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Mixture Integer Programming Based Optimal Transmission Policy Design for Multiple Applications in Wireless Sensor Networks

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To support multiple applications in an energy aware manner is very important for wireless sensor networks (WSNs). One key issue in supporting multiple applications is to search for the optimal transmission policy for each application so as to execute as many important applications as possible under the remaining network energy constraint. In this paper, the transmission policy is abstracted as the number of packets transmitted along each possible link. An energy consumption model is developed to investigate the energy consumption for packets transmission along each link. Then, a mixture integer programming model is developed to search for the optimal transmission policy for each application under the delay constraint. Based on the model, a management mechanism is developed to schedule the packets transmission for each application. And a novel concept of energy reservation is introduced in supporting multiple applications. Then, a global optimization model is developed to derive the performance upper bound in the investigated multiple applications scenarios. Simulation results show that the mechanism can save energy greatly in the investigated scenarios.

Keywords: Wireless Sensor Network, Multiple Applications, Energy Aware Design, Mixture Integer Programming.

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1. INTRODUCTION

Due to its advantages on the cost, coverage and self configuration, wireless sensor network (WSN) will be a novel information gathering tool. However, the limited sensor energy and difficulties on energy recharging pose big challenges for WSNs. Energy efficient algorithms have been investigated in most research areas related to WSNs, such as networking,[1,2] wireless communications,[3,4] and signal processing.[5] Especially, there have been a lot of research efforts recently at the networking layer on devising flow routing algorithms to maximize network lifetime.[6–13]

However, most of these algorithms focus on the energy efficient design in the single application scenarios. To the best of the author's knowledge, there are much less specific design efforts on energy aware schemes for the multiple applications scenarios in WSNs.

In fact, to support multiple applications is a characteristic of WSNs. First, since the nodes of WSNs have been equipped with multiple sensors, WSNs have the ability to support multiple application data requests. For example, the Rockwell WINS sensor node has been equipped with the sensors of seismic, acoustic, temperature, and pressure.[14] Second, there are many scenarios with multiple application data requests. For example, in the environmental monitoring application, there are application requests to gather data from different places at different time, and the position of the sink maybe fixed or dynamic. In the investigated scenarios in this paper, multiple application requests are assumed to arrive from the same sink or different sinks in an unknown sequence. On the other hand, the energy cost and the importance in terms of user reward for the gathered data are different for each application. User reward is a value to describe the importance of the application request, which depends on the parameters of the application request. Therefore, to execute as many important applications as possible under the remaining energy constraint becomes the objective of the energy management scheme in the multiple applications scenarios. In order to design such scheme, new techniques in addition to the

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energy saving techniques in single application scenarios are needed. There are two key issues in saving energy in the multiple applications scenarios. First, we need to find the optimal transmission policy for each application so as to minimize the energy cost. In finding the policy, we need not only to consider the energy optimization problem in the single application scenario, but also to make sure that the optimal transmission policy for the current application do not influence the execution of the already admitted applications. Second, we need to design an admission control scheme to determine the execution of an application based on its user reward and energy cost by the optimal transmission policy. The purpose is to maximize the overall user rewards under the energy constraint of the network. In this paper, we will investigate the first issue and design a mechanism to find the optimal transmission policy for each application request. And we have also investigated the second issue and designed the admission control scheme elsewhere, which will not be discussed here due to the limited space.

In the design, the application request is abstracted as to command several source nodes $V_s = \{N_1, N_2, \ldots, N_k\}$ to gather data at the rates $M_s = \{M_1, M_2, \ldots, M_k\}$ (packets per second), where k is the number of source nodes, and transmit the data to the sink in time T. The application requests may come from the same sink or the different sink. The optimal transmission policy for an application should minimize the energy cost of the application, which is defined as the reduction of the *remaining network energy* for executing the application. In this paper, we define the network lifetime of WSNs as the time elapsed until the first node in the network depletes its energy, as the definition in Refs. [6, 7, 9, 10]. The motivation of such definition is to balance the energy consumption among the nodes so as to prolong the network lifetime. Based on this definition, the *remaining network energy* can be defined as the remaining energy of the node with minimum energy level in the network. On the other hand, the transmission policy is abstracted as the number of packets transmitted along each possible link. Therefore, the search for the optimal transmission policy can be formulated as a mixture integer programming model, in which the optimal number of packets on each link is determined so as to transmit all data packets with the minimum energy cost under the delay constraint. In order to formulate the model, an energy consumption model is developed to investigate the energy consumption for packets transmission on each node. Furthermore, in supporting multiple applications, a novel concept of energy reservation is introduced. The basic idea is that after determining the optimal transmission policy for the current application, before the real execution the record about the remaining energy of each node will be subtracted the energy needed to execute the application by the policy. Then, the updated remaining energy will be used in determining the optimal transmission policies for future applications. Based on the energy consumption model and the *remaining* energy of each node, the mixture integer programming model can be formulated to find the optimal transmission policy. Then, the mature optimization techniques are used to solve the problem. In the current design, we assume a centralized management mechanism to find the optimal transmission policy. The information about the topology and the remaining energy of each node should be reported to sink periodically.

Then, we assume the whole applications sequence set is known. A global optimization model is developed to derive the performance upper bound by the joint design of the optimal admission control scheme and the optimal transmission policy. The performance upper bound can be approached by designing appropriate admission control scheme and transmission policy in the real situations.

