CLEEP: A Novel Cross-Layer Energy-Efficient Protocol for Wireless Sensor Networks

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Abstract—In the wireless sensor networks (WSNs), severe energy constraint necessitates energy-efficient protocols to fulfill application objectives. In this paper, we propose a Novel Cross-Layer Energy-efficient protocol—CLEEP, which adopts cross-layer strategy that considers physical layer, MAC layer, and network layer jointly. In the physical layer, we first coordinate the transmission power between two nodes and maintain the nodes' neighbor tables periodically to save the transmission energy. Then we construct the optimal routing path by exploiting the transmission power and neighbor tables of the physical layer, which minimize the total energy consumption. Finally, MAC layer make use of the routing information to determine the node's duty-cycle, in order to prolong the node's sleep time. Simulation reveals that CLEEP is energy-efficient and able to achieve significant performance improvement as well.

Keywords- Wireless sensor networks, energy optimization, cross-layer, protocol

I. Introduction

For wireless sensor networks (WSN), the main challenge to achieve some applications (e.g. habitat monitoring, border surveillance et. al) is mainly posed by severe energy. Since sensor nodes is equipped with limited battery. Clearly, an energy-efficient communication protocol should be developed to maximize energy efficiency for the WSNs.

To devise an energy-efficient communication protocol of WSNs, most of existing research works only focus on the individual layer issues. That is, most of MAC layer protocols[6] only concern about how to avoid the collision between two nodes, and do not consider the network layer routing information and the characteristics of applications, while routing protocols[7] just pay attentions to the connectivity of entire network and validity of routing selection, and ignore the duty-cycle of the MAC layer. Although these protocols may achieve very high performance in these individual layers, they ignore the importance of interaction between different layers, resulting in inefficient energy conservation.

In fact, recent work on WSNs reveals that cross-layer design techniques result in significant improvement in term of energy conservation in WSNs. This requires an energy-efficient communication protocol of WSNs should apply cross-layer strategy, which may consider all of the networking layer involving in the communication in WSNs. In this paper, we use the cross-layer approach to design an energy-efficient communication protocol for the wireless sensor networks——CLEEP. CLEEP first obtains the minimum transmission power between two nodes in the physical layer, and maintains a neighbor table for each node in WSNs, which could be utilized by the network layer to choose a better routing path to send data. Then CLEEP utilizes routing information to determine the nodes' duty-cycle in MAC layer, so that sleep duration of nodes in MAC layer can be maximized. We also conduct extensive experiments to evaluate the performance of CLEEP on the simulator TOSSIM, and the results demonstrate that our protocol is more effective than the state-of-the art methods.

The rest of this paper is organized as follows. The details of CLEEP are described in Section II, followed by the performance evaluation in Section III. Finally, Section IV concludes the paper.

II. Protocol Design Principle

Our CLEEP protocol replaces the individual layer protocols which have so far been used in WSNs. The principle of design is to exploit the interactions among physical layer, MAC layer and network layer, so that each layer could use other layers'

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information to optimize the performance of entire protocol. Fig.1 shows the framework of CLEEP protocol. In the physical layer, CLEEP controls transmission power dynamically and obtains the minimum transmission power between two nodes, and decides which nodes are neighbors to maintain neighbor tables. Then each node in the network layer constructs its routing table by utilizing the neighbor table and the minimum transmission power of the physical layer. Finally CLEEP uses the routing information to determine the duty-cycle of each node, and meanwhile CLEEP also pays attentions to collision and overhearing problem in the MAC layer.

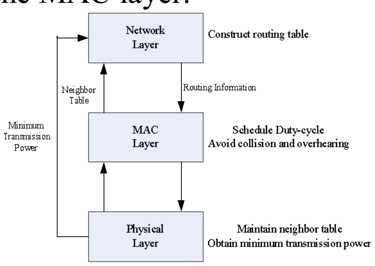

Figure 1. the framework of CLEEP protocol

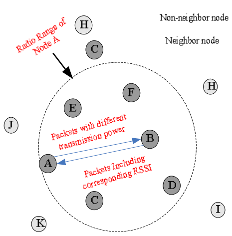

Figure 2. Operation of the transmission power control

A. *Tranamission Power Control and Neighbor Table Maintaince*

The aim of controlling transmission power is to let nodes use transmission power as low as possible to transmit data. ATPC [1] reveals that the transmission power between nodes is affected by spatial and temporal factors, and it also studies systematically the spatial and the temporal impact on the correlation between transmission power and Received Signal Strength Indicator (RSSI). In the end, ATPC concludes the correlation between RSSI and transmission power is approximately linear. Therefore we use an approach which controls the power transmission dynamically, so that each node can find minimum transmission power to communicate with its neighbor nodes successfully, and at the same time each node maintains a neighbor table to record this minimum transmission power(P_{tx_min}) and the neighbor node's number.

