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Cross Layer Design and Implementation for Balancing Energy Efficiency in Wireless Sensor Networks

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Abstract: In this study, we propose a cross layer joint routing and MAC-PHY design to achieve energy balance and energy efficiency simultaneously in Wireless Sensor Networks (WSN). The energy balanced routing distributes the levels of residue energy evenly throughout the network, while the optimal transmission power control achieves further energy savings by adjusting transmission power to meet communication quality requirement at the receiver. Further more, we have implemented the proposed approach into TinyOS component running on Tmote-Sky sensor nodes. The results of our experimental study clearly show that the proposed the cross layer approach with energy balanced routing scheme and optimal power control improves energy efficiency while achieving energy balance as well.

Key words: Cross layer design, optimal power control, wireless sensor networks, energy balance, energy efficiency

INTRODUCTION

Energy consumption is a critical issue in Wireless Sensor Networks (WSN), because sensor nodes are powered by batteries which are not rechargeable in many applications. The smooth operation and energy efficiency of any WSN depends, to a large extent, on the effectiveness of Routing, MAC and PHY layers' responsibility. Recently, there have been many research activities in designing energy-efficient communication protocols for wireless sensor networks. Many protocols in the literature focus on finding minimum energy consumption paths for transmission and neglect the survivability of the whole network. Although these minimum energy consumption approaches may minimize energy consumption per packet, they can forward many packets using small number of popular paths. Therefore, energy consumption of the nodes on these paths will increase quickly and there would be a wide difference in the levels of the residual energy throughput the network. This will decrease the overall performance of the network and eventually partition the network into multiple sub-networks.

In this study, we propose and evaluate a new cross layer paradigm, where routing and MAC-PHY layers are jointly considered and optimized not only to achieve energy efficiency but also energy balance. The proposed optimal transmission power control dynamically adjusts the level of transmission power to meet signal strength requirement and Bit Error Ratio (BER) at the receiver end. The proposed energy balanced routing schemes choose the next hop based on neighboring nodes' residue energy, which distributes the energy consumption more evenly through the network.

There are many routing schemes designed for mobile ad hoc networks and wireless sensor networks. The protocols presented in previous researches (Parka *et al*., 1997; Perkins *et al*., 1994) use a shortest path to deliver packets. The problem of this approach is that the selected shortest path might not be a minimum energy cost route. Some other works concentrate on decreasing the energy consumption by replacing the hop-count routing with minimum energy routing (Banerjee and Misra, 2004). They compute a minimum-energy path for packet delivery in a multi-hop wireless network. However, the nodes on this path will get depleted soon.

The Directional Source-Aware Routing Protocol (DSAP) in (Salhieh and Schwiebert, 2004; Salhieh *et al*., 2001) incorporates power considerations into routing tables. This algorithm assumes that each node aware of its location. In DSAP, each node has a unique identifier that is called a directional value (DV). The DV represents the location of each node in the network with respect to its neighbors. These values can be determined in the setup phase of the network.

Another algorithm is proposed, which takes the remaining battery of each node into consideration (Chokhawala and Cheng, 1998). The main idea is to

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Corresponding Author: Wei Wang, Computer and Electronics Engineering, University of Nebraska Lincoln, USA combine the Existing Power Aware Metrics and cost-aware Metrics. This protocol introduces a threshold value for the remaining battery power of the nodes. While selecting a route, nodes with battery power greater than the threshold will only be considered. It would then go on to compute the minimum power cost route.

The protocols presented by (Shah and Rabaey, 2002) amend the shortcomings of the above algorithm. They consider the energy consumption and battery power and then probabilistically choose a route. This ensures that the optimal path does not get depleted and the network degrades gracefully as a whole rather than getting partitioned. To achieve this, multiple paths are found between source and destinations and each path is assigned a probability of being chosen, depending on the energy metric. When a packet is to be sent from the source to destination, one of the paths is randomly chosen depending on the probability distributions. This means that none of the paths is used all the time. Also different paths are tried continuously, improving tolerance to nodes moving.

On the other hand, few previous works address optimal power control in WSN, although here are extensive researches related to dynamic power control have been conducted extensively for general wireless network system (Sung and Wang, 2001; Kim *et al*., 2003) and they aim to reduce interference and increase channel capacity. However, besides the implementation complexity, an extension of this scenario to WSN with power efficiency does not necessarily lead to energy efficiency, let alone energy balance in WSN due to high redundancy, unfortunately.