In this paper, the design of the mixture integer programming model and the related centralized management mechanism will be discussed. The rest of the paper is organized as follows. The related work of designing transmission policy based on programming model will be discussed in Section 2; The problem statement of search for the optimal transmission policy is given in Section 3; The optimization model and the related centralized management mechanism are developed and analyzed in Section 4; Then, the performance upper bound model is developed in Section 5; The simulation results are provided and discussed in Section 6; At last, in Section 7, the conclusion is drawn and the future research work is discussed.

2. RELATED WORKS

The work in this paper is closely related to the research work focused on the lifetime maximization design in WSNs by the linear programming model.

In Ref. [7], Bhardwaj et al. developed a linear programming model to assign the optimal role of sensor, relay, and aggregator to each node so as to maximize the lifetime of the network in data gathering. The topology is abstracted as a *data gathering tree* during transmission. Bhardwaj et al. also derived the upper bound of the lifetime of the network by the linear programming model.[6, 7] In Refs. [9, 10], Chang et al. also identified the maximum lifetime routing problem as a linear programming problem. And the linear programming models are proposed to find the optimal route in both the scenarios of fixed information-generation rates and arbitrary information-generation rates. The models were also extended to the *multicommodity case*. In such models, the network lifetime is defined as the duration until the first node fails. Hou et al.[12] considered the issue of maximizing the lifetime for, not only the first node, but also all the other nodes in the network, which is called *Lexicographic Max-Min (LMM) node lifetime* problem. Then, a linear programming model was developed to solve the problem and derive the LMM-optimal node lifetime vector, which was used to schedule the packets transmission. In Ref. [13], DuarteMelo developed a fluid-flow based computational framework to investigate the relationships between the spatial distribution of node density, energy density, sensed data rated and the lifetime, information capacity in WSNs. The information capacity was defined as the maximum amount of information (bits) that can be transferred from the sensing field to the collector regions until the first sensor node gets completely drained off its battery and dies. Then, a linear programming model was developed to maximize the lifetime and information capacity.

The previous work have made many good linear programming model in the transmission policy design to maximize the lifetime of WSNs. However, almost all the previous work focused on the transmission policy design in the single application scenario. In fact, for a real WSN, there will be multiple applications requests arriving in an unknown sequence. Also, the sink maybe fixed or dynamic. In order to maximize the value of WSNs, the network should transmit as many important data as possible. So in our work, we focus on the design of the energy management scheme to execute as many important applications as possible under the remaining network energy constraint. The idea is similar to maximize the *information capacity* in Ref. [13]. However, in our work, the *information capacity* is just the sum of the amount of data gathered of all admitted applications. In order to design such energy management scheme, one key issue is to search for the optimal transmission policy for each application so as to minimize the *energy cost* and not influence the execution of the already admitted applications. Therefore, a novel mixture integer programming model is developed to search for such optimal transmission policy in the multiple applications scenarios.

3. PROBLEM STATEMENT

As stated in Section 1, the application is abstracted as follows. Sink commands the source node set V_s to gather data at the rate M_s and transmit the data to the sink in time T.

Denote the topology of the network as $G = \langle V, E\rangle$, where node set V denotes the set of n sensor nodes in the network; Sink is denoted as N_n; Edge set $E = \{e_{ij}\}$ denotes the set of directed communication links between the sensor nodes. If there is a directed communication link between node i and node j, $e_{ij} = d_{ij}$, where d_{ij} is the distance between node i and node j, otherwise $e_{ij} = 0$. Denote A_{ij} as the number of packets transmitted from node i to node j. Then, the transmission policy can be represented by the set of $\{A_{ij}\}$. So the problem to search for the optimal transmission policy is turned into finding the optimal set of $\{A_{ij}\}$ to minimize the energy cost under the delay constraint. As stated in Section 1, the energy cost for executing an application by one transmission policy is defined as the reduction of the *remaining network energy*, which is just the remaining energy of the node with minimum energy level in the network. Therefore, the optimization objective should be to maximize the remaining energy of the node with minimum energy level. As for node i, if the remaining energy before executing the application is E_{0i}, and the energy consumed in executing the application by the policy $\{A_{ij}\}$ is $E_{\mathrm{ci}}(\{A_{ij}\})$, then the remaining energy after executing the application is $E_i = E_{0i} - E_{\mathrm{ci}}(\{A_{ij}\})$. On the other hand, in order to prefer lower energy consumption routers, a weighted term taking into account the total energy consumption should also be introduced into the objective function with a little weight set. So the problem can be formulated as the optimization problem in Eq. (1).

$$\max_{\{A_{ij}\}}\left(\min_{i\in V,\, i\neq N_n}(E_{0i} - E_{\mathrm{ci}}(\{A_{ij}\})) - w\sum_{i\in V,\, i\neq N_n} E_{\mathrm{ci}}(\{A_{ij}\})\right) \quad \text{s.t.} \quad (1)$$

$\{A_{ij}\}$ is a feasible transmission policy for the application.

where w is a small positive weight value. Therefore, in order to solve the optimization problem, we must develop the energy consumption model in terms of $E_{\mathrm{ci}}(\{A_{ij}\})$, and identify the constraints on $\{A_{ij}\}$ for the feasible transmission policy of the application.

4. THE OPTIMIZATION MODEL AND RELATED CENTRALIZED MANAGEMENT MECHANISM

In this section, we will develop the optimization model to find the optimal transmission policy. First, we will develop the energy consumption model in terms of $E_{\mathrm{ci}}(\{A_{ij}\})$ in subsection 4.1. The constraints on $\{A_{ij}\}$ for the feasible transmission policy and the optimization model will be discussed in subsection 4.2. Then, in subsection 4.3, a centralized management mechanism is developed to schedule the packets transmission based on the optimization model. At last in subsection 4.4, we also introduce a novel concept of *energy reservation* in supporting multiple applications.

