mechanism in network with high deployment density and heavy load will lead to a significant waste of energy. Motivated by the costly overhearing avoidance operations and inherent data correlation, we attempt to take advantage of the overheard data by compressing.

In this paper we propose a CCS-MAC protocol. Instead of simply avoiding all overhearing, it takes advantage of some effective overhearing and the overheard data to save energy. The main mechanism of CCS-MAC is to perform the compression collaboratively by utilizing the overheard data in a distributed fashion. Firstly we describe the collaborative compression issue into a lifetime vector optimization (LVO) problem, based on which we construct a linear programming model to formulate the LVO problem. Furthermore we propose a heuristic yet near optimal node-selection algorithm with a time complexity of ($O(N^2)$) to solve the linear programming problem. The node-selection algorithm can be implemented at each sensor node in a distributed manner, meanwhile the collaborative compression of sensor data can be achieved

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under the help of the overheard data from the subset of those selected nodes. Simulation results show that the proposed CCS-MAC protocol is efficient in both energy conservation and WSN lifetime improvement.

The rest of this paper is organized as follows. Section 2 introduces the related work. Sections 3 and 4 will discuss and analyze the collaborative compression problem in detail. Section 5 presents the linear programming model for the LVO problem. The heuristic node-selection algorithm is proposed and analyzed in Section 6 and the design and implementation of CCS-MAC protocol is given in Section 7. Extensive simulation works are conducted in Section 8 and we finally conclude this paper in Section 9.

2. Related work

The idea of compressing the data redundancy is not new in WSN. But we make the first attempt to compress the data by exploiting the overheard data in link layer. There has been some related research effort to study the spatial correlation and in-networking data aggregation in WSN [24–31]. Considerable existing researches focus on the information theoretical aspects of the correlation [24–28], and they do not provide efficient networking protocols capable of directly exploiting the spatial correlation in WSN. The proposal in [29] aims to find the optimum rate to compress redundant information in sensory data and they also do not propose to exploit correlation for developing efficient network protocols. Correlation based directed diffusion scheme in [30] works as a routing protocol. However, it performs the data in-networking aggregation by simply replacing the multiple interests containing completely overlapping attributes with a single interest entry. The joint routing and source coding is introduced in [31] to reduce the amount of traffic with spatially correlated records. While most of these data aggregation schemes only reduce the number of transmitted bits at cluster heads on the delivery route; from the network point of view, the amount of transmitted sensory data can be further minimized at the source nodes by regulating the channel access based on the overheard data.

Current literature on medium access in WSN focuses mainly on energy-latency tradeoff. MAC design for WSN can be broadly divided into contention based and TDMA protocols.

The contention based MAC protocols try to avoid energy waste due to collisions, idle listening, overhearing and control packet overhead. The efficiency of S-MAC [4] relies on both a locally managed synchronization scheme and a periodic sleep/listen schedule. T-MAC [5] aims to enhance the poor results of S-MAC under variable traffic load. In T-MAC, listening period ends when no activation event has occurred for a time threshold. The decision for the threshold is presented along with some solutions to the early-sleeping problem defined in [5]. Similarly, instead of having fixed sleep-wakeup schedules in S-MAC, P-MAC [15] uses adaptive schedules for each node based on the node's own traffic and that of its neighbors. This way it can achieve more energy savings under light loads, and higher throughput under heavier traffic loads. In B-MAC [6], prior to DATA frame transmission, a sender transmits a long wake-up signal, named a preamble, which lasts longer than the receiver's sleep interval. B-MAC is energy efficient only under light traffic since a node spends only a very short period of time in idle listening the channel activity. However, a node with B-MAC may wake up and remain awake due to channel activity, only to, in the end, receive one or more frames actually destined for other nodes. X-MAC [16] solves the preamble overhearing problem in B-MAC by using a strobed preamble that consists of sequence of short preambles prior to data transmission. SCP-MAC [7] achieve better energy efficiency than B-MAC by means of a short scheduled channel polling, which replaces the costly long preambles used in low-power listening operations. The receiver-initiated RI-MAC [8] attempts to minimize the time a sender and its intended receiver occupy the channel to find a rendezvous time for exchanging data. In RI-MAC, each node periodically wakes up and broadcasts a beacon. When a node wants to send a data frame to a neighbor, it stays active silently and starts data transmission upon receiving a beacon from that neighbor. DSMAC [17] adds dynamic duty cycle feature to S-MAC. The aim is to decrease the latency for delay-sensitive applications. The principal aim of DMAC [18] is to achieve very low latency, but still to be energy efficient. It could be summarized as an improved slotted aloha algorithm where slots are assigned to the sets of nodes based on a data gathering tree. CC-MAC [14] may be the closest work to our method. It employs the representative nodes in correlation region to directly reduce the transmitted packets with respect to the spatial correlation. *While our proposal exploits the overheard data to perform collaborative data compression. Notably, the representative nodes selected in CC-MAC can utilize CCS-MAC to further compress the redundancy in their sensory data.*

TDMA protocols have a natural advantage of energy conservation compared to contention protocols, because the duty cycle of the radio is reduced and there is no contention-introduced overhead and collisions. However, TDMA protocol usually requires the nodes to form real communication clusters, like Bluetooth [19] and LEACH [20]. Most nodes in a real cluster are restricted to communicate within the cluster. Managing inter-cluster communication and interference is an ad hoc task. So its scalability is normally not as good as that of a contention-based protocol. TRAMA [21] is proposed to increase the utilization of classical TDMA in an energy-efficient manner. It is similar to NAMA [22], where for each time slot a distributed election algorithm is used to select one transmitter within two-hop neighborhood. Designed for low rate wireless network applications, IEEE 802.15.4 [23] introduces a superframe structure with two disjoint periods, i.e. contention access period and contention free period. But the network topology is also assumed to be cluster-based, requiring significant additional processing complexity and overhead in the overall sensor network.

In summary, prior existing MAC protocols place a emphasis on the energy-latency tradeoff by varying medium access techniques. Unlike all above MAC proposals, the event-based CCS-MAC *aims to collaboratively compress the spatial redundancy of observations by utilizing the overheard data, which is often treated useless. Especially it is proposed to co-exist with other MAC protocols such as S-MAC, CC-MAC and so on.*

3. Models and design goals

3.1. Spatial correlation model

Many WSN systems have been developed for the specific applications such as environment monitoring, target tracking, disaster rescue, etc. [32,33]. A representative sensor node for these applications, like Micaz node, has adequate memory to store the necessary protocol parameters. Because of high deployment density, the sensory data is spatially correlated. Moreover, we assume each node could measure the distance between the neighbor to itself by some means. (For instance, at the system initialization stage, each node can control the sounder on its sensor board to broadcast a sound sample to the neighbors. This way all receivers are able to estimate the distance $D = T \cdot s$ between the sender to themselves according to the sound propagation delay T and speed s).

Let's take an arbitrary monitoring node as the source node of the information. Suppose each node has been pre-installed certain spatial correlation model, which is only relevant to distance between sender and receiver. Assume that the sensory data gathered