As a result, the dynamic power control schemes in these works are not suitable for WSN. Using spreading gain can achieve low power; however, it does not necessarily result in low energy consumption. In contrast, our approach is to fine tune a simple WSN communication platform and manipulate the power supply and achieve the significant energy efficiency.

The major difference between our work and the existing approaches for dynamic power control in wireless networks (in the contexts other than WSN) is that we are intensively focused on improving WSN energy efficiency. This higher-priority goal leads to two important design principles different from the earlier ones are: (1) WSN PHY explores optimal transmission power to meet desirable BER requirement, which in turn achieves energy efficiency (2) WSN routing provides energy balance to improve the whole network performance.

OPTIMAL TRANSMISSION POWER CONTROL

In wireless signal transmission, one of major sources of loss is attenuation. Fundamentally, communication range decreases as the transmission data rate increases, considering all other factors being held equal. The signal loss can be expressed as follows (Stallings, 2004), where d is the distance and λ is the wavelength.

$$L = 10\log\left(\frac{4\pi d}{\lambda}\right)^2 \text{db} \tag{1}$$

As we can see from the previous formula, the strength of radio signal decreases as the distance increases. The desirable BER value can be mapped into a desirable SNR value for a given modulation scheme and the desirable SNR value required by a given data rate increases with the data rate. That is, if data rate increases, the probability of error also increase and then a higher SNR value is required at the transmitter to achieve the same BER at the receiver. Thus, power supply increases with the SNR value. However, there is maximum power supply limited by the hardware and then maximum SNR value.

According to the AWGN communication channel analysis, the SNR value required at the receiver end can be calculated from the BER value once the modulation scheme is determined. The relationship between BER and SNR for BPSK and QPSK (Haykin, 1994) is

$$\text{BER}^{\text{BPSK}} = \text{BER}^{\text{QPSK}} = \frac{1}{2}\text{erfc}(\sqrt{\frac{E_b}{N_0}}) \tag{2}$$

where BER is nonlinear inverse proportional to the energy per bit and the noise power density ratio. So, the ratio of energy per bit to the noise power density can be calculated from the BER value as follows, for BPSK modulation schemes:

$$\frac{E_b}{N_0}^{\text{BPSK}} = \left[\text{erfc}^{-1}\left(2\cdot\text{BER}^{\text{BPSK}}\right)\right]^2 \tag{3}$$

For QPSK modulation scheme, the ratio of energy per bit to the noise power density is expressed as:

$$\frac{E_b}{N_0}^{\text{QPSK}} = \left[\text{erfc}^{-1}\left(2\cdot\text{BER}^{\text{QPSK}}\right)\right]^2 \tag{4}$$

The equation shown above gives a theoretical relationship between BER and the ratio of energy per bit to noise power per Hertz. It only gives the relationship between BER and ratio of energy per bit to noise power per hertz and the relationship between BER and SNR is anticipated, because channel loss is based on SNR calculations. The following Eq. 5-9 give the relationship between SNR and the ratio of energy per bit to noise power per Hertz (Stallings, 2000). Ps is the power supply of transmit radio, Tb is the transmission time of one bit, R is the data rate in bite per second, b is constellation size or bit per symbol, Rs is the symbol rate, N is the noise power in the specific bandwidth defined by Rs. Equation 5 gives the per bit energy consumption:

$$E_b = Ps \cdot T_b \tag{5}$$

Equation 6 expresses the transmission time of each bit corresponding to the specific transmission rate.

$$T_b = \frac{1}{R} \tag{6}$$

The transmission rate can be explicitly determined by the transmission symbol rate and modulation constellation size:

$$R = Rs \cdot b \tag{7}$$

The noise power can be expressed as the noise power density and transmission symbol rate:

$$N = N_0 \cdot Rs \tag{8}$$

As a result, the signal to noise ratio is related to specific modulation constellation size and ratio of energy per bit to noise power per hertz:

$$SNR_{rx} = \frac{E_b}{N_0} \cdot b \tag{9}$$

The formulas 5-9 give the foundation that SNR at the receiver that can be acquired from the BER threshold and modulation schemes. The relationship between transmit power Ps and the SNR value at the receiver end is given in (10), where A is the channel attenuation factor including antenna gain in transmission (Srivastava, 2001):

$$SNR_{rx} = \frac{Ps}{N} \cdot A \tag{10}$$

So the optimal transmission power in terms of specific desirable BER at receiver end can be expressed as follows, according to Eq. 3-10.