4.1. Energy Consumption Model

Based on the analysis in Section 3, we need to develop the energy consumption model in terms of $E_{\mathrm{ci}}(\{A_{ij}\})$. In order to develop the model, we make the following definitions and assumptions. For node $i \in V$, we define R_i as the set of the nodes which can receive data from node i, and S_i the set of nodes which can send data to node i.

$$R_i = \{j\colon e_{ij} > 0\}, \quad R_{N_n} = \phi$$
$$S_i = \{j\colon e_{ji} > 0\}$$

The remaining energy of node i before executing the application is assumed to be E_{0i}, especially $E_{0N_n} = \infty$. Recall that N_n is the sink node. And we also assume the transmission time for each link does not overlap the others, so the collision is removed by TDMA. BPSK is used as

RESEARCH ARTICLE

the modulation scheme. No error correcting code is used. The bandwidth for transmission is denoted as B Hz. So the bit rate of the transmission is approximately B bps. And the channel is assumed to be the AWGN channel with squared power path loss. In the future work, we will consider the joint design of adaptive modulation and coding in the transmission policy.

In the analysis of energy consumption of each node, we adopt the methods in Ref. [15].

First, the energy consumption in the receive mode of each node can be expressed as $E_r = P_{\rm cr}T_{\rm cr}$, where $P_{\rm cr}$ is the circuit power consumption, $T_{\rm cr}$ is the duration of the receive mode. According to the receive circuit design, $P_{\rm cr}$ can be expressed as $P_{\rm cr} = P_{\rm mix} + P_{\rm syn} + P_{\rm LNA} + P_{\rm filr} + P_{\rm IFA} + P_{\rm ADC}$, where $P_{\rm mix}$ is the power consumption of the mixer; $P_{\rm syn}$ is the power consumption of the frequency synthesizer; $P_{\rm LNA}$ is the power consumption of low power noise amplifier; $P_{\rm filr}$ is the power consumption of the receiver filter; $P_{\rm IFA}$ is the power consumption of intermediate frequency amplifier; $P_{\rm ADC}$ is the power consumption of the Analog-to-Digital converter.[15] If there are r packets to receive, $T_{\rm cr}$ can be expressed as $T_{\rm cr} = rv/B$, where v is the packet size. Therefore, the energy consumption in the receive mode can be expressed as $E_r = P_{\rm cr}(rv/B)$. Let $P_1 = P_{\rm cr}(v/B)$, then $E_r = P_1 r$.

Second, the energy consumption in the transmission mode of each node can be expressed as $E_t = (1+\alpha)E_{\rm tr} + E_{\rm c}$, where $E_{\rm tr}$ is the transmission energy consumption; $E_{\rm c}$ is the circuit energy consumption; α is the efficiency of the RF amplifier. If there are s packets to send, $E_{\rm tr} = svE_{\rm bt}$, where $E_{\rm bt}$ is the transmission energy consumption per bit. For BPSK, the BER performance can be expressed as $P_b = Q(\sqrt{2\text{SNR}})$, where $\text{SNR} = E_{\rm b}/N_0$ is the signal to noise ratio. Since $Q(x)$ can be approximated by $Q(x) \approx e^{-x^2/2}$ in high SNR regime, $E_{\rm b}$ can be approximated as $E_{\rm b} \approx -N_0 \ln(P_b)$. It should be noted that $E_{\rm b}$ is the energy per bit in the receiver side. Since the channel is assumed to be the flat Rayleigh fading channel with squared power path loss, $E_{\rm bt}$ can be expressed as follows:[15]

$$E_{\rm bt} = \frac{(4\pi d)^2}{G_{\rm t}G_{\rm r}\lambda^2} M_{\rm l} N_{\rm f} E_{\rm b}$$

where d is the distance between the sender and the receiver; $G_{\rm t}$ and $G_{\rm r}$ are the transmitter and receiver antenna gains respectively; λ is the carrier wavelength; $M_{\rm l}$ is the link margin; $N_{\rm f}$ is the receiver noise figure.

On the other hand, the time to transmit s packets is $T_{\rm ct} = sv/B$, and the power consumption of the transmit circuit is $P_{\rm ct} = P_{\rm mix} + P_{\rm syn} + P_{\rm filt} + P_{\rm DAC}$, where $P_{\rm filt}$ is the power consumption of transmitter filter; $P_{\rm DAC}$ is the power consumption of Digital-to-Analog converter. Therefore, the total energy consumption for transmitting s packets is

$$E_t = -(1+\alpha)N_0 \ln(P_b)\frac{(4\pi d)^2}{G_{\rm t}G_{\rm r}\lambda^2} M_{\rm l} N_{\rm f} sv + P_{\rm ct}\frac{sv}{B} \qquad (2)$$

Let

$$P_2 = -(1+\alpha)N_0 \ln(P_b)\frac{(4\pi)^2}{G_{\rm t}G_{\rm r}\lambda^2} M_{\rm l} N_{\rm f} v$$

$$P_3 = P_{\rm ct}\frac{v}{B}$$

E_t can be expressed as $E_t = P_2 d^2 s + P_3 s$.

