An Energy Optimization Protocol Based on Cross-Layer for Wireless Sensor Networks

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*Abstract***— Survivability is one of the critical issues and the most important research topics in the fields of wireless sensor networks (WSNs). Energy efficiency is one of the determining factors for survivability and lifetime of WSNs. In the WSNs, severe energy issue necessitates energy-efficient approach to fulfill application objectives.**

In this paper, we propose an Energy Optimization Approach based on Cross-Layer for Wireless Sensor Networks named as EOA, which consider the joint optimal design of the physical, medium access control (MAC), and routing layer. The focus of EOA is on the computation of optimal transmission power, routing, and duty-cycle schedule that optimize the WSNs energy-efficiency. We first propose a feedback algorithm that computes the proper transmission power level between nodes. Then, routing protocol can make use of the transmission power as a metric by choosing route with optimal power consumption to forward packets. Finally, the cross-layer routing information is exploited to form a duty-cycle schedule in MAC layer. EOA is validated on a CROSSBOW's MicaZ mote platform, and evaluated using the TOSSIM simulator, the simulation results show that EOA is an energy-efficient approach and able to achieve significant performance improvement as well.

Index Terms- **wireless sensor networks, energy optimization, cross-layer**

I. INTRODUCTION

Recent years have seen the applications of wireless sensor networks (WSNs) in a variety of applications including habitat monitoring, border surveillance and structural monitoring. In most applications, WSNs are required to be operating in order to months to years but constituent sensor nodes have limited battery power. Therefore survivability is one of the critical issues and the most important research topics in the fields of wireless sensor networks (WSNs). Energy efficiency is one of the determining factors for survivability and lifetime of WSNs. Thus it is not surprising that developing approach to optimize the energy efficiency of WSNs has been a major research topic.

Major source of energy waste are idle listening, retransmission resulting from collision, unnecessarily high transmission power and sub-optimal utilization of the available resource [1]. Corresponding to these problems, there is a significant body of approaches to addressing different aspects of energy waste. To mitigate this energy consumption of idle listening, duty cycling mechanisms have been introduces in sensor network MAC protocol. For example, S-MAC [2], SCP-MAC [7] and so on. In [4, 5], some approaches control the transmission power aiming to reduce the unnecessary transmission energy consumption and decrease the interference among nodes while maintaining network connectivity. Power aware routing protocols [8, 9] save significant energy by choosing the appropriate route according to the available energy of nodes or energy demand of transmission paths. Clearly, a WSN needs to reduce the energy consumed in all states (i.e., transmission, reception, idle) in order to minimize its energy consumption. This requires a WSN to effectively apply all the above approaches. In this paper, we propose a cross-layer energy optimization approach named as EOA, which minimizes the aggregate energy consumption in all power states. In sharp contrast to above these approaches that optimized some aspect of energy waste. EOA provides a cross-layer approach that integrates these approaches as a joint optimization problem.

This paper makes the following key contributions. First, at the physical layer, we present a feed-back transmission power control algorithm that obtains the minimum transmission power level between each node and its neighboring nodes aiming to reduce power consumption and decrease the interference between two nodes. In the meanwhile, when the spatial and temporal factors change, this algorithm could adjust the minimum transmission power level dynamically to maintain the good link quality over time. A neighbor table is maintained at each node. The neighbor table contains the minimum transmission power level that this node should use for its neighbor nodes. Second, at the network layer, we utilize an online algorithm called Incremental Short-path Tree Heuristic (ISTH) [10] and nodes' neighbor tables to design a routing algorithm that is different from conventional routing algorithms. In this algorithm, we regard energy consumption between two node in all state (e.g. transmit, receive, idle, sleep) as a metric, and choose the route with the least energy consumption to the sink node to forward packets. Third, we exploit the cross-layer routing information to form the sleep/listen scheduling scheme for each sensor node at MAC layer. By this scheme, a node must be awake if and only if it takes part in the actual transmission activity; otherwise it continues to keep asleep in the rest of time. As a result, the idle-listening duration of the node decreases and the energy consumption further reduces. To evaluate the performance of EOA, we have implemented the approach over the MicaZ mote [11] platform and the simulator TOSSIM [12]. The result of both tests demonstrate that EOA is an energy-efficient approach and able to achieve significant performance improvement as well.