The main idea of the approach is that each node maintains a neighbor table and each pair of nodes use a feedback closed loop for controlling transmission power, and each node sets a received data packets threshold. To simplify the description, we show a pair of nodes (node A and node B) in Fig.2. At the beginning, node A broadcasts data packets using different levels of transmission power. Let node B is the receiver. It obtains corresponding RSSI according to the level of transmission power, and then puts this value into data packet which is returned to node A. Because the rate that a node successfully receives data is inversely proportional to the radio range between nodes, when the number of data packets that node B returns to node A is greater than the threshold set by node A , node A believes that node B is in the radio range, and considers it to be its neighbor node , meanwhile node A utilizes these RSSI included by data packets to estimate the minimum transmission power between node A and node B, then B and minimum transmission power are recorded in the neighbor table of node A. Each node repeats this approach periodically to control the transmission power and maintain the neighbor table in real time.

B. *Routing Table Constructions*

In this section, we discuss the construction routing table using the minimum transmission power between nodes and nodes' neighbor tables. Firstly, we describe an online algorithm called Incremental Shortest-path Tree Heuristic (ISTH) [3]. ISTH algorithm requires that different source nodes share the node of the routing path found as much as possible, which makes the number of nodes in active less, and hence more nodes are in sleep state. Now we explain the basic idea of ISTH; a detailed description can be found in [3].ISTH finds the energy-efficient route to the sink according to the following cost metric:

$$C(u,v) = \begin{cases} \frac{R_i}{B} * C_{u,v} + Z, & u \text{ is inacitve} \\ \frac{R_i}{B} * C_{u,v}, & u \text{ is acitve} \end{cases} \quad (1)$$

where node v is the next-hop node of u on the path, $C(u,v)$ represents the total power consumption between node u and node v, and $C_{u,v} = P_{tx}(u,v) + P_{rx} - 2P_{id}$ is the total power consumption in all modes of node u, where $P_{tx}(u,v)$ is the P_{tx_min} (between node u and node v) mentioned in previous section, P_{rx}, P_{id} represent reception, and idle power consumption respectively, Z is the nodal power consumption, R_i is the date rate, the bandwidth of all nodes is B. In (1), if node u is not on the path from any source nodes to sink node, node u is inactive, and $C(u,v)$ not only includes $C_{u,v}$ but also includes the power consumption of node u . Otherwise, if node u is already on the path from other source nodes to sink node, node u is active, and $C(u,v)$ only includes $C_{u,v}$ .This is because Z has been counted by the existing routes.

We construct the nodes' routing table based on the ISTH algorithm and the nodes' neighbor table described in previous section. Each node calculates the power consumption with neighbor nodes by (1), and finds an energy-efficient routing path to the sink by ISTH algorithm. During this process, each node sets the neighbor node with the minimum power consumption to the sink as its next-hop node and constructs a table to record its routing information.

C. Duty-cycle Scheduling

In this section, we focus on the duty-cycle scheduling based on routing information. In the section B, we find the routing path for each source node in the WSNs. Therefore, when any source node transmits data to sink, only nodes in this routing path are active, and other nodes continue to sleep. In order to avoid collision and overhearing, we adopt the RTS/CTS mechanism similar to the 802.11 MAC protocol. Now, we explain the

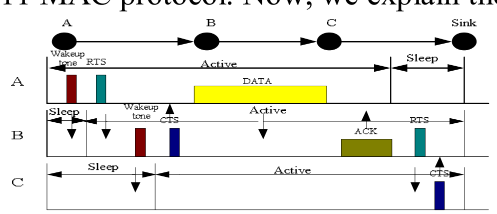

Figure 3. Operation of the duty-cycle scheduling

Duty-cycle scheduling scheme with the help of the following example. We assume that a routing path (A->B->C->sink) has existed in Fig. 3.Initially, all nodes keep sleep state, source node A start sending data to the sink at any time when triggered by an event of interest. Firstly node A listens to the radio channel. If the channel is idle, node A knows the node B is its next-hop node from the routing table, and wakes node B up by sending a short wake-up tone to B. then node A sends RTS packet to node B. When node B receives RTS packet sent by node A, it sends a short wake-up tone to the next-hop node C. And node B returns CTS packet to node A to imply that node A and B occupy the channel. Node A begins to transmit data to node B. Node B returns an ACK packet to node A until node B receives data successfully. After that, node B starts to detect the channel and send RTS packets to node C, and node C receives RTS packet to wake up its next-hop, and continues to transmit data. After these nodes receive the ACK packet, they continue to listen to the channel, if there are data to send/receive, they keep awake, otherwise they switch sleep state.