If $\{A_{ij}\}$ is the set of packets transmission in one transmission policy for the application, then for node $i \in V$, $i \neq N_n$, the number of packets to receive is $r = \sum_{j\in S_i} A_{ji}$, and the number of packets to send is $s = \sum_{j\in R_i} A_{ij}$. Therefore, the energy consumption of node i in this policy can be expressed as

$$E_{\rm ci}(\{A_{ij}\}) = P_1\left(\sum_{j\in S_i} A_{ji}\right) + \sum_{j\in R_i}(P_2 d_{ij}^2 A_{ij} + P_3 A_{ij}) \qquad (3)$$

4.2. The Optimization Model and Corresponding Constraints

Based on the above analysis, the objective function of the optimization model should be

$$\max_{\{A_{ij}\}}\left(\min_{i\in V,\, i\neq N_n}(E_{0i} - E_{\rm ci}(\{A_{ij}\})) - w\sum_{i\in V,\, i\neq N_n} E_{\rm ci}(\{A_{ij}\})\right)$$

$$E_{\rm ci}(\{A_{ij}\}) = P_1\left(\sum_{j\in S_i} A_{ji}\right) + \sum_{j\in R_i}(P_2 d_{ij}^2 A_{ij} + P_3 A_{ij}) \qquad (4)$$

s.t.

Constraints on $\{A_{ij}\}$

In order to formulate the optimization model in Eq. (4), we must identify the constraints on $\{A_{ij}\}$. First, according to the constraint of flow conservation, the number of packets generated by node i should be equal to the number of packets sent by node i minus the number of packets received by node i. On the other hand, the number of packets generated by node i in T is $M_i T$. So one constraint should be

$$\sum_{j\in R_i} A_{ij} - \sum_{j\in S_i} A_{ji} = M_i T$$

Second, sink only receives packets, and all packets must be sent to sink. So we can define M_n as following.

$$M_n = -\sum_{j\in V_s} M_j$$

Third, all packets must be sent to sink in T, and the transmission time for each link does not overlap the others. So, another constraint is

$$\frac{v}{B}\sum_{i=1}^{n-1}\sum_{j=1}^{n} A_{ij} \leq T$$

Fourth, the energy consumption of each node $E_{\rm ci}(\{A_{ij}\})$ should not be larger than the remaining energy of the node. So, an another constraint is

$$E_{\rm ci}(\{A_{ij}\}) \leq E_{0i}$$

RESEARCH ARTICLE

Based on the analysis, the optimization model can be reformulated as Eq. (5).

$$\max_{\{A_{ij}\}}\left(\min_{i\in V,\, i\neq N_n}(E_{0i}-E_{\rm ci}(\{A_{ij}\}))-w\sum_{i\in V,\, i\neq N_n}E_{\rm ci}(\{A_{ij}\})\right)$$

s.t.

$$\begin{aligned}
&\sum_{j\in R_i}A_{ij}-\sum_{j\in S_i}A_{ji}=M_iT, \quad (i\in V)\\
&\frac{v}{B}\sum_{i=1}^{n-1}\sum_{j=1}^{n}A_{ij}\le T\\
&E_{\rm ci}(\{A_{ij}\})=P_1\left(\sum_{j\in S_i}A_{ji}\right)+\sum_{j\in R_i}(P_2d_{ij}^2A_{ij}+P_3A_{ij})\\
&E_{\rm ci}(\{A_{ij}\})\le E_{0i}\\
&A_{ij}\ge 0, \quad (i,j=1,2,\dots,n,\, i\neq j)\\
&A_{ii}=0\\
&M_nT=-\sum_{j\in V_s}M_jT\\
&A_{ij}\in N
\end{aligned} \tag{5}$$

In the optimization model shown in Eq. (5), the objective function $\min_{i\in V,\, i\neq N_n}(E_{0i}-E_{\rm ci}(\{A_{ij}\}))$ is not a linear function. So the optimization model in Eq. (5) is not a linear optimization model.[16] It will be difficult to solve in the polynomial time. But we can convert it to a linear optimization model shown in Eq. (6).

$$\max_{\{A_{ij}\}}\left(L-w\sum_{i\in V, i\neq N_n}E_{\rm ci}(\{A_{ij}\})\right)$$

s.t.

$$\begin{aligned}
&\sum_{j\in R_i}A_{ij}-\sum_{j\in S_i}A_{ji}=M_iT, \quad (i\in V)\\
&\frac{v}{B}\sum_{i=1}^{n-1}\sum_{j=1}^{n}A_{ij}\le T\\
&E_{\rm ci}=P_1\left(\sum_{j\in S_i}A_{ji}\right)+\sum_{j\in R_i}(P_2d_{ij}^2A_{ij}+P_3A_{ij})\\
&E_{\rm ci}(\{A_{ij}\})\le E_{0i}\\
&E_{0i}-E_{\rm ci}\ge L, \quad (i\in V, i\neq N_n)\\
&A_{ij}\ge 0, \quad (i,j=1,2,\dots,n,\, i\neq j)\\
&A_{ii}=0\\
&M_nT=-\sum_{j\in V_s}M_jT\\
&A_{ij}\in N
\end{aligned} \tag{6}$$

According to the definition of the *remaining network energy*, L is just the *remaining network energy*. And the remaining energy of node i after executing the application by the transmission policy $\{A_{ij}\}$ is just $E_i=E_{0i}-E_{\rm ci}(\{A_{ij}\})$.

