Joint Routing, MAC, and Link Layer Optimization in Sensor Networks with Energy Constraints

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***Abstract*— We consider sensor networks where energy is a limited resource so that energy consumption must be minimized while satisfying given throughput requirements. Moreover, energy consumption must take into account both the transmission energy and the circuit processing energy for short-range communications. We emphasize that the energy efficiency must be supported across all layers of the protocol stack through a cross-layer design. In this context, we analyze energy-efficient joint routing, scheduling, and link adaptation strategies that maximize the network lifetime. We propose variable-length TDMA schemes where the slot length is optimally assigned according to the routing requirement while minimizing the energy consumption across the network. We show that the optimization problems can be transformed into or approximated by convex problems that can be efficiently solved using known techniques. The results show that multihop routing schemes are more energy-efficient when only transmission energy is considered, but single-hop transmissions may be more efficient when the circuit processing energy is considered.**

I. Introduction

In a typical sensor network, sensors are powered by small batteries that cannot be replaced. Under this hard energy constraint, sensor nodes can only transmit a finite number of bits in their lifetime. Consequently, reducing the energy consumption per bit for end-to-end transmissions becomes an important design consideration for such networks. Since all layers of the protocol stack contribute to the energy per bit consumed in its end-to-end transmission, energy minimization requires a joint design across all these layers as well as the underlying hardware where the energy is actually expended [1].

While there has been much recent work in cross-layer design for wireless networks [2]-[6], the hardware is typically ignored. Network optimization including hardware considerations was investigated in [7]-[11], where the authors consider a joint design between the link layer and the silicon layer. By considering constraints such as power consumption imposed by the underlying circuits, optimal modulation schemes are derived to minimize the total energy consumption. In [12], joint design between MAC and link layers is considered and an optimal variable-length TDMA scheme is proposed to minimize the energy consumption across the network. However, these results do not take into account routing protocols. In this work, we consider the joint design of the MAC, routing, and link layer to minimize the total energy consumption in the network.

We only consider the simplified case where interference is eliminated by using Time Division Multiple Access (TDMA) schemes, which are appropriate for small-scale sensor networks. We consider the joint design across hardware, link, MAC, and routing. We show that if link adaptation is not allowed, the energy minimization problem is a convex problem and can be efficiently solved. If link adaptation is allowed, the energy minimization problem can be relaxed to a convex problem and efficient algorithms exist to achieve a near-optimal solution. We will see that taking into account hardware considerations associated with the energy consumption can lead to different design guidelines than where the underlying hardware is ignored.

The remainder of this paper is organized as follows. Section II describes the system model. In Section III, we fix the link layer and discuss the optimal routing and MAC schemes. In Section IV, the complete model is constructed to jointly design the routing and MAC combined with the optimal link adaptation. Section V briefly discusses the delay performance and the scalability issues. Section VI summarizes our conclusions.

II. System Model

In a typical sensor network, information collected by multiple sensors needs to be transmitted to a remote central processor that we call a hub node. If the hub node is far away, the information may first be transmitted to a relay node, then multihop routing will be used to forward the data to its final destination. We assume that there are multiple nodes that want to transmit their collected information to the hub node. The corresponding scenario is illustrated in Fig. 1.

For each link, the transmit and receive signal paths are illustrated in Fig. 2, respectively. In order to minimize the total energy consumption, all signal processing blocks at the transmitter and the receiver need to be considered in the optimization model. However, in this paper we neglect the energy consumption of baseband signal processing blocks (*e.g.*, source coding, pulse-shaping, and digital modulation). We also assume that the system is uncoded. Thus, no energy consumption in error-correction coding/decoding is included. Note that although this model is based on a generic low-IF

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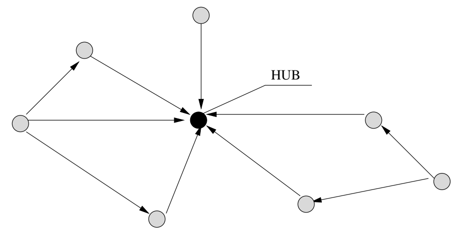


Fig. 1. Data collection in a sensor network

transceiver structure, our framework can be easily modified to analyze other architectures as well.