$$\begin{aligned} Ps &= SNR_{rx} \cdot N \cdot \frac{1}{A} \\ &= SNR_{rx} \cdot Rs \cdot \frac{N_0}{A} \\ &= Rs \cdot b \cdot \frac{N_0}{A} \cdot \frac{E_b}{N_0} \end{aligned} \tag{11}$$

Where the factor A is the product of antenna gain k and the channel loss, expressed by Eq. 12. Theoretically, channel loss is related to distance between sensor nodes:

$$A = k \times L^{-1} \tag{12}$$

From the equations shown above, we can derive the optimal transmit power for BPSK and QPSK expressed by BER at the receiver end, to meet specific communication quality, i.e., desirable BER requirement:

$$Ps^{BPSK,QPSK} = Rs \cdot b \cdot \left[erfc^{-1}\left(2 \cdot BER^{BPSK,QPSK}\right)\right]^2 \cdot \frac{N_0}{A} \tag{13}$$

The signal strength at the receiver end can be acquired from the strength field of TOS_Msg packet and can be fed back in the beacon message to let the transmitter know the received signal strength. Of course, several signal strength values may be aggregated into one beacon packet. Based on the received feedback, the transmitter either increases or decreases the transmit power. If the signal strength at the receiver is too high, it gradually reduces transmission power until the signal strength at the receiver is slightly above the threshold level.

ENERGY BALANCED ROUTING

Now it is described that the proposed cross routing-mac-phy approach and design-implementation details. The energy aware routing has been proposed (Shahand Robaey, 2002), but it is not in a cross layer paradigm and energy efficiency can be further improved by the proposed approach. We apply the proposed optimal transmission power to radio module in dynamic power scaling method to the energy balanced routing, to achieve further energy savings. Each node maintains the amount of residual energy for its neighboring nodes, then calculate the costs of the links to each neighbor and selects next hop based on the calculated link costs.

Since the calculation of these link costs brings additional overheads, the proposed protocol chooses the next-hop using the statistical residual energy. The residual energy of a node is recursive defined as following formula 14:

$$E_{i\_statistical} = E_i + \sum_{j=0}^{N-1} P_j \times E_j \qquad (14)$$

where $E_{i\_statistical}$ is the statistical energy of node I, where E_i is the residue energy left in the battery, P_j is the probability of choosing node j as the next hop and E_j is the residue energy left in battery of node j, N is the total number of next hop neighbors of node I, that is, the number of parents of node I. The probability of choosing a node as the next hop node is the ratio of statistical energy of node j to the total statistical energy of all the next hop neighbors of node I, which can be presented as follows 15:

$$p_j = \frac{E_{j\_statistical}}{\sum_{k=0}^{N-1} E_{k\_statistical}} \qquad (15)$$

We design and implement *EBMultiHopRouter*, a TinyOS multihop routing component written in NesC. In this component, there are several important modules and configurations. There are two major modules: the engine module and the path management module. The engine module, called *EBMultiHopEngineM*, is a module which is mainly responsible for forwarding data packet received from the upper layer to the next node according to the Energy Balanced algorithm. The engine module calls the method provided by the path management module to get the proper next hop node's address and then stuffs the next hop node's address into the packet header to forward the packet to the next hop. The architecture of the protocol is shown in Fig. 1.

The path management module implements the Energy Balanced Algorithm. The path management module *EBMultiHopPathMgmtM* is used to maintain a neighbor table that includes statistical energy and radio signal strength indicator per a neighbor. It periodically broadcasts beacon messages to inform its children the statistical energy and node status information. When a child node receives a beacon message, it updates the corresponding item stored in its neighbor list. The node eliminates a node from its neighbor list if it did not receive any beacon message for a period of threshold time. By using the updated neighbor list, the routing scheme can be resilient to dynamic topological changes in the network.

To generate probability based random numbers, we develop a Probability Based Random Generator Unit inside the path management module. This is shown in Fig. 2. Upon receiving a command of get next hop address, the path management module creates a random number by invoking the probability based random generator unit.