The optimization model in Eq. (6) is also a mixture integer programming model since $\{A_{ij}\}$ must be integer, which can be solved in the polynomial time by many mature algorithms. In the simulation, we use the mature software package, GLPK (GNU Linear Programming Kit),[17] to solve the problem.

After solving the optimization problem, the optimal transmission policy $\{A_{ij}\}^*$ will be used to schedule the packet transmission in the network.

4.3. A Centralized Management Mechanism

A centralized management mechanism is then developed based on the optimization model. It will schedule the packets transmission in the network for the application. There are three key steps in the mechanism. First, after constructing the topology of the network, the information about the topology is sent to the sink. Second, when an application request arrives, the sink will find the optimal transmission policy for the application based on the optimization model in Eq. (6). Third, the sink will command the nodes in the network to transmit the packets according to the optimal transmission policy. In order to improve the efficiency and scalability, we can integrate the multi-hop clustering schemes in the centralized management mechanism. First, the sensor nodes can be grouped into several clusters and each cluster head gathers the data from the cluster members. And the cluster heads will form a multi-hop backbone. Then, we can use the centralized management scheme to find the optimal transmission policy for the cluster heads to transmit data to the sink. The performance of energy saving and QoS of data gathering can be improved by jointly optimizing the clustering schemes and the centralized management scheme.

According to the objective function in Eq. (5) and Eq. (6) and the nature of the centralized design, the mechanism can achieve the optimal performance, which can be seen as an upper bound in the design of the heuristics algorithms.

4.4. Energy Reservation in Supporting Multiple Applications

In the investigated multiple applications scenarios, using *remaining energy* of nodes as the criterion in determining the optimal transmission policy may result in the problem of *energy bottleneck path*. The reason can be explained by the example in Figure 1. In Figure 1, there are two applications requests, denoted as A and B, arriving at t_1 and $t_1+T_A/4$. Let us assume A will cost 4 J energy on each node in the transmission path, and B will cost 5 J energy on each node in the transmission path. The duration of the two applications are T_A and T_B, respectively. The remaining energy is shown beside each node. At $t=t_1$ A arrives, in order to maximize the minimal remaining energy after executing A, the optimization model will choose path $N_1\rightarrow N_3\rightarrow N_4\rightarrow N_7$ to transmit the data. Then at $t=t_1+T_A/4$,

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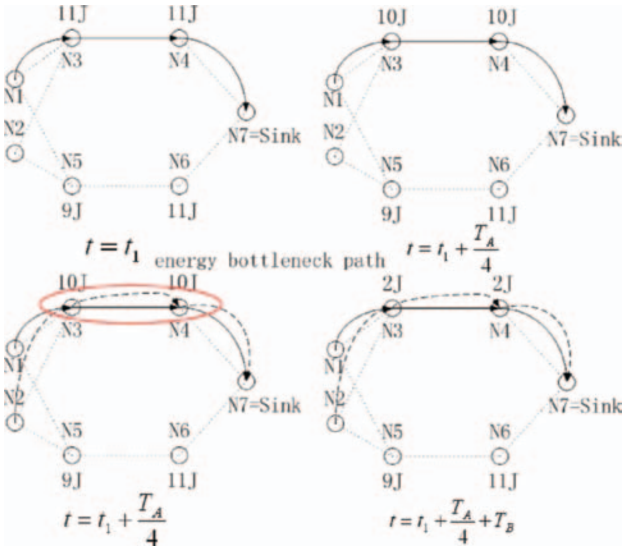

Fig. 1. Two applications with no energy reservation.

B arrives and the remaining energy of N_3 and N_4 are 10 J. In order to maximize the minimal remaining energy based on the current remaining energy of each node, the model will choose the path $N_2 \to N_3 \to N_4 \to N_7$ to transmit data, which makes the path $N_3 \to N_4$ an *energy bottleneck path*. When A and B are both executed, the remaining energy of N_3 and N_4 is just 2 J, which results in that the *remaining network energy* is only 2 J and the energy consumption of N_3, N_4, N_5, and N_6 are unbalanced. The main reason is that the remaining energy of the nodes are reduced gradually in executing the application, the instantaneous remaining energy can hardly describe the tasks assigned to the node. Based on this observation, we introduce the concept of *energy reservation*. The basic idea is that after determining the optimal transmission policy $\{A_{ij}\}^*$ for the application by the model, the record about *remaining energy* of

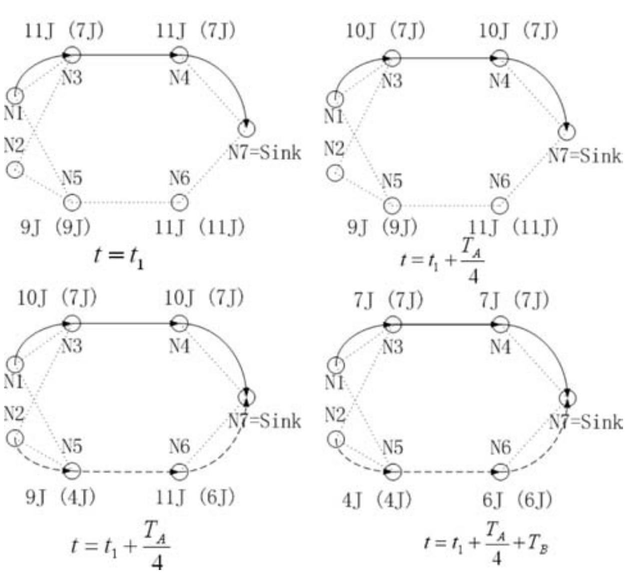

Fig. 2. Two applications with energy reservation.

each node, E_{0i} will be updated to $E_{0i} - E_{ci}(\{A_{ij}\}^*)$ before the real execution of the application. So the necessary energy to execute the application will be *reserved*. Then, the updated *remaining energy* will be used in determining the optimal transmission policy for future applications. By applying the concept of *energy reservation* in the example of Figure 1, the optimal transmission policy for A and B are shown in Figure 2, which results in that the *remaining network energy* is 4 J and the energy consumption of N_3, N_4, N_5, and N_6 are more balanced.

