Cross-Layer Energy Efficiency Analysis and Optimization in WSN

Qiuling Tang, Changyin Sun, Huan Wen, and Ye Liang

Abstract—**Energy conversation is a critical problem in wireless sensor networks (WSNs) so that the energy consumption must be minimized while satisfying application requirements. The energy efficiency can be supported across all layers of the protocol stack. In this paper, we propose and analyze a cross-layer energy efficiency model, which takes routing layer, MAC layer, data link layer, hardware circuitry, and battery discharge nonlinearity into account. For successfully delivering all data generated by source nodes to the sink node with minimal network energy consumption, we consider two orthogonal modulation schemes of M-ary pulse position modulation (PPM) and frequency shift keying (FSK), and distribute an appropriate time slot to every link so that the optimal routing can be obtained. Based on the model, we formulate the optimization problem of minimizing network energy consumption and solve it by existed approaches. The numerical results show that, if PPM scheme is adopted, the cross-layer energy efficiency model with optimal routing has up to 99% lower network energy consumption than that with a uniform single-hop routing in general WSN, and the optimal model also exists 93% energy saving if FSK is used. Multi-hop routing is more energy efficiency than single-hop routing in general WSN, while single-hop routing is more preferable in dense WSN.**

I. Introduction

In a typical WSN, nodes are powered by non-rechargeable batteries and thus energy is a scarce resource. It is imperative that energy conservation is considered across all layers of the protocol stack in order to minimizing the total network energy consumption and prolong the operational lifetime of the network.

WSNs have extensive potential applications. Nodes of a WSN are generally deployed to collect the interested data (temperature, chemicals, etc.) or just sense the presence or the absence of a phenomenon of interest in an information field. The amount of data collected by nodes varies with the application requirement of the WSN. The application requirement can be simply embodied by source rates of nodes. Typically, the data generation and transmission rates of nodes are low by reason of the scarce of power and the limitation of capacity of storage, processing and communication of nodes in WSNs. Therefore, the energy efficient approaches for the low rate setup should be explored for WSNs.

Among arts of energy efficiency in WSNs, joint cross-layer design stands as the most alternative to inefficient traditional layered protocol architectures [1]. There has been some cross-layer work aiming to optimize the network energy consumption and prolong the lifetime of the network. In [2], authors characterize an inherent trade-off in simultaneously maximizing the network lifetime and the application performance (characterized as network utility) by considering a cross-layer design problem in a wireless sensor network with orthogonal link transmissions. In [3], an energy optimization approach based on cross-layer for WSNs is put forward. The approach considers the joint optimal design of the physical, MAC, and routing layer. Its focus is on the computation of optimal transmission power, routing, and duty-cycle schedule that optimize the energy-efficiency of WSNs. In [4], a TDMA scheduling algorithm for energy efficiency and optimized delay is proposed based on a cross-layer optimization mode for clustered WSNs. The system model combines physical, MAC and network layers for wide energy conservation. The slot reuse concept is utilized for significantly reducing the end-to-end latency in WSNs. In [5], joint routing, MAC, and link layer optimization for maximizing the lifetime of the network 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.

In our previous work [6-8], for the low rate setup of WSN, we design and compare two energy efficiency FSK and PPM schemes [6]; model and analyze the actual energy consumption of a link by considering the signal transit power, hardware circuit of nodes and the battery discharge nonlinearity [7]; and formulate and optimize the actual network energy consumption for a star topology based on a TDMA scheme [8]. In this paper, we extend our previous work to provide, optimize and analyze a cross-layer energy efficiency model by jointly considering routing, MAC, data link, physical, hardware, and battery discharge nonlinearity under a topology with nodes randomly-deployed and an application requirement with source rates of nodes given.

In the following sections, we provide the cross-layer

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energy efficient model; optimize the model for minimizing the network energy consumption; then analyze its energy efficiency by numerical results; finally, concluding remarks are presented.

II. CROSS-LAYER ENERGY EFFICIENCY MODEL

Without loss of generality, we consider a WSN with its source nodes randomly deployed in the interested information field and its sink node located at the edge of the field. It is illustrated in Fig. 1. There are N sensor nodes in the network. The sink node is denoted as the N th node. The other $N-1$ nodes are source nodes for generating their own data to send to node N directly by single hop routing, or resort to other source nodes to relay the data to node N by multiple hop and even multiple paths routing. According to the requirements of application of nodes in the WSN, the data rate generated at each source node (called source rate) may be different. We denote it as R_i in the unit of packets per second (pps), $i=1,...,N-1$. In this paper, we assume a constant packet size ν =100bits.