III. Experimentation

A. Simulation Environment and Approach

In this section, we present the performance study of CLEEP. All experiments are done through the simulation implemented in TOSSIM [4], which is the simulation of TinyOS by UC Berkeley and extends the power modeling—PowerTossim[5], which may accurately model power consumed by TinyOS applications, and includes a detailed model of the power consumption of the Mica2 motes. Therefore we set parameters according to the power model of Mica2 in [5]. In the simulation environment, 100 nodes are deployed in a 150 $m\times$ 150m region, source nodes are randomly chosen, and the sink node is far away from sensor region. Each simulation lasts for 300 sec and the results are average over 5 runs. Each source node sends a packet every 5 seconds and the number of source varies from 5 to 30.

For performance comparison, in addition to CLEEP, we have implemented S-MAC protocol [6] and MAC-CROSS protocol [2]. S-MAC is a contention-based channel access protocol, and it uses periodic sleep intervals to conserve energy. MAC-CROSS is an energy efficient cross-layer MAC protocol, and it utilizes the routing information in the network layer to coordinate the duty-cycle of node. In addition, S-MAC is coupled with a routing protocol—DSDV to transmit interesting data from source node to sink. MAC-CROSS uses the routing protocol based on the greedy approach, where a next-hop node of each node is the nearest neighbor node to the sink node. In DSDV and MAC-CROSS, all communication links use the same transmission power.

B. Simulation Results and Analysis

The most important metric of our performance evaluation is energy consumption. For each protocol, we measure the total energy consumption that all source nodes successfully send data packets to sink. Fig. 4 shows that CLEEP consumes the least energy than the others. As the number of source nodes increases, different source nodes share more middle nodes in the CLEEP, resulting in more nodes in sleep state and better energy efficient. Although MAC-CROSS lets nodes continue to keep asleep, since they don't participate in the transmission activity and its routing paths contain fewer nodes and hence more nodes keep asleep, it doesn't optimize the transmission energy so that all communication links use the same transmission power. As result, MAC-CROSS consumes more energy than CLEEP. In S-MAC protocol, node has a fixed listen/sleep cycle, so a node must be waked up when its sleep period expires, even if the node hasn't any activity, resulting in unnecessary energy consumption. In contrast to MAC-CROSS or S-MAC that only reduces the node energy cost under partial working modes. CLEEP effectively minimizes the total energy cost of the nodes.

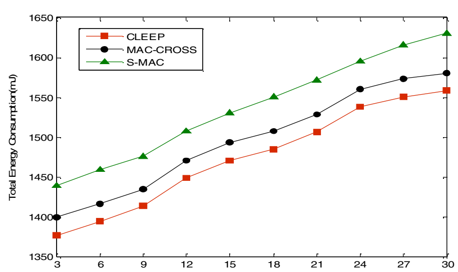

Figure 4. Total Energy Consumption according to the number of source nodes

In Fig. 5, we conclude the average end-to-end delay time. CLEEP yields the shortest delay time, since we wake up nodes in the routing path before the data is to be sent. Not surprisingly, MAC-CROSS and S-MAC yield higher delay, since node starts to send/receive data until its sleep period expires. While MAC-CROSS yields the lower delay, because it use the fewest node to send data from source node to the sink. However, as the number of source nodes increases, CLEEP yields higher delay, because network load increases due to the path sharing between different source nodes.

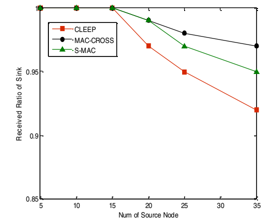

Figure 5. End-to-end data delay

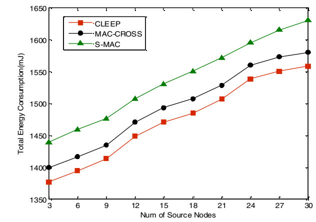

Figure 6. The packets-receive ratio at the sink node

Fig. 6 illustrates the packet-receive ratio of sink node in different protocols. As the number of source nodes increases, the packet-receive ratio of all protocols would reduce. However, the other two protocols are able to achieve higher packet-receive ratio than CLEEP. This is because more middle nodes are shared to transmit the data when the number of source nodes increases in CLEEP, which causes higher radio channel contention. However, CLEEP still keep the receive-packet ratio beyond 90% in all conditions.

IV. CONCLUSIONS

In this paper, a novel energy-efficient protocol for wireless sensor networks is presented, named CLEEP which exploits the cross-layer approach that takes into the physical layer, MAC layer and network layer account. The results of analytical simulation experiment show that CLEEP conserves more energy and leads to the better system performance.

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