5. THE PERFORMANCE UPPER BOUND MODEL FOR THE JOINT DESIGN OF ADMISSION CONTROL SCHEME AND TRANSMISSION POLICY

As stated in Section 1, in the scenarios with multiple applications requests arriving in unknown sequence, the objective to execute as many important applications under the remaining network energy constraint can be achieved by the joint design of the optimal transmission policy for each application and the optimal admission control scheme for multiple applications.

If we assume the whole applications sequence set is known, we can formulate a global optimization model as a performance upper bound based on the mixture integer programming model in Section 4.

Denote the whole applications sequence set as $A_S = \{a_k\}$, the source nodes set for a_k is denoted as $V_{sk} = \{N_{k1}, N_{k2}, \ldots, N_{km_k}\}$, and the corresponding data gathering rates set is denoted as $M_{sk} = \{M_{k1}, M_{k2}, \ldots, M_{km_k}\}$, where m_k is the number of source nodes for a_k. Denote the corresponding sink node for a_k as N_{nk}. And we also assume the user reward for a_k is R_{ek}.

Denote the admission control scheme as $\{b_k\}$, where $b_k = 1$ represents a_k can be admitted to execute, otherwise rejected to execute. Denote the transmission policy for a_k as $\{A_{ijk}\}$.

Then, the overall user reward can be described by

$$O_1 = \sum_{k=1}^{N_A} b_k R_{ek} \tag{7}$$

where N_A is the number of applications requests. And the number of packets transmitted from node i to node j can be described by

$$A_{ij} = \sum_{k=1}^{N_A} b_k A_{ijk} \tag{8}$$

Then the energy consumption of node i, denoted as $E_{ci}(\{b_k\}, \{A_{ijk}\})$, can be described by

$$E_{ci}(\{b_k\}, \{A_{ijk}\}) = P_1\left(\sum_{k=1}^{N_A} b_k\left(\sum_{j\in S_i} A_{jik}\right)\right) + \sum_{k=1}^{N_A} b_k\left(\sum_{j\in R_i}(P_2 d_{ij}^2 A_{ijk} + P_3 A_{ijk})\right) \tag{9}$$

Then the remaining network energy after executing the whole applications set by the admission control scheme, $\{b_k\}$ and the transmission policies, $\{A_{ijk}\}$ can be described by

$$O_2 = \min_{i\in V}\,(E_{0i} - E_{\text{ci}}(\{b_k\},\,\{A_{ijk}\})) \tag{10}$$

And the total energy consumption can be described by

$$O_3 = \sum_{i\in V} E_{\text{ci}}(\{b_k\},\,\{A_{ijk}\}) \tag{11}$$

Based on Eq. (7) to Eq. (11), we can formulate the global optimization model to maximize the overall user reward and minimize the energy cost as Eq. (12).

$$\begin{aligned}
&\max\,(O_1 + w_1 O_2 - w_2 O_3),\ (w_2 \ll w_1 \ll 1)\\
&\text{s.t.}\\
&\quad E_{\text{ci}}(\{b_k\},\{A_{ijk}\}) \le E_{0i}\\
&\quad \sum_{j\in R_i} A_{ijk} - \sum_{j\in S_i} A_{jik} = M_{ki}T, \quad (i\in V,\ \forall k\in A_s)\\
&\quad \frac{v}{B}\sum_{i=1}^{n-1}\sum_{j=1}^{n} A_{ijk} \le T, \quad (\forall k\in A_s)\\
&\quad A_{ijk} \ge 0, \quad (i,j = 1,2,\ldots,n,\ i\ne j,\ \forall k\in A_s)\\
&\quad A_{iik} = 0, \quad (\forall k\in\{a_k\})\\
&\quad M_{nk}T = -\sum_{j\in V_{sk}} M_j T, \quad (\forall k\in A_s)\\
&\quad A_{ijk}\in N, \quad (\forall k\in A_s)
\end{aligned} \tag{12}$$

where w_1 and w_2 are small positive weight values to take into account the remaining network energy and total energy consumption in the objective function.

Based on Eq. (12), we can find the optimal admission control scheme, $\{b_k^*\}$ and optimal transmission policies for admitted applications, $\{A_{ijk}^*\}$. And the optimal overall user reward can also be treated as the performance upper bound.

6. SIMULATION RESULTS

In order to evaluate the performance of energy saving of the centralized management mechanism, a simulator is developed using the PARSEC[18] software, which is a discrete-event simulation language. In the simulation, the system parameters are summarized in Table I.