A. Routing and MAC Design

For indicating all possible links of the network, we first discover the position of each node and calculate the distance from each node to the sink node. Then, we number all nodes in order from No. 1 for marking the node of maximal distance to No. $N-1$ for marking the node of minimal distance. Since data of source nodes have to be delivered to the sink node, the network routing could be represented by a directed graph (as shown in Fig. 1. A directed link from node i to node j exists only if $j>i$. We denote the link as l_{ij}. For node i, we use N_i to denote the set of nodes that send data to node i, and use M_i to denote the set of nodes that receive data from node i.

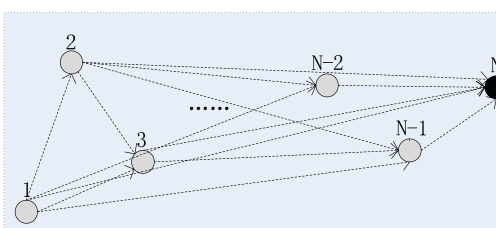

Fig. 1. A WSN with directed links

A Time Division Multiple Access (TDMA) scheme with variable time slot is applied in the model, in which interference among links is eliminated. Within each period of T, a transmission time slot of length t_{ij} is assigned to link l_{ij}, and the total transmission time of all links $\sum_i \sum_j t_{ij} \le T$.

Since our objective in this paper is to minimize the total network energy consumption, every time slot t_{ij}, $i=1,...,N-1$ and $j>i$, is decided by comprehensively considering the source rates of nodes, the data rates of links and the energy consumption of links. Consequently, the optimal routing for minimal network energy consumption could be resulted in.

B. Link Design

For reducing network energy consumption, links of network should be tailored for energy efficiency. We consider a link shown in Fig. 2. It consists of a transmitting node and a receiving node. The transmitting node includes a battery, a transmitter module, and a DC/DC converter to generate a desired and stable supply voltage for the transmitter. Likewise, the receiving node is also powered by a battery through a DC/DC converter.

For decreasing the link energy consumption, we adopt two

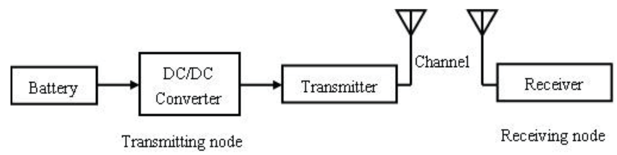

Fig. 2. A link diagram

energy efficient modulation schemes, namely PPM and FSK schemes. Both of them use non-coherent detection and take circuit work/sleep operating modes, carrier transmission, as well as low power low-IF transceiver design into account.

FSK and PPM are both commonly-used orthogonal modulation. M-ary FSK and PPM with rectangular transmit current waveforms have the same maximal bandwidth efficiency $2b_{ij}/M$, where $b_{ij}=\log_2 M$ is the number of bits per symbol. As the constellation size M increases, their bandwidth efficiency decrease, but the required energy for transmitting a bit also decreases for any preset error probability. Being orthogonal, they both enable constant-modulus transmissions during their pulse intervals and can afford low-complexity non-coherent detection. They have the same transmit energy per symbol for any prescribed SER p_e. For k th - power path-loss channels, it is approximately in [6]:

$$\varepsilon_s = 2n_0 G \ln\{2[1-(1-p_e)^{1/(2^{b_{ij}}-1)}]\}^{-1}, \qquad (1)$$

where n_0 is the thermal noise spectral density and $G=M_l d^k G_1$ is the power gain factor with M_l the link margin and G_1 the gain factor at transmission distance d = 1m. With a rectangular pulse shaper of duration T_p, the transmit power

$$P_s = \varepsilon_s / T_p . \qquad (2)$$

Given the channel bandwidth B, $T_p = T_s \approx M/2B$ with FSK, $T_p = T_s / M \approx 1/2B$ with PPM, where T_s denotes symbol period.

The same analog circuitry design is used as that in [6], which is a general low power low-intermediate frequency (low-IF) transceiver structure. In the design, the power consumption in the digital logic parts could be neglected as no complex algorithm is used. The circuit power consumptions P_{ct} and P_{cr} are considered and quantified by the power consumption of the analog circuitry at the transmitter and receiver respectively (see [6]).

Circuit active/ sleep operating modes are applied to save energy. When a node transmits data during the time slot assigned by the TDMA scheme, it commonly works in active mode. After finishing the data transmission, it turns off all the circuits to be in the sleep mode. Specially, PPM could work with active/ sleep modes even during every symbol period due to its intermittent pulse waveform. The rectangular transmit current waveforms of PPM and FSK are depicted in Fig 3. Combing Circuit active/sleep operating modes, the battery discharge current waveforms at a transmitting node are the profiles of those in Fig. 3 for both PPM and FSK.