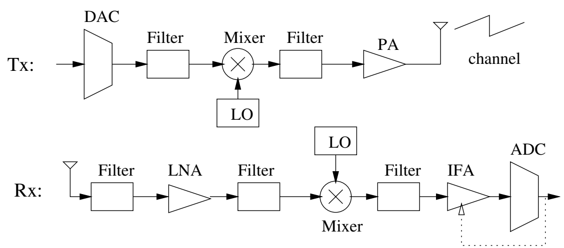


Fig. 2. Transceiver Circuit Blocks (Analog)

We assume that there are N sensor nodes in the network. Without loss of generality, we denote the hub node as the Nth node. The other $N-1$ nodes either have their own data to send to node N, or they just act as relay nodes to help others. We denote the data rate generated at each node as R_i in the unit of packets per second (pps), $i = 1, \cdots, N$. In this paper we assume a constant packet size $\nu = 100$ bits. Obviously, for the hub node, we have $R_N = -\sum_{i=1}^{N-1} R_i$, where the negative sign means that the hub node has only incoming traffic. For relay nodes, the value of R_i is equal to zero.

We assume that uncoded MQAM is used and the constellation size assigned to link $i \rightarrow j$ is denoted as $b_{ij} = \log_2 M_{ij}$. We also assume that a variable-length TDMA scheme is used where the transmission time t_{ij} assigned to link $i \rightarrow j$ is equal to $\frac{\nu W_{ij}}{B b_{ij}}$ under the assumption that the symbol rate is approximately equal to the bandwidth B and W_{ij} is the number of packets transmitted over link $i \rightarrow j$ in a period of T. It is obvious that $\sum_i \sum_j t_{ij} \leq T$. From these relationships we see that as long as we find the optimal values for any two variables among b_{ij}, W_{ij}, and t_{ij}, the optimal value for the third one can be determined.

We denote the distance between node i and node j as d_{ij} and assume an AWGN channel with a κ^{th}- power path-loss for link $i \rightarrow j$. The received power P_r is thus given by $P_r = P_t/G_d$, where P_t is the transmit power and $G_d \triangleq G_0 d^\kappa$ is the power loss factor with G_0 the loss factor at $d = 1$ m, which is defined by the antenna gain, carrier frequency, link margin, and other system parameters [11].

We assume that each node has three possible modes [11]: active mode, sleep mode, and transient mode. Specifically, during the time slot assigned by the TDMA scheme, the corresponding node works in the active mode. After finishing the data transmission, it turns off all the circuits to be in the sleep mode to save energy. When switching from the sleep mode to the active mode, there is the transient mode that is mainly caused by the recovery of the phase-lock loop [11]. In the sleep mode the power consumption is dominated by the leakage current of the switching transistors if the circuitry is properly designed. Since for analog circuits the leakage power consumption is usually much smaller than the power consumption in the active mode (which may not be true for digital circuits with deep sub-micron CMOS technology [13]), it is neglected in the total energy consumption. However, it is straightforward to extend our model to include the energy consumption in the sleep mode.

For uncoded MQAM, as discussed in [11], the energy consumption for link $i \rightarrow j$ to transfer W_{ij} packets with a target probability of bit error P_b can be bounded as

$$\epsilon_{ij} \leq x_{ij} \frac{2^{b_{ij}} - 1}{b_{ij}} \nu W_{ij} + y_{ij} \frac{\nu W_{ij}}{b_{ij}} + z_{ij}, \tag{1}$$

with the coefficients x_{ij}, y_{ij}, and z_{ij} defined as [11]

$$\begin{aligned} x_{ij} &= 2 N_f N_0 G_d \ln \frac{2}{P_b}, \\ y_{ij} &= \frac{P_{ct}^i + P_{cr}^j}{B}, \\ z_{ij} &= 2 P_{syn} T_{tr}, \end{aligned} \tag{2}$$

where N_f is the receiver noise figure, N_0 is the single-sided thermal noise spectral density, P_{ct}^i is the total transmitter circuit power consumption for node i in the active mode excluding the power consumed in the power amplifier, P_{cr}^j is the total receiver circuit power consumption for node j in the active mode, B is the modulation bandwidth, P_{syn} is the power consumption of the frequency synthesizer, and T_{tr} is the transient mode duration. We assume that P_{syn} and T_{tr} are the same across all the sensor nodes.

It is well known that QPSK requires the same transmission energy per bit as BPSK while satisfying the same bit error rate requirement. However, to transmit a certain number of bits, QPSK only requires half the transmission time as BPSK so its circuit energy consumption can be reduced by half [11]. Therefore, the minimum candidate constellation size can be predetermined as $b_{min} = 2$ in order to obtain an energy-efficient solution. The maximum allowable constellation size is constrained by the maximum available power P_{max} at the transmitter, specifically

$$b_{ij} \leq C_{ij} = \log_2 (1 + \frac{P_{max} - P_{ct}^i}{B x_{ij}}). \tag{3}$$

Our goal is to maximize network lifetime by minimizing the energy consumption. In our optimization we minimize the network energy consumption that is the overall energy consumption across all nodes. This optimization criterion maximizes average node lifetime on a long-term basis if we assume that in the network the data rate generated at each node is randomly changing according to the same distribution and the combination of source/destination pairs is also randomly changing in an uniform way.