Table I. The system parameters.

f_c	2.5 GHz	λ	$3\times10^8/f_c$	P_{mix}	30.3 mw	P_{syn}	50 mw	P_{filt}	2.5 mw
P_{LNA}	20 mw	P_{IFA}	3 mw	P_{filr}	2.5 mw	P_b	0.001	N_0	−115 dBm/Hz
G_tG_r	5 dBi	M_t	40 dB	N_f	10 dB	B	10 KHz	α	0.4706
P_{DAC}	15.4 mw	P_{ADC}	6.7 mw	w	0.0001				

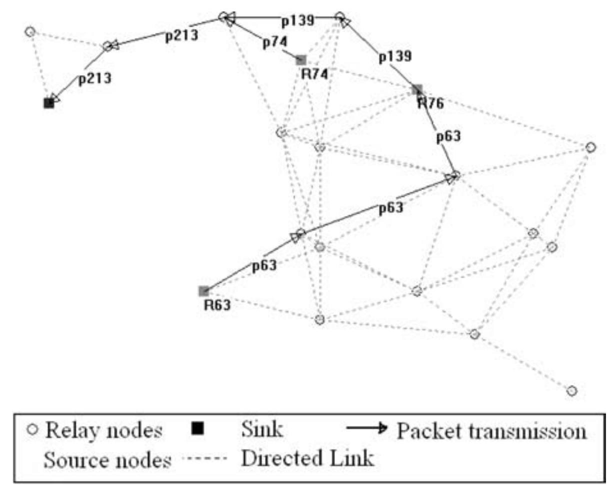

Fig. 3. Scenario 1 with 20 nodes in [30 m, 30 m].

In the simulations, the topology of the network is generated randomly. Figures 3 to 8 are examples in the simulation with different random topology and related applications.

In Figures 3 to 8, the directed communication link between each pair of nodes is marked as the dotted line, the sink is marked as the black block, the source nodes are marked as gray blocks, the data gathering rate for each source node is marked beside the node as Rxx, the optimal transmission policy is marked as the solid line in the figure, the packets transmitted in the optimal transmission policy is also marked on the solid line.

In order to show the performance of energy saving of the mechanism, we compared it with a baseline mechanism, in which the packets are always sent to the sink by the route that maximize the total available power in the nodes along the path. The baseline mechanism is introduced in Ref. [19]. It's simple but heuristic. In comparison, we adopted the topology in Figure 6. In the simulation,

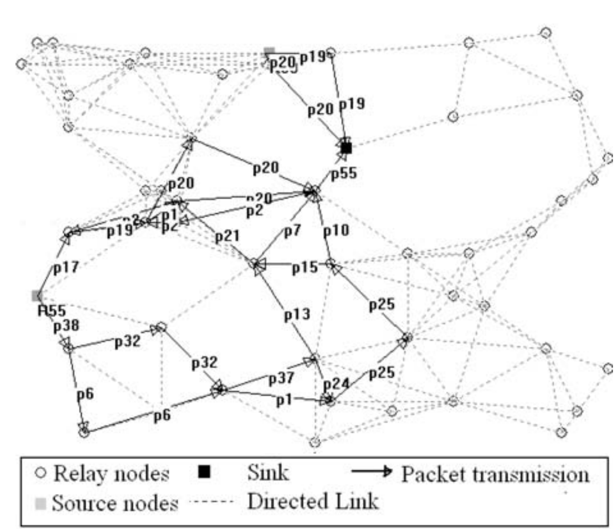

Fig. 4. Scenario 2 with 50 nodes in [40 m, 40 m].

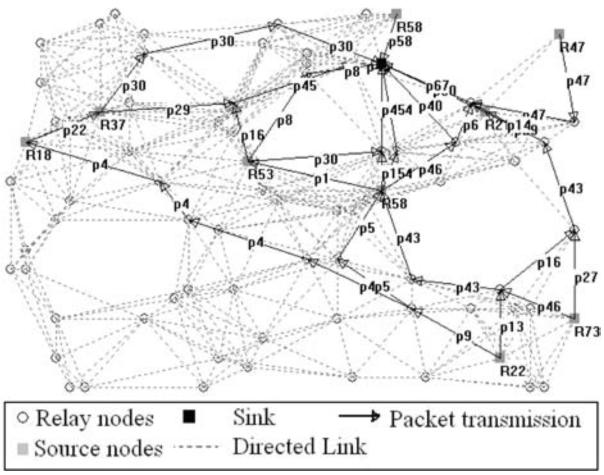

Fig. 5. Scenario 3 with 80 nodes in [40 m, 40 m].

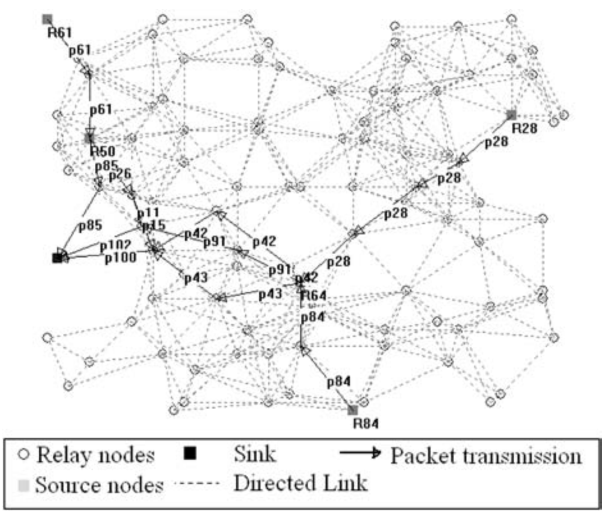

Fig. 6. Scenario 4 with 100 nodes in [50 m, 50 m].