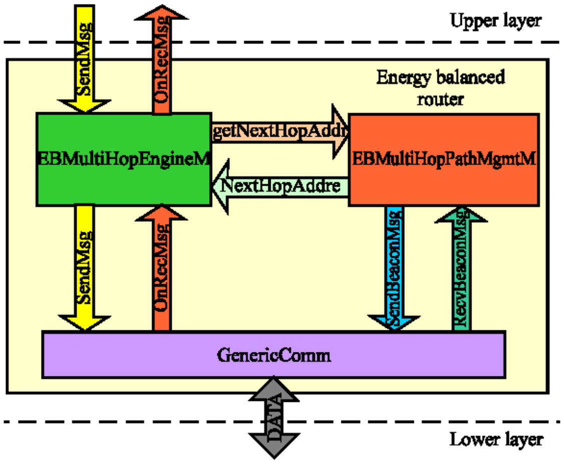


Fig. 1: Energy balanced router architecture

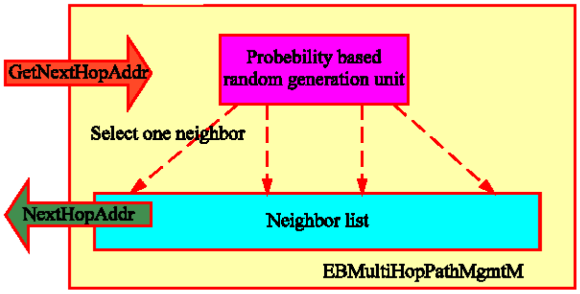


Fig. 2: Probability base random number generator in path management module

Given a probability distribution function (PDF) f (x), the probability of x which is between x1 and x2 is defined as the difference of Cumulated Distribution Function (CDF). So, given a random number X generated by the evenly distributed function, the decision making number Ndec is decided by the formula below:

$$N_{dec} = \sum_{k=0}^{i} E_{k\_statistical} \qquad (16)$$

where the integer I meet the requirement that Ndec is the smallest number in the record set but larger than X mod total statistical energy.

By slightly enlarging the integer I, we get a series of decision numbers. The goal of this task is to find a decision number that is the smallest but still larger than the result of X mod TotalStatisticalEnergy. This process is shown in Fig. 3. Once we find a proper value I, it will be used as an index or offset of the neighbor list to decide the next hop address.

The optimal transmission power control can be performed in frame granularity in the cross layer paradigm.

The processing approach is shown in Fig. 4. Before frame transmission, radio is started up from sleep state, perform carrier sensing and access channel. After that, channel attenuation factor is acquired and transmission power optimization is performed right before frame transmission. Optimal transmission power is implemented into look up table for fast real-time applications according to Eq. 13. After data-ack frames transfer, radio is turned into sleep mode by MAC layer to save energy.

The signal strength used by previous data transfer is used to calculate the channel attenuation factor, which in turn determines the optimal transmission power. Previous researches on channel prediction and acquisition focus on heuristic approaches using handshakes (Gomez *et al*., 1999; Lu *et al*., 1997), with simple implementation but with communication overhead; or mathematical approaches using past channel conditions to predict future ones (Hu *et al*., 2000; Sternad *et al*., 2001), with low communication overhead but high computation complexity. In our design we take similar heuristic approach. The signal strength used to calculate the channel attenuation factor is the feed backed RSSI (Radio Signal Strength Indicator) value of previous DATA packet at receiver, rather than the RSSI value measured at transmitter, due to the asymmetric nature of wireless channel.