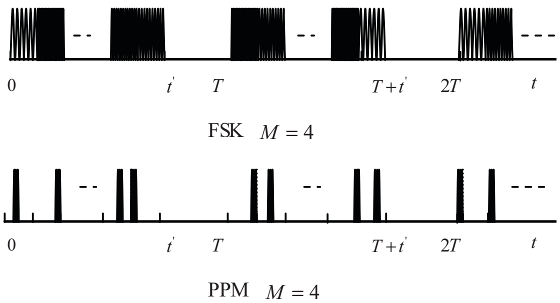

Fig. 3. the rectangular transmit current waveforms of PPM and FSK

Besides signal transmit and circuit operation, the discharge nonlinearity of battery also gives a contribution to the energy consumption of a node. The main capacity-related nonlinearity of battery is known as rate capacity effect. If the discharge current is small, the stored energy will be completely used or released. In this case, the battery can be considered as linear. But if the discharge current has large magnitude, nonlinearities emerge and considerable portion of the stored energy is wasted. The energy actually released C is related to the total energy stored C_0 through the so termed battery efficiency factor $\mu := C/C_0$. And in [9], the relationship between μ and discharge current i is described as

$$\mu(i) = 1 - \omega i, \tag{3}$$

where ω are positive constant. It follows that the actual power consumption of the battery is $V\,i/\mu(i)$, where V is the discharge voltage. If $f(i)$ denotes the probability density function (pdf) of discharge current i, then the average actual power consumption of battery can be expressed as $P_0 = V\int_{i_{\min}}^{i_{\max}} f(i)\cdot i/\mu(i)di$, where $i_{\max}$ and $i_{\min}$ are the rated maximum and minimum of battery discharge current respectively.

By combining the transmitting node and the receiving node, the actual energy consumption of the link for keeping active t' s is that

$$\varepsilon_{link} = Vt'\left(\int_{I_{\min}}^{I_{\max}} \frac{i_t}{\mu(i_t)} f(i_t)di_t + \frac{i_r}{\mu(i_r)} f(i_r)di_r\right). \tag{4}$$

Where i_t and i_r are the battery discharge currents in the transmitting node and receiving node respectively, $f(i_t)$ and $f(i_r)$ are their probability density functions (pdf). And the battery discharge currents have that

$$\begin{cases} \text{during pulse intervals:}\ \ i_t = ((1+\alpha)P_s + \mathrm{P}_{ct})/\eta V, \\ \qquad\qquad\qquad\qquad\quad i_r = \mathrm{P}_{cr}/\eta V, \\ \quad \text{at other times:}\qquad i_t = 0, \quad i_r = 0. \end{cases} \tag{5}$$

In (5), αP_s ($0<\alpha<1$) corresponds to the power consumed by the power amplifier. Factor α depends on the drain efficiency of the RF power amplifier and the peak-to-average power ratio of the transmitted signal. For convenience, we call $(1+\alpha)P_s$ the total transmit power. η (< 1) is the transfer efficiency of the DC/DC converter. Different modulation schemes (FSK and PPM in our work) give rise to different $f(i)$'s ($f(i_i)$ and $f(i_r)$) due to their different discharge current waveforms. In the transmitting node, the probability density functions are that

$$\begin{cases} f(i) = \dfrac{t'}{T}\delta(i-i_t) + (1-\dfrac{t'}{T})\delta(i), \text{ for FSK}, \\ f(i) = \dfrac{t'}{MT}\delta(i-i_t) + (1-\dfrac{t'}{MT})\delta(i), \text{ for PPM}, \end{cases} \tag{6}$$

while in the receiving node, they have the same expressions by replacing i_t with i_r.

III. Network Energy Consumption and Its Minimization

With TDMA scheme, links work in turn with period of T. During every T, a time slot t_{ij} is assigned to link l_{ij} for transmitting W_{ij} packets. Substituting Eq. (3), (5) and (6) into (4), the actual energy consumption for link l_{ij} within each period of T can be derived as

$$\varepsilon_{ij} = \begin{cases} \dfrac{2t_{ij}}{\eta 2^{b_{ij}}}\left(\dfrac{\beta\varepsilon_s + 2^{b_{ij}}P_{ct}}{\mu(I_t)} + \dfrac{2^{b_{ij}}P_{cr}}{\mu(I_r)}\right), & \text{for FSK}, \\ \dfrac{2t_{ij}}{\eta 2^{b_{ij}}}\left(\dfrac{\beta\varepsilon_s + P_{ct}}{\mu(I_t)} + \dfrac{P_{cr}}{\mu(I_r)}\right), & \text{for PPM}, \end{cases} \tag{7}$$

where $\beta = (1+\alpha)B$.