The rest of this paper is organized as follow: Section 2 reviews existing cross-layer scheme. The frame of EOA is described in Section 3.In section 4, the implement of EOA is state; the performance is evaluated. Finally, section 5 concludes the paper.

II. Related Work

Some cross-layer approaches have been proposed for WSNs in literature. They can be roughly classified into three approaches in terms of interaction or modularity among physical (PHY), medium access control (MAC), routing, and transport layers.

MAC+PHY: The energy consumption for physical and MAC layer is analyzed in [3], the conclusion is that single-hop communication can be more efficient if real radio model are used. However, the analysis is based on a linear networks, the conclusion may not be practical in realistic scenarios. In [6], a cross-layer solution among MAC layer, physical phenomenon, and the application layer for WSNs is proposed. The spatial correlation in the observed physical phenomenon is exploited for medium access control. Based on a theoretical framework, a distributed, spatial correlation-based collaborative medium access control (CC-MAC) protocol is proposed.

MAC+Routing: In many work, the receiver-based routing is exploited for MAC and routing cross-layer modularity. In this approach, the next hop is chosen as a result of contention in the neighborhood. Receiver-based routing has been independently proposed in [21], [22], and [23]. In [22] and [23], the authors discuss the energy efficiency, latency, and multihop performance of the algorithm. In [24], the work in [22] and [23] is extended for a single radio node. In [21], the receiver-based routing is also analyzed based on a simple channel model and lossless links. Moreover, the latency performance of protocol is presented based on different delay function and collision rates. Similarly in [25], the routing decision is performed as a result of successive competitions at the medium access level. More specifically, the next hop is selected based on a weighted progress factor and the transmit power is increased successively until the most efficient node is found. Moreover, on-off scheduled are used. The performance evaluations of all these propositions present the advantages of cross-layer approach at the routing and MAC layer. The usage of on-off schedules in a cross-layer routing and MAC framework is also investigated in [28]. In this work, a TDMA-based MAC scheme is devised, where nodes distributively select their appropriate time slots based on local topology information. The routing protocol also exploits this information for route establishment.

PHY+MAC+Routing: In addition to the proposed methods that focus on pairwise cross-layer interaction, more general cross-layer approaches among three protocol layer exist. In [26], the optimization of transmission power, transmission rate, and link schedule for TDMA-based WSNs is proposed. The optimization is performed to maximize the network lifetime, instead of minimizing the total average power consumption. In [27], joint routing, MAC, and link layer optimization is proposed. The authors consider a variable-length TDMA scheme and MQAM modulation. The optimization problem considers energy consumption that includes both transmission energy and circuit processing energy. Based on this analysis, it is shown that single-hop communication may be optimal in some cases where the circuit energy dominates the energy consumption instead of transmission energy.

These above works either provide analytical results without any communication protocol design, or perform pairwise cross-layer design within limited scope, e.g., only routing and MAC layer, which do not consider all of the networking layers involving in the communication in WSN, such as routing, medium access and physical layers..

III. EOA Design Priciple

Cross-layer approach mentioned in this paper considers the interaction between corresponding protocol layers, and preserves the traditional layered structure. Each layer is informed about the conditions of other layers, while the mechanisms of each layer still stay intact. Guided by above cross-layer principle, we design our cross-layer optimization approach named as EOA. Fig.1 shows the frame of EOA. In the physical layer, EOA controls transmission power dynamically and obtains the proper transmission power level between two nodes. In the meanwhile, each node maintains a neighbor table to record this proper transmission power level. Then each node in the network layer constructs its routing table by utilizing the neighbor table of the physical layer. Finally, EOA uses the cross-layer routing information to determine the duty-cycle of each node, and meanwhile EOA also pays attentions to collision and overhearing problem in the MAC layer.