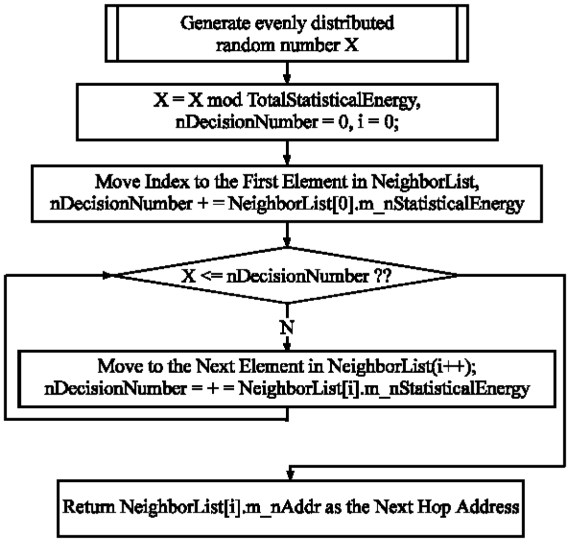


Fig. 3: Probability based random generator flow chart

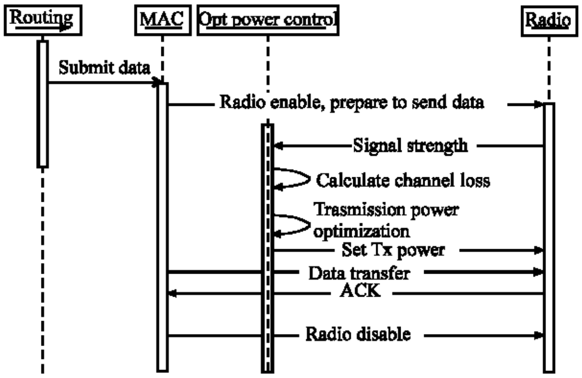


Fig. 4: Processing flow of optimal transmission power and data transmission

RESULTS OF EXPERIMENTAL STUDY

The proposed cross layer approach is implemented into TinyOS () components using open source NesC (Gay *et al*., 2003) and performance is measured by experimental results on sensor nodes. We use the TmoteSky motes for this experimental study. The TmoteSky mote has an 8 MHZ TI MSP430 microcontroller and a 2.4 GHz IEEE 802.15.4 Chipcon wireless transceiver.

The 4×4 mesh network topology used in this study is shown in Fig. 5. The test-bed has been established in University of Nebraska at Omaha South Campus. The total 16 nodes are divided into 7 levels and the number of hops between Node 0 and Node 15 is 6. The data packet generated at Node 15 at 7th level will be forwarded to either Node 13 or Node 14 at the 6th level and, either Node 10, Node 11 or Node 12 at the 5th level and so on until this packet arrives at Node 0. Here one path is chosen from multiple possible paths. Node 0 is a sink node which is connected to a laptop computer on which the data processing tasks is performed. Because of the USB connection between the sink node and the laptop

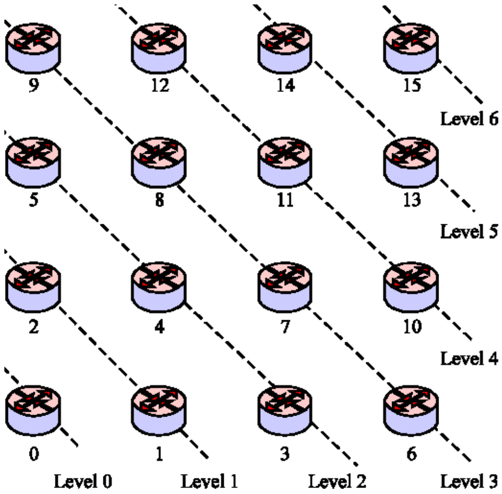
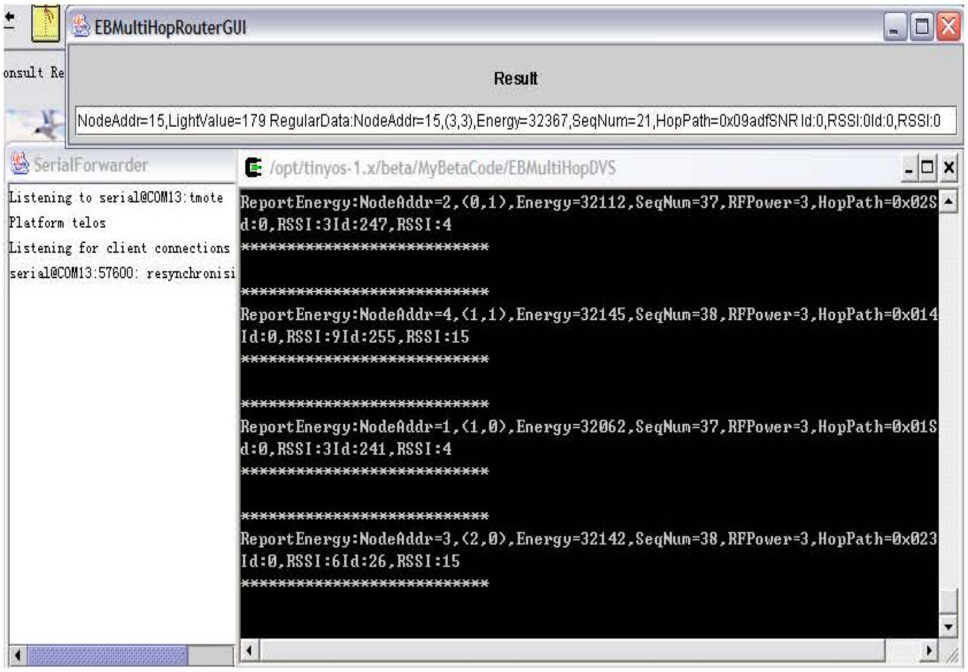