III. Routing and MAC Optimization with Fixed Links

In a typical sensor network, if the hub node is far away, the information may first be transmitted to a relay node, then multihop routing will be used to forward the data to its final destination. This general case is shown in Fig. 1. In this section, we assume that all the nodes support a fixed transmission rate (without link adaptation). If we assume that QPSK with a 10 KHz symbol rate is used, the transmission rate (denoted as S_i, $i = 1, \cdots, N$) at each node is given by $S_i = 200$ pps, $i = 1, \cdots, N$. In the next section, we will discuss the case where the modulation constellation can also be optimally adapted for each link.

For node i, we use $\mathcal{N}_i$ to denote the set of nodes that send data to node i, and use $\mathcal{M}_i$ to denote the set of nodes that receive data from node i. We denote the normalized time slot length for link $i \to j$ as $\delta_{ij} = \frac{t_{ij}}{T}$, where $\sum_{i=1}^{N-1} \sum_{j \in \mathcal{M}_i} \delta_{ij} \leq 1$. To simplify the formulation we neglected the effect of the transient mode [11]. At each node, as mentioned before, we use P_{ct}^i and P_{cr}^i to denote the circuit power consumption values for the transmitting circuits and the receiving circuits, respectively. The transmit power needed for QPSK transmission satisfying a target probability of bit error P_b from node i to node j is denoted as $P_t^{ij} = P_0 d_{ij}^{\kappa}$, where P_0 is the required power when the transmission distance is equal to 1 m. Therefore, the average power spent by node i is given as

$$P_{avg}^i = P_{cr}^i \sum_{j \in \mathcal{N}_i} \delta_{ji} + \sum_{j \in \mathcal{M}_i} \delta_{ij} (P_{ct}^i + P_t^{ij}), \quad i = 1, \cdots, N, \tag{4}$$

where $\sum_{j \in \mathcal{N}_i} \delta_{ji}$ is the fraction of time that node i spends in the receiving mode and $\sum_{j \in \mathcal{M}_i} \delta_{ij}$ is the fraction of time that node i spends in the transmitting mode.

A. Minimizing the Network Energy Consumption

Given the average power consumed by each node, the network energy consumption during each period T is given by $\sum_{i=1}^{N} T P_{avg}^i$. As discussed before, to increase the network lifetime we can choose to minimize the network energy consumption as follows

$$\begin{array}{ll} \min & T \sum_{i=1}^{N} P_{avg}^i \\ \text{s. t.} & \sum_{i=1}^{N-1} \sum_{j \in \mathcal{M}_i} \delta_{ij} \leq 1 \\ & \sum_{j \in \mathcal{M}_i} S_i \delta_{ij} - \sum_{j \in \mathcal{N}_i} S_j \delta_{ji} = R_i, \quad i = 1, \cdots, N \end{array}, \tag{5}$$

where the first constraint is the TDMA constraint and the last constraint is the flow conservation constraint, which guarantees that at each node the difference between the total outgoing traffic and the total incoming traffic is equal to the traffic generated by the node itself. By default we have $\{\delta_{ij} \geq 0, \quad i, j = 1, \cdots, N\}$, $\{\delta_{ii} = 0, \quad i = 1, \cdots, N\}$, and $\{\delta_{Nj} = 0, \quad \forall j \in \mathcal{M}_N\}$. Unless otherwise redefined, these defaults hold throughout this paper. Since the objective function and the constraints are all linear, the resulting Linear Programming (LP) problem can thus be efficiently solved. There exist many efficient algorithms to solve the LP problem [14]. In this paper, we use an existing software package SeDuMi [18]. Note that the optimal δ_{ij} may not lead to an integer number of packets for link $i \to j$ that is given by $W_{ij} = S_i \delta_{ij}$. In this paper we round the resulting W_{ij} to obtain integer values with slight performance degradation. To minimize the degradation, relaxation methods proposed in [12] can be used to further refine the result.

TABLE I
System Parameters

$f_c = 2.5$ GHz	$B = 10$ KHz
$\kappa = 3.5$	$P_b = 10^{-3}$
$P_{ct}^i = 98.2$ mW	$P_{cr}^i = 112.5$ mW
$P_{max} = 500$ mW	$P_0 = -34$ dBm
$T = 1$ s	$T_{tr} = 5$ μs
$G_0 = 70$ dB	

In order to calculate the actual total energy consumption, the related system parameters need to be defined. We assume the same setup as in [11] and the main parameters are listed in Table I. We also assume that all the sensor nodes use the same hardware platform. Some numerical results are shown below.