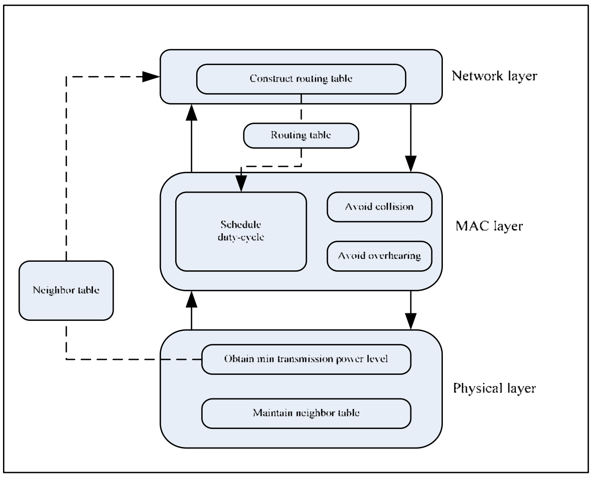

Figure.1. the frame of EOA

A. Description of Transmission Power Contol Algorithm

The transmission power between two nodes is affected by spatial and temporal factors. The spatial factors include the surrounding environment, such as terrain and the distance between the transmitter and the receiver. Temporal factors include surrounding environmental changes in general, such as weather conditions. This phenomenon indicates the previous topology control solutions, which use static transmission power, lead to worse link quality and unnecessarily high energy consumption. As a result, the transmission power of each node needs to be set the right level dynamically with spatial and temporal change. ATPC [11] reveals that radio CC1000 [12] and CC2420 [13] offers a Received Signal Strength Indicator (RSSI) to specify the transmission power level during runtime, such that system design is able to dynamically control the transmission power. Therefore, we present a dynamic transmission power control algorithm based on RSSI, which contains two phases, the initialization phase and the running tuning phase. At the initialization phase, the objective of this algorithm is to make every node in a WSNs find the minimum transmission power level that can communication with its neighboring nodes successfully. At the same time, the neighbor table is maintained at each node. The neighbor table contains the proper transmission power level and the number of neighbor node. At the runtime tuning phase, this algorithms could adjust the proper transmission power dynamically to adapt environmental change.

1) The Initialization Phase:

We suppose the communications are almost symmetric between the nodes, namely the transmission power is almost equal when the two nodes communicate each other, and set a threshold of RSSI $R_{threshold}$ which is the minimum necessary RSSI for the reception of a data packet. Assessing the minimum transmission power level requires three steps (Fig.2):

1) Each node broadcasts a beacon message with the maximum transmission power level P_{t_max};

2) A node B that receives the beacon message from node A gets the transmission power level P_r according to the RSSI reading, and uses the Equation(1) in[14] to calculate the minimum transmission power level P_{t_min} :

$$P_{t\_m} = \frac{P_{t\_max} R_{threshold}}{P_r} \quad (1)$$

Then node B sends the ACK message that contains P_{t_m} to node A.

3) Node A gains the value of P_{t_m} from ACK message of B, and record this value and B in the neighbor table.

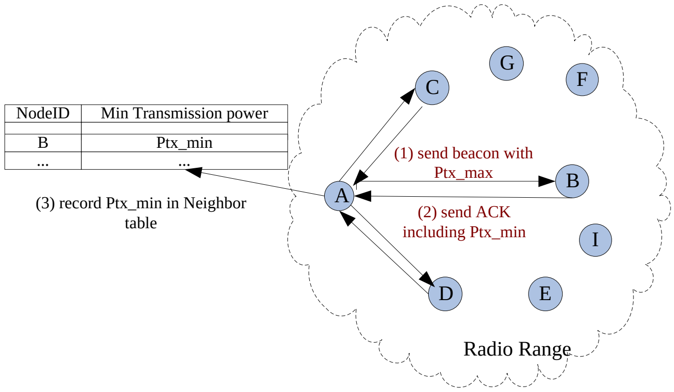

Figure.2. Operation of transmission power control

2) The runtime tuning Phase:

In the runtime tuning phase, a feedback mechanism is adopted to tune the transmission power level. Figure 3 is an overview of the feedback mechanism. To simplify the description, we show a pair of nodes. When node A has a packet to send to its neighbor B, it first adjusts the transmission power level indicated by its neighbor table in the initialization phase, and then transmission the packets. When node B receives this packet and read RSSI value, then send back ACK message including RSSI value. Node A compares this RSSI with a lower threshold $R_{threshold\_low}$, if the RSSI value is below $R_{threshold\_low}$, Node A increases the transmission power level step by step, and send the packet until the RSSI value is above $R_{threshold\_low}$. Otherwise, if the RRSI value is above than an upper threshold $R_{threshold\_upp}$, Node A decreases the transmission power level step by step, and send the packet until the RSSI value is below $R_{threshold\_upp}$. $R_{threshold\_low}$ and $R_{threshold\_upp}$ are $R_{threshold} - 6$ and $R_{threshold} + 6$ respectively since the RSSI accuracy of the CC1000 and CC2420 are ± 6 .In this phase, each node precisely determines the minimum transmission power level that provides good link quality and dynamically maintains the transmission power level over time.

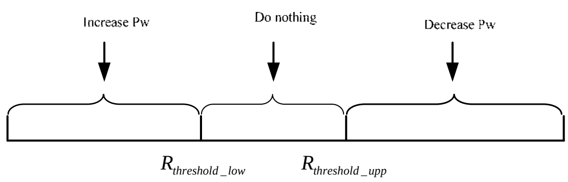

Figure.3. Adjusting transmission power level

B. Method of Routing Table Construction

In this section, we discuss the construction of route using the neighbor table mentioned in previous section. At the route construction step, each sensor node needs to figure out a better way to select its next-hop node. An efficient route for WSNs is expected to be able to 1) minimize the end-to-end delivery time, i.e. the sensing data could be timely delivered to the sink such that the decision maker can take immediate action to deal with that emergency event, and 2) save more energy consumption via the better routing decision. Therefore, source nodes must find the energy-efficient routing path to the sink node.

1) ISTH Algorithmic Description:

Firstly, we describe an online algorithm called Incremental Shortest-path Tree Heuristic (ISTH) [10]. 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 [10].ISTH finds the energy-efficient route to the sink according to the following cost metric:

$$C(u,v)=\begin{cases}\frac{R_i}{B}*C_{u,v}+Z, & u \quad is \quad inacitve\\ \frac{R_i}{B}*C_{u,v}, & u \quad is \quad acitve\end{cases} \quad (2)$$

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 $P_{t\_\min}$ (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 data rate, the bandwidth of all nodes is B. In (2), 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.

2) Construct Routing Table

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 (2), 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 energy consumption to the sink as its next-hop node and constructs a table to record its routing information.

Each node in WSNs maintains a routing table that contains the routing entries and status of neighbors. Specifically, an entry in the routing table of node u includes following fields: < *next_hop*, *cost*, *power_level*, *destination*>where *next_hop* is the neighbor node with the minimum cost to the sink, *cost* is the cost of node u to the sink through *next_hop*, *power_level* is the power level between node u and *next_hop*. *destination* is the routing path's destination node. Table 1 shows a routing table of a node.

C. Duty-cycle Scheduling of Nodes

Duty cycle mechanisms have been used in sensor networks to improve energy efficiency. For example S-MAC [2], each sensor node follows a periodic synchronized listen/sleep schedule. However, S-MAC introduces nonessential idle-listening, since node must be waken up when its sleep period expires, even when the node is not transmitting or receiving a data packet. This nonessential idle-listening is very inefficient and wasted significant energy. In the meanwhile, the duty-cycle mechanisms have other limitations. Most importantly, end-to-end delivery latency may be increased substantially; for example, with S-MAC, in each operational cycle, a data packet can be forwarded over a single hop only, since an intermediate relaying node has to wait for its next-hop node to wake up to receive the packet. Motivated by the above problem, we exploit cross-layer routing information to design the duty-cycle scheduling scheme for each sensor node. In this scheme, we exploit the routing information to form the nodes' duty-cycle schedule. This process contains two stages: synchronization stage and packets' transmitting stage.