Fig. 5: The 4×4 mesh network topology of test bed



```
NodeAddr=15,LightValue=179 RegularData:NodeAddr=15,(3,3),Energy=32367,SeqNum=21,HopPath=0x09adfSNR Id:0,RSSI:0Id:0,RSSI:0
```

```
Listening to serial@COM13:tmote
Platform telos
Listening for client connections
serial@COM13:57600: resynchronisi
```

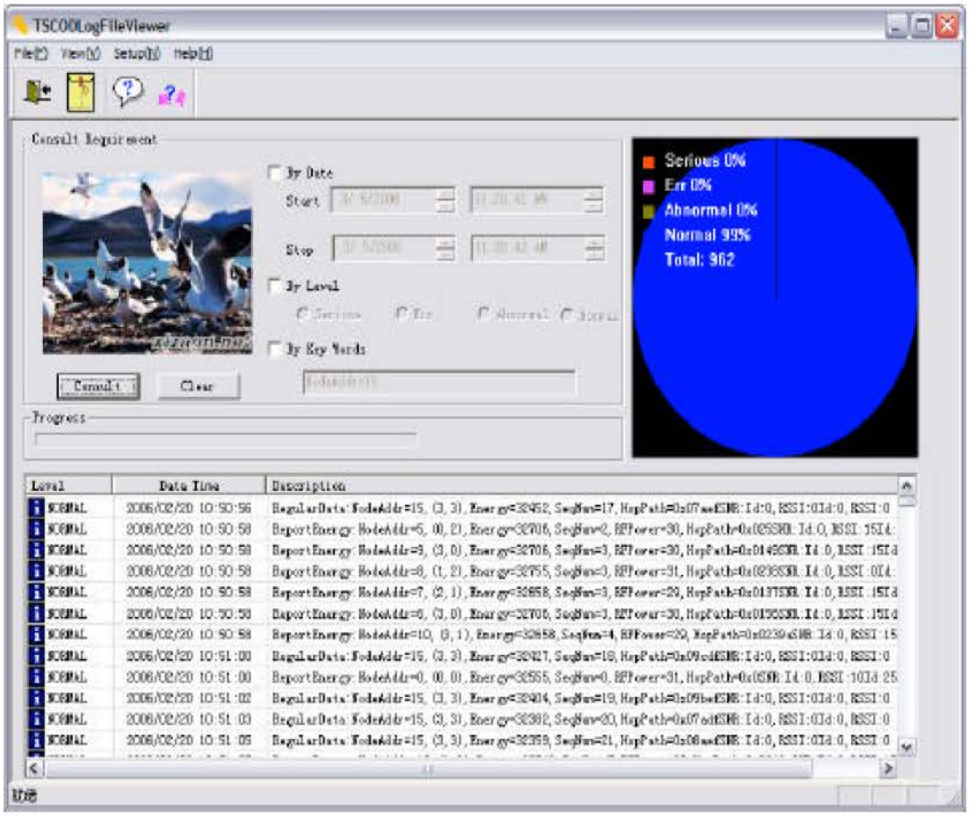
```
ReportEnergy:NodeAddr=2,(0,1),Energy=32112,SeqNum=37,RFPower=3,HopPath=0x02S
d:0,RSSI:3Id:247,RSSI:4
****************************

****************************
ReportEnergy:NodeAddr=4,(1,1),Energy=32145,SeqNum=38,RFPower=3,HopPath=0x014
Id:0,RSSI:9Id:255,RSSI:15
****************************

****************************
ReportEnergy:NodeAddr=1,(1,0),Energy=32062,SeqNum=37,RFPower=3,HopPath=0x01S
d:0,RSSI:3Id:241,RSSI:4
****************************

****************************
ReportEnergy:NodeAddr=3,(2,0),Energy=32142,SeqNum=38,RFPower=3,HopPath=0x023
Id:0,RSSI:6Id:26,RSSI:15
****************************
```