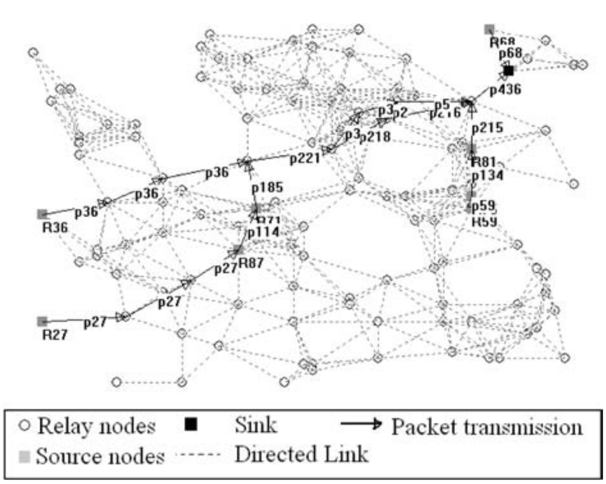

Fig. 7. Scenario 5 with 120 nodes in [60 m, 60 m].

10000 applications data requests arrive in sequence. The sink and the source nodes of the requests are distributed uniformly among the nodes, and the data gathering rates

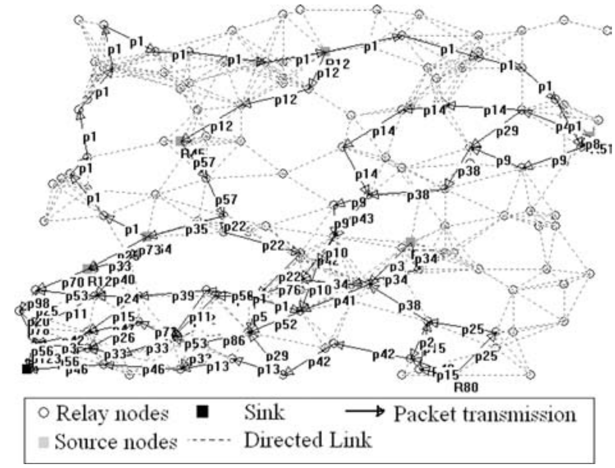

Fig. 8. Scenario 6 with 150 nodes in [70 m, 70 m].

are distributed uniformly between 10 and 90 pps. And the time constraint is fixed as 1 s for all applications. Each application request is executed by the centralized management mechanism and the baseline mechanism. Then, the *energy cost* for each application by the two mechanisms are collected. The *energy cost* for an application is defined as the reduction of *the remaining network energy* due to the execution of the application by the two mechanisms. Then, the plot of the probability distribution function (PDF) of the *energy cost* of the two mechanisms are shown in Figure 9.

From the results shown in Figure 9, it can be observed that the distribution of the energy cost of the optimal transmission policy lies mainly below 0.05 J, and the distribution of the energy cost of the baseline policy lies mainly between 0.1 J and 0.3 J. And the mean of the energy cost by the optimal transmission policy and the baseline policy in all investigated scenarios are 0.0273 J and 0.2 J, respectively. Therefore, the performance of energy saving of the optimal transmission policy is significant. The reason can be explained as following. The definition of *energy cost* in Figure 9 is a two-objective criterion, reflecting the balance

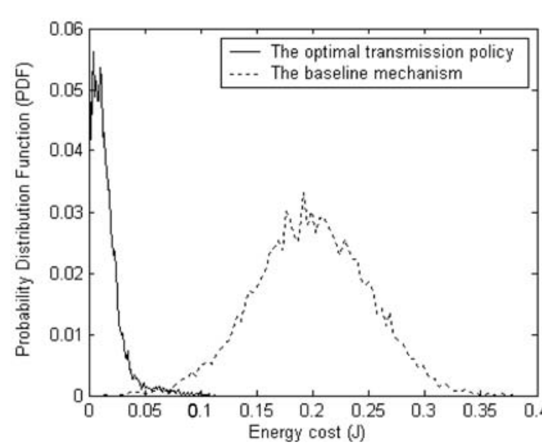

Fig. 9. The probability distribution of the energy cost.

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and the amount of energy consumption. From Eq. (5), we can find both the balance and amount of energy consumption are considered. So the optimal transmission policy by the optimization model can get less *energy cost* than the baseline policy.

7. CONCLUSION

In this paper, the problem of finding the optimal transmission policy for each application is investigated, which is the key issue in supporting multiple applications in WSNs. The purpose is to maximize the *remaining network energy* after executing the application, so as to execute as many important applications as possible under the remaining energy constraint of the networks. In finding the optimal transmission policy, the transmission policy is abstracted as the different set of packets transmission between each pair of nodes. And an energy consumption model is developed to investigate the relationship between the different transmission policy and the overall energy consumption. Then, a mixture integer programming model is developed to find the optimal transmission policy. Based on the optimization model, a centralized management mechanism is developed to schedule the packets transmission for each application. Simulation results show that the centralized management mechanism can save energy significantly in the investigated scenarios.

We conclude the paper with a brief discussion of the future work. This paper considers the issue of finding the optimal transmission policy in supporting multiple applications in WSNs. An centralized management mechanism is designed. In the mechanism, the sink needs to collect and maintain all the information about the network topology, which result in the optimal performance on energy conservation. However, the centralized management mechanism is not scalable to manipulate the large scale network. To improve the scalability of the centralized management mechanism, we will consider in the future work to implement the optimization procedure in a more distributive manner. On the other hand, in the optimal transmission policy, we only considered the route of each packet in transmission. In fact, a broader tradeoff space could be explored to improve the energy efficiency further, such as the joint design of adaptive modulation and coding.

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