1) Synchronization Stage

In the synchronization stage, nodes in the same routing path own the same duty-cycle schedule in order to reduce end-to-end delivery latency, So that data packets would be forwarded to sink node rapidly. Firstly, sink node computes duty-cycle schedules according to known routing information. Then, sink node disseminates computed duty-cycle schedules to every node through the routing paths. Each node exchanges duty-cycle schedules with all 1-hop neighbors, so that nodes in the same path wake up and sleep at the same time. Specially, if a node belongs with multiple paths, it follows the duty-cycle schedule of source node which has early wake-up schedule. If a node doesn't belong to any routing paths, its duty-cycle schedule is set to infinity. Fig.4 shows a simple network topology, node E, node F and node A belong to path-1; node A, node B, node C and node D belong to path-2.node E and node F own the same duty-cycle schedule; node B, node C and node D also own the same duty-cycle. And node A not only belongs to the path-1, but also belongs to the path-1, so its schedule depends on source node F and D. If node F's schedule is earlier than node D's, node A follow the schedule of node F, or it follow the node D. Node G don't any routing paths, then its schedule is set to infinity.

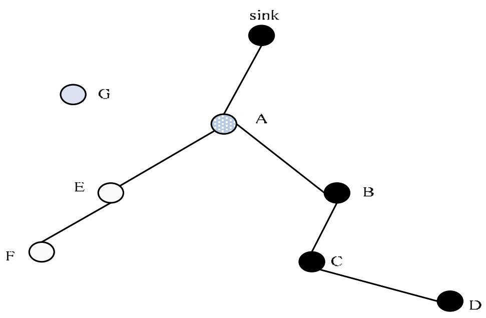

Figure.4. a network topology

To record each node's schedule, routing tables is modified by introducing a new field. So an entry in the routing table of node u becomes following fields: < *next_hop*, *cost*, *power_level*, *destination*, *schedule* >.

In the S-MAC protocol, nodes exchange and coordinate on their sleep schedules by periodically broadcasting SYNC frame to all immediate neighbors. We also employ SYNC frame to exchange all nodes' duty-cycle schedule. After sink node computed duty-cycle for each path, sink node send SYNC frame to disseminate schedule information, node that receives this SYNC frame record his duty-cycle.

2) Transmission Stage

Packet transmitting stage contains wake-up stage and transmission stage. When a node has data to send, the node firstly checks whether intermediate nodes are active period in the wake-up stage. In Figure 5, source node A has data to send to final destination sink node. Node A first picks a random period from the contention window and waits for the medium to be quiet for that period and an additional (DIFS) period before sending a wake-up frame to B. If node B is active state, and receives the wake-up frame from node A, then it sends a CTS frame back to node A. After B receives a wake-up frame, unless B is the final destination of this routing path, B gets the next-hop address for this destination from its own routing table. B then waits a SIFS period before transmitting its own wake-up frame. As in IEEE 802.11, SIFS is long enough for a node to switch its transmitting/receive mode and to do necessary data processing. Upon receiving B's wake-up frame, C performs the same steps as A. This process of receiving a CTS and immediately transmitting another wake-up frame continues until either the final destination has received the wake-up frame or the end of the current node's active period is reached

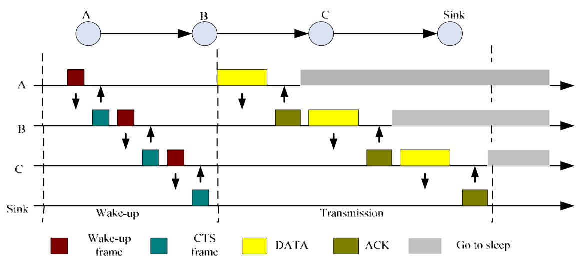

Figure.5. The overview of the duty-cycle scheduling scheme

All data packets are transmitted in the transmission stage. In the example in Figure 5, when the first node A receives the CTS frame, it waits until the start of the transmission stage to transmit the data packets. Node B keeps awake to receive the data packet at the start of the transmission stage, and after node B receives the data packet, it sends and ACK frame to S. After receiving the ACK, node A goes to sleep mode. This data packets relaying process continues at each hop until the final destination is reached or the data frame reaches some node that did not receive a CTS from it next hop, in which case the node just hold data frame until the wake-up period of the next operational cycle. This entire process is repeated until the final destination is reached.