Fig. 6: Java program GUI and console



Level	Date Time	Description
NORMAL	2006/02/20 10:50:56	RegularData:NodeAddr=15, (3, 3), Energy=32452, SeqNum=17, HopPath=0x07aefSNR:Id:0, RSSI:0Id:0, RSSI:0
NORMAL	2006/02/20 10:50:58	ReportEnergy:NodeAddr=5, (0, 2), Energy=32706, SeqNum=2, RFPower=30, HopPath=0x025SNR:Id:0, RSSI:15Id:
NORMAL	2006/02/20 10:50:58	ReportEnergy:NodeAddr=9, (3, 0), Energy=32706, SeqNum=3, RFPower=30, HopPath=0x0149SNR:Id:0, RSSI:15Id
NORMAL	2006/02/20 10:50:58	ReportEnergy:NodeAddr=8, (1, 2), Energy=32755, SeqNum=3, RFPower=31, HopPath=0x0236SNR:Id:0, RSSI:0Id:
NORMAL	2006/02/20 10:50:58	ReportEnergy:NodeAddr=7, (2, 1), Energy=32858, SeqNum=3, RFPower=29, HopPath=0x0137SNR:Id:0, RSSI:15Id
NORMAL	2006/02/20 10:50:58	ReportEnergy:NodeAddr=6, (3, 0), Energy=32706, SeqNum=3, RFPower=30, HopPath=0x0156SNR:Id:0, RSSI:15Id
NORMAL	2006/02/20 10:50:58	ReportEnergy:NodeAddr=10, (3, 1), Energy=32858, SeqNum=4, RFPower=29, HopPath=0x0239aSNR:Id:0, RSSI:15
NORMAL	2006/02/20 10:51:00	RegularData:NodeAddr=15, (3, 3), Energy=32427, SeqNum=18, HopPath=0x09cdfSNR:Id:0, RSSI:0Id:0, RSSI:0
NORMAL	2006/02/20 10:51:00	ReportEnergy:NodeAddr=0, (0, 0), Energy=32555, SeqNum=0, RFPower=31, HopPath=0x0SNR:Id:0, RSSI:10Id:25
NORMAL	2006/02/20 10:51:02	RegularData:NodeAddr=15, (3, 3), Energy=32404, SeqNum=19, HopPath=0x09befSNR:Id:0, RSSI:0Id:0, RSSI:0
NORMAL	2006/02/20 10:51:03	RegularData:NodeAddr=15, (3, 3), Energy=32382, SeqNum=20, HopPath=0x07adfSNR:Id:0, RSSI:0Id:0, RSSI:0
NORMAL	2006/02/20 10:51:05	RegularData:NodeAddr=15, (3, 3), Energy=32359, SeqNum=21, HopPath=0x08aefSNR:Id:0, RSSI:0Id:0, RSSI:0

Fig. 7: Log file parsing program GUI

computer, the residue energy of node 0 is not cared in this experiment. Node 15 is a data generating node.

In order to monitor the network status and residue energy of every node, we have developed a java program that processes and dumps incoming data packets from the sensor network into log files via the Seril Fowarder TinyOS application. Figure 6 shows the developed a Java GUI and console. We also developed a log file parser in C++, which is also running on the laptop computer. This user friendly log file parser is very useful in this experiment, since the data analysis can be done automatically after data acquisitions. The GUI of this log file parser is shown in Fig. 7.

The experiment is performed with 3 different routing protocols: the Nearest Forward Progress (NFP) routing, the energy balanced routing scheme without power optimization and the energy balanced routing scheme with optimal power control. NFP is a typical position based routing scheme, where the packet is transmitted to the nearest neighbor of the sender, which is closer to the destination (Jain *et al*., 2001; Stojmenovic *et al*., 2002). In NFP routing, the packets will always take the same path that established.