For both M-ary FSK and PPM schemes, the symbol rate of link can be approximately taken as $2B/M$. It follows that $t_{ij} = 2^{b_{ij}}\nu W_{ij}/2b_{ij}B$. Then Eq. (7) can be rewritten as

$$\varepsilon_{ij} = \begin{cases} \dfrac{\nu W_{ij}}{\eta B b_{ij}}\left(\dfrac{\beta\varepsilon_s + 2^{b_{ij}}P_{ct}}{\mu(I_t)} + \dfrac{2^{b_{ij}}P_{cr}}{\mu(I_r)}\right), & \text{for FSK}, \\ \dfrac{\nu W_{ij}}{\eta B b_{ij}}\left(\dfrac{\beta\varepsilon_s + P_{ct}}{\mu(I_t)} + \dfrac{P_{cr}}{\mu(I_r)}\right), & \text{for PPM}. \end{cases} \tag{8}$$

Since there is no interference between two links or two paths in TDMA scheme, the total actual network energy consumption is the sum of energy consumption of all links $\varepsilon = \sum_{i=1}^{N-1}\sum_{j\in M_i} \varepsilon_{ij}$, $i = 1,..., N-1, j = 2,..., N$, and $j > i$.

In order to minimize the total actual network energy consumption, we could optimize the cross-layer model in the last section. If the transmission rate of link is unfixed (b_{ij} is variable), the optimization model could be expressed as

$$\min \quad \sum_{i=1}^{N-1}\sum_{j\in M_i} \varepsilon_{ij}$$

$$\text{s.t.} \quad \sum_{i=1}^{N-1}\sum_{j\in M_i} t_{ij} \le T \quad \text{or} \quad \sum_{i=1}^{N-1}\sum_{j\in M_i} \frac{2^{b_{ij}} \nu W_{ij}}{2 b_{ij} B} \le T, \tag{9}$$

$$\sum_{j\in M_i} W_{ij} - \sum_{j\in N_i} W_{ij} = R_i T,$$

$$b_{\min} \le b_{ij} \le b_{\max}, \quad i = 1,\ldots, N-1, j = 2,\ldots, N, i < j,$$

where ε_{ij} is specified by Eq. (7) and (8). The first constraint is the frame length constraint based on the fact that each link is allotted a slot with the duration t_{ij} to transmit data. The second constraint is the flow conservation constraint, which guarantees for each node that the difference between the total outgoing traffic and the total incoming traffic is equal to the traffic generated by the node itself. The last constraint is based on the upper limit and lower limit of b_{ij} , which depend on the peak-power and delay respectively. We could optimize b_{ij} , t_{ij} and W_{ij} in order that the total network energy consumption is minimized. We first fix b_{ij} . The optimization problem becomes a linear problem, which can be solved by MATLAB optimization toolbox. Then by exhaustively searching all possible b_{ij} , the optimal variable set (b_{ij} , t_{ij} , W_{ij}) for the minimal network energy consumption can be obtained.

IV. Numerical Results and Analysis

In order to gain more insight into the energy efficiency of the cross-layer model, we take a numerical analysis in this section. We solve the optimization problem in (6) for both FSK and PPM by exhaustive search, and compare the resulting optimal routings and the minimal network energy consumptions between FSK and PPM. By comparing with a uniform routing, we evaluate energy conversation of the cross-layer model with the optimal routing.

We present simulation results for a general WSN and a dense WSN, in which nodes are densely deployed in a small area. The general WSN is assumed to have a topology of 6 source nodes randomly deployed in a 100×200 m^2 field and its sink located at coordinates (200, 50). The dense WSN is a miniature of the general WSN with the coordinate of every node shortened by 10 times so that the 6 source nodes deployed in a 10×20 m^2 field and its sink located at (20,5). The link system parameters, including battery, circuitry and channel parameters, are taken from Table I of [6]. Given the data generation rates of 6 source nodes [R_1 , R_2 , R_3 , R_4 , R_5 , R_6]= [5, 3, 9, 7, 6, 5] pps and the work period in TDMA T =3s.

Based on the optimization problem in (6), taking $b_{\min}$ = 1, $b_{\max}$ = 6, we numerically search the optimal variable sets (b_{ij} , t_{ij} , W_{ij}) for all the links to minimize the network energy consumption. The results are shown in Table I for the general WSN and Table II for the dense WSN.