IV. Validation and Performance Evaluation

To evaluate our approach, we first used a real MicaZ [8] mote platform to implement EOA. The real experimental platform enables us to study the applicability and some performance. Second, we use simulation to compare EOA with other energy-saving approach, since we can not measure energy consumption of real nodes due to lacking the appropriate tools. The simulation not only provides us with energy consumption of nodes, but also provides us other detailed information about performance of approach.

A. EOA's Validation on MicaZ mote

We implemented our approach in hardware using the low power MicaZ [8] platform. MicaZ mote represents the latest generation of Berkeley motes, and is commercialized by Crossbow. It is built around an ATMega128L microprocessor, and features a CC2420 802.15.4-compliant ZigBee-ready radio. IEEE 802.15.4 is a standard for low-rate, wireless personal area networks which provides specification for the physical and the MAC layer. At the physical layer, it defines a low-power spread spectrum radio operating at 2.4GHz with a bit rate of 250kb per second. ZigBee is a collection of high level communication protocols built on top of the IEEE 802.15.4 MAC layer.

We implemented the scheme with the operation system TinyOS [17]; our code has a reasonably small footprint (about 14KB of ROM occupancy, and less than 1KB of RAM occupancy).

Figure.6. MicaZ mote Test-platform

We placed 8 MicaZ motes in a lab environment in an arrangement shown in Fig.6. Mote 1 and mote 2 are source nodes which generates a data packet in every 5 seconds. Mote 0 is the sink mode set an MIB600 gateway to receive data from source nodes. Fresh batteries are used. To evaluate the runtime performance of EOA, we compare EOA with against MicaZ mote's default MAC protocol which is similar to B-MAC [19], but has the Low Power Listening functionality. Besides, this MAC protocol associates with a routing protocol named as DSDV [18] which has been implemented in TinyOS. A 72-hour experiment is conducted to demonstrate the advantage of EOA.

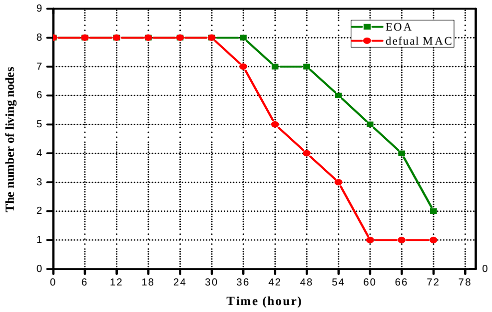

Figure.7. The Number of Living Nodes over Time

Fig.7 shows the number of living nodes over time. From the Fig.7, we can observe that: the defective nodes increases with the runtime increasing, but the number of living nodes of EOA is more than default MAC of MicaZ mote. The reason is that EOA lets nodes sleep when they don't take part in actually transmission activity, so that nodes is impossible to waste the idle-listening energy, the lifetime of nodes' battery is extended. However, in default MAC of MicaZ mote, nodes are set in receive mode whenever they don't transmit data packets, and prepare to receive data sent by other nodes at any time. This so-called idle listening leads to nodes always keep active state, even if they hasn't any communication activity. Thus, when the runtime increases, the energy consumption of nodes significantly increases, and lifetime of nodes reduces. When the number of the living nodes drops to a certain extent, the entire WSN becomes failure.

To investigate further the performance of EOA, the packet reception ratio (PRR) of sink node is measured in the experiment. Fig.8 shows the measurement results. As the time increases, the PRR of the EOA and default-MAC reduces. According to the result of Fig.7, the number of living nodes decreases after 42 hours in both schemes, so that the quality of links reduce, sink node's packets reception ratio reduce. However, EOA has a little better performance than default-MAC. The main reason is that EOA optimizes energy in all state (namely, transmission state, idle-listening state). As the result, the number of living nodes of EOA is more than the default MAC. When the number of living nodes only remains one, this node is sink node, so than packets aren't sent by source nodes, the PRR of both schemes becomes zero. Meanwhile, default MAC employs the static transmission power. The static transmission power no longer adapts the change of environment, the quality of link becomes frequently, so the sink node's PRR of default MAC is much more vulnerable than the EOA over time.