All the nodes start at the energy value of 0×7 fff and decrease one after one second. If a node sending a beacon packet, the energy value will decrease by 2 since beacon packets are usually very small comparing to regular data packets in terms of the packet size. The energy consumption of receiving a beacon packet is ignored in this experimental study. We assume receiving and sending a regular data packet cost 20 and 30 energy units respectively. For optimal power scaling scheme in our implementation, the energy cost of sending a regular data packet is proportional to the level of transmission power. This value will be no larger than 30 units, which is the energy cost of sending a regular data packet at the max power supply. For every seconds of the experimental duration, the residual energy decreases by 1 unit. The experiment runs 10 min and the final residue energy is compared and shown.

Node 0 is the base station and is connected to the laptop computer, so it will have infinite energy and is not incorporated in the residue energy compare graphs. Only the nodes with the ID through 1 to 15 are measured with residue energy.

Figure 8 shows the residual energy of the NFP routing. From this figure, we can see that the nodes on the NFP path will run out of energy quickly while other nodes still have very high level of energy. The nodes 14, 11, 8, 5, 2 compose the path left residue energy about 60% of the initial energy after the experiment. Other nodes still have more than 97% of the initial energy.

Figure 9 shows the energy consumption using the energy balanced routing without optimal power scaling. This protocol achieves 75 to 85% of the initial energy. This protocol distributes the energy consumption more evenly throughout the network. The Node 6, Node 7, Node 8 and 9 achieves higher residual energy than other nodes because there are 4 nodes in this hop level while other hop levels have 3 or 2 nodes only. This is because the traffic load of the levels 3 is lower than that of other levels. However, the nodes in the same level have almost same amount of the residual energy.

Figure 10 shows the amount of remaining energy in the energy balanced routing with optimal power scaling. This routing scheme achieves further energy saving compared to the energy balanced routing without optimal power scaling. This protocol achieves the residual energy around 95% of the initial energy for almost all 15 nodes. This is because the nodes are intelligently using only

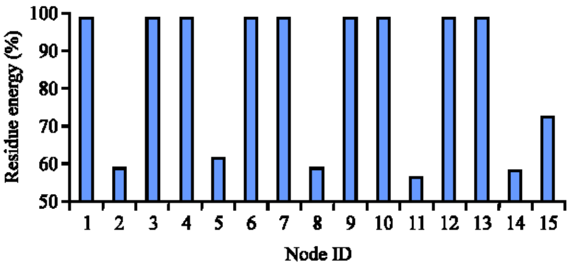


Fig. 8: Remaining energy per node in NFP

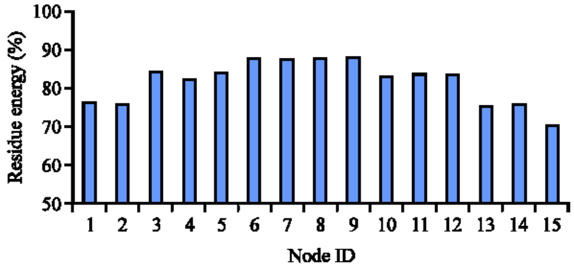


Fig. 9: Remaining energy per node in energy balanced routing without transmission power optimization

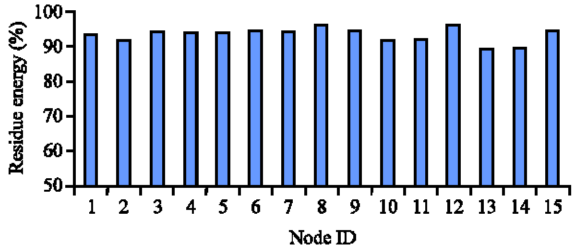


Fig. 10: Remaining energy per node of energy balanced routing with optimal power control

acceptable transmit power to send data packets. Therefore, the energy consumption can be reduced compared to the transmission scheme using maximum transmission power. The energy balance is achieved by energy balanced routing and the energy saving is achieved by optimal power scaling.

CONCLUSION

In this study, we propose a new cross layer paradigm to achieve energy balance as well as energy efficiency simultaneously. In the proposed approach, energy efficiency is significantly improved by optimal transmission power control and energy balance is achieved by the energy balanced routing. We implement the proposed design and two other routing schemes into TinyOS components in NesC language and conduct the experimental study to evaluate the performance of the proposed scheme. The results of our experimental study clearly show that the proposed approach improves energy efficiency while achieving energy balance as well. This work can serve as a generic TinyOS component for optimal power scaling and can be incorporated into other communication modules that need to conserve energy through optimal transmission power control.

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