From Table I, we observe that, although there are different optimal sets (b_{ij} , t_{ij} , W_{ij}) between FSK and PPM, they both remain the same available links after optimization. The same result appears in Table II.

TABLE I
Optimal Parameters for General WSN

Link	FSK			PPM		
	b_{ij}	t_{ij} (s)	W_{ij} (p)	b_{ij}	t_{ij} (s)	W_{ij} (p)
l_{17}	2	0.15	15	4	0.26	15
l_{27}	2	0.09	9	3	0.12	9
l_{37}	2	0.42	42	4	0.72	42
l_{47}	2	0.30	30	3	0.41	30
l_{57}	2	0.90	90	3	1.29	90
l_{67}	2	0.15	15	3	0.20	15
others	---	0	0	---	0	0

TABLE II
Optimal Parameters for Dense WSN

Li nk	FSK			PPM		
	b_{ij}	t_{ij} (s)	W_{ij} (p)	b_{ij}	t_{ij} (s)	W_{ij} (p)
l_{17}	2	0.15	15	5	0.43	15
l_{27}	2	0.09	9	5	0.26	9
l_{37}	2	0.27	27	5	0.77	27
l_{47}	2	0.21	21	5	0.60	21
l_{57}	2	0.18	18	5	0.51	18
l_{67}	2	0.15	15	5	0.43	15
others	---	0	0	---	0	0

The optimal routings exported from Table I and Table II are illustrated in Fig. 4 and Fig. 5 for the dense WSN and the general WSN respectively. The optimal routings in Fig. 4 and Fig. 5 show that multi-hop routing is more energy-efficient than single-hop routing in general WSN while single-hop routing becomes more preferable in dense WSN. The result is reasonable for the tradeoff between the transmit energy and the circuit energy consumption in long-haul data transmission.

In all above scenarios, the network energy consumption by

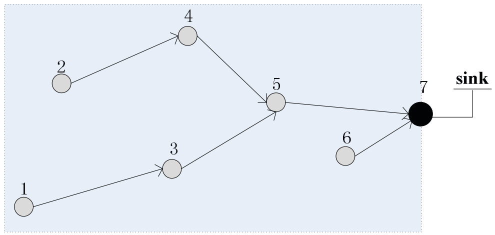

Fig. 4. The optimal routing for general WSN

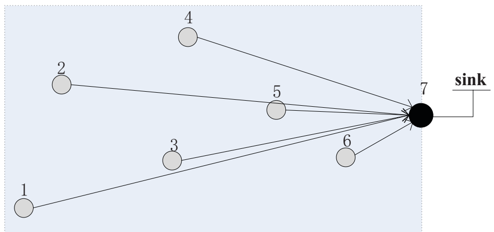

Fig. 5. The optimal routing for dense WSN

using PPM is much less than that by FSK. In the general WSN, the minimal network energy consumption ε = 225.74mJ for PPM versus 1126.81mJ for FSK. And in the dense WSN, ε = 44.55mJ for PPM versus 468.80mJ for FSK. The reason is that the intermittent pulse waveform of PPM can more fully take advantage of active/sleep operation modes of circuitry of node so that more circuit energy consumption is saved than the continuous waveform of FSK during a symbol interval.

For further observing the optimization gain of the cross-layer model in general WSN, a uniform routing is used as a reference, in which single-hop routing is chosen and each link is assigned that $b_{ij} = 2$ constantly. For FSK, the network energy consumption for the uniform routing ε =18291.29mJ while the optimal network energy consumption is 1126.81mJ. Then the energy gain from the optimization is about 93%. For PPM, there also exists an optimization energy gain up to 99%, which corresponds to the network energy consumption for the uniform routing being 44454.58mJ and its optimal counterpart only 161.23mJ. Thus, the energy efficiency of the optimal cross-layer model is significant.

V. Conclusion

In this paper, we present, optimize and analyze a cross-layer energy efficiency model under the application requirement, in which battery discharge nonlinearity, circuitry of node, two FSK and PPM schemes, a variable time slot TDMA scheme and node-randomly-deployed small-scale WSNs are considered. For minimizing the network energy consumption, the time slot assigned to each link is optimized and the optimal routings are derived for a dense WSN and a general WSN. The results show that multi-hop routing is more energy efficiency than single-hop routing in general WSN, while single-hop routing is more beneficial in dense WSN. By taking the single-hop uniform routing as a reference, the cross-layer model with optimal routing shows a noticeable decreasing of network energy consumption, which is 99% for PPM and 93% for FSK. And the cross-layer model with PPM scheme performs much better than that with FSK in term of energy conservation in both dense and general WSN.

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