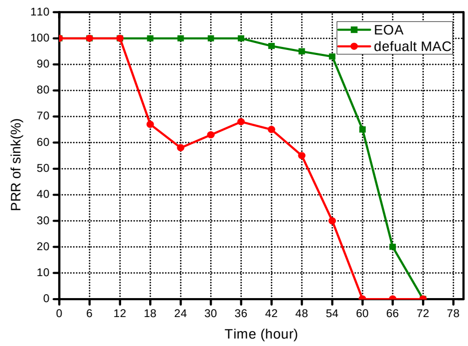

Figure.8. PRR of Sink Node over Time

B. Simulation Results and Analysis

We conduct computer simulation to evaluate the performance of the proposed approaches. For the performance comparison, we consider four different schemes: 1) non-transmission power control and routing and duty-cycle scheduling (namely, NTPC-EOA), 2) non-duty-cycle scheduling and transmission power control and routing (namely NDCY-EOA),3) non-transmission power control and DSDV[18] and S-MAC (namely NTPC-S-MAC), 4) transmission and routing and duty-cycle scheduling (namely EOA). In the case of non-transmission power control, we take the following arrangement: the static transmission power is used in the approaches, which is set to the average value between the maximal value and minimal value. The CSMA mechanism is used in the process of non duty-cycle, where nodes keep idle listening without transmitting data.

1) Simulation Environment Setup.

In this section, we present the performance study of EOA. All experiments are done through the simulation implemented in TOSSIM [10], which is the simulator of TinyOS by UC Berkeley. TOSSIM runs actual TinyOS code but provide software replacement for the simulated hardware and model network interaction at the bit of packet level, and extends the power modeling—PowerTossim[16], 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 power parameters according to the power model of Mica2 in [16] as follows. Each node is capable of transmitting data at 10 power levels ranging from -20dBm to 10dBm. The corresponding current consumptions range from 3.7mA to 21.5mA, the receiving and idle current is set to 7mA. In the simulation environment, we use the disc radio model provided by TinyOS in defining the range of a sensor node. In this model, a mote receives message from and sends message to other motes within its communication range without any error. The transmission range is specified as the radius of this disc. 100 nodes are deployed in a 150 m× 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.

The performance metrics used in this work are: 1) the total energy consumption that all source nodes sent data to sink successfully. 2) The packet reception ratio (PRR) at the sink. 3) The average end-to-end delivery time of a received packet.

2) Power Consumption

The most important metric of our performance evaluation is energy consumption. For each approach, we measure the total energy consumption that all source nodes successfully send data packets to sink. Fig.9 shows EOA is the most energy-efficient solution. As the number of source nodes increases, different source nodes share more middle nodes in the EOA, resulting in more nodes in sleep state and better energy efficient. In NTPC-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. At the same time, NTPC-S-MAC uses the static transmission power to transmit packets. However, though all nodes are deployed in the same environment, the transmission power between nodes is influenced by the environment. So transmission power between nodes should change with the environment. If the static transmission power is employed, link quality between nodes would change, and more energy is wasted. As a result, NTPC-S-MAC consumes the most energy.

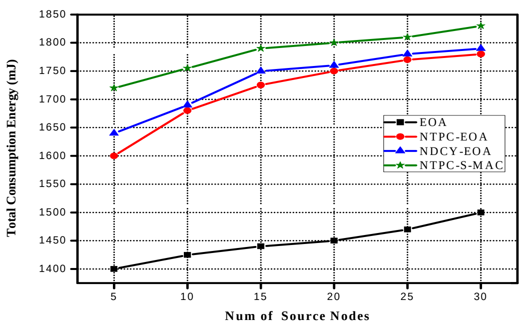

Fig.9. Total energy consumption according to the number of source nodes

The NDCY-EOA adopts idle-listening mechanism, so that nodes keep listening state when there are packets sent by them. This idle-listening mechanism leads in the waste of unnecessary energy. While NTPC-EOA employs the static transmission power, the reason of consuming energy is the same with the NTPC-S-MAC. Nevertheless the NTPC-EOA adopts the same duty-cycle mechanism with EOA. So it consumes less energy than NTPC-S-MAC.

3) End-to-End Delay

In Fig.10, we conclude the average end-to-end delay time. As the number of source nodes increases, all protocols yield higher delay, because network load increases due to the path sharing between different source nodes.

Not surprisingly, NTPC-S-MAC yields higher delay, since node starts to send/receive data until its sleep period expires. Because nodes keep idle-listening without transmitting packets in the NDCY-EOA, end-to-end data delay is the least than the other protocols.

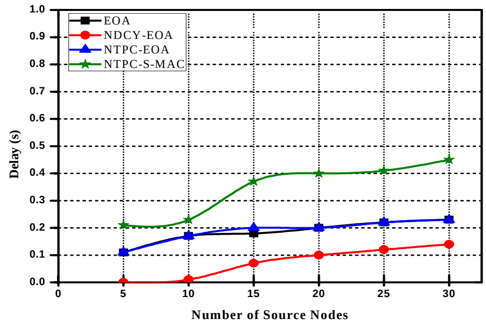

Figure.10. End-to-End data delay

The same duty-cycle mechanism is employed by EOA and NTPC-EOA, so their end-to-end data delay is almost same.

4) Data Delivery Ratio.

Fig. 11 illustrates the packet-receive ratio of sink node in different protocols. From this figure, we can see all protocol achieve beyond 90% PRR. However, as the number of source nodes increases, the packet-receive ratio of all protocols would reduce.

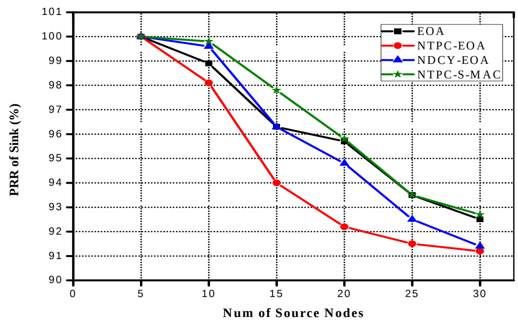

Fig.11. PRR of sink node according to the number of source nodes

NTPC-S-MAC is able to achieve the highest packet-receive ratio. The others have a litter less performance than NTPC-S-MAC. But the reasons for packet loss of these four solutions are quite different. For NTPC-SMAC, the reason is using the static transmission power. When the number of source nodes increases, interference among multi-path would become very frequent. As a result, there is collision in the processes of transmitting data, so data received by sink nodes reduces. For the others, when the number of source nodes increases, more middle nodes are shared by more paths to transmit the data. However, EOA has better performance than NDCY-EOA and NTPC-EOA.

When the number of source nodes is less than 15, the PRR of NDCY-EOA is more than EOA. Because the idle listening mechanism is employed by the NDCY-EOA, the event of losing packets happens unfrequently. The number of source nodes is beyond 15, the interference between nodes increase and the number of middle nodes shared by multi-path. As a result, the PRR of sink node reduces.

In the NTPC-MAC protocol, the static transmission power is employed. However, the link quality changes over time. When the quality changes, the static transmission power no longer is adapt to the quality, so that the loss of packets and collision of packets increase. As a result, the PRR of sink node reduces.

V. CONCLUSION

In this paper, an energy optimization approach for wireless sensor networks is present, named EOA which exploits the cross-layer principle that takes into the physical layer (i.e. the transmission power), MAC layer (i.e. the duty-cycle scheduling), and network layer (i.e. the routing protocol) account. EOA is able to use the physical layer's transmission power as metric to choose the routing path with optimal energy consumption, and use the network layer's routing information to determine the MAC layer's duty-cycle. The results of analytical simulation experiment and real platform shows that EOA conserve more energy and leads to the better system performance.

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