String Topology:

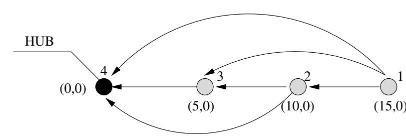
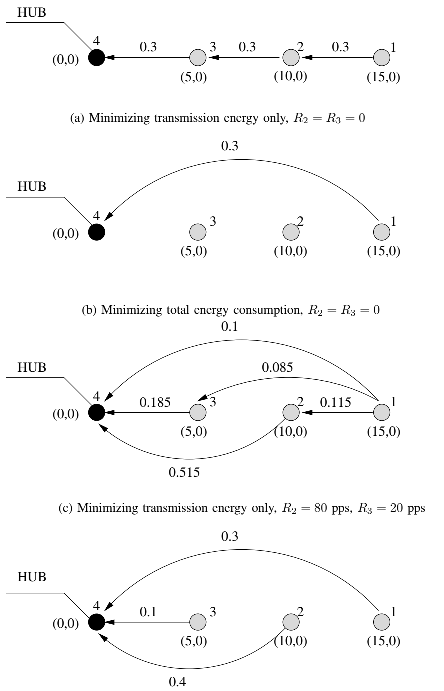


Fig. 3. String Topology

The network with string topology is shown in Fig. 3, where each node is labeled with its (x, y) location. We first assume that node 2 and node 3 have no data to transmit, and node 1 generates data at a rate of $R_1 = 60$ pps. If we only take the transmission energy into account, the optimal routing and scheduling result is shown in Fig. 4 (a), where the time slots assigned to each link are labeled above the link. When we consider the total energy consumption, which includes both the transmission energy and the circuit energy consumption, the optimal routing and scheduling result is shown in Fig. 4 (b). From the results we see that for this example when only the transmission energy is considered, multihop routing is more energy-efficient. However, when the circuit energy is included, hopping will cause more circuit energy consumption in the relay nodes, which may be higher than the energy saved in transmission, especially in short-range applications such as sensor networks. Therefore, when the total energy consumption is considered, single-hop transmission from the source node to the hub node may be more efficient.

We now consider the case where node 2 and node 3 both



(a) Minimizing transmission energy only, $R_2 = R_3 = 0$

(b) Minimizing total energy consumption, $R_2 = R_3 = 0$

(c) Minimizing transmission energy only, $R_2 = 80$ pps, $R_3 = 20$ pps

(d) Minimizing total energy consumption, $R_2 = 80$ pps, $R_3 = 20$ pps

Fig. 4. Optimal Routing and MAC

have their own data to transmit. In this case, these two nodes can no longer serve as full-time relays for node 1. As a result, node 1 has to use single-hop transmission to send some packets in order to satisfy the throughput requirement even when the circuit energy is not considered. Such an optimal routing and scheduling result is shown in Fig. 4 (c) where $R_2 = 80$ pps and $R_3 = 20$ pps. If we minimize the total energy consumption, the optimal result is illustrated in Fig. 4 (d), where we see that pure single-hop transmissions are more efficient in this case.

IV. Joint routing, scheduling and link adaptation

From the previous results we see that by jointly optimizing routing and MAC we are able to tell exactly when multihop routing is preferred over single-hop transmissions. We expect that by adding the link adaptation into the model, we can gain more insights into how to increase network energy efficiency. Therefore, in this section we extend the model to optimize W_{ij}, b_{ij}, and t_{ij} at the same time. Specifically, we can formulate the optimization problem as follows

$$\begin{array}{ll} \min & \sum_{i=1}^{N-1}\sum_{j\in\mathcal{M}_i}\epsilon_{ij} \\ \text{s. t.} & \sum_{i=1}^{N-1}\sum_{j\in\mathcal{M}_i}\frac{\nu W_{ij}}{Bb_{ij}} \le T-(N-1)T_{tr} \\ & \sum_{j\in\mathcal{M}_i}W_{ij}-\sum_{j\in\mathcal{N}_i}W_{ji}=R_iT, \quad i=1,\cdots,N \\ & 2\le b_{ij}\le C_{ij}, \quad i=1,\cdots,N-1, \quad j=1,\cdots,N \end{array}, \tag{6}$$

where ϵ_{ij} is given in Eq. (1) and by default we have $\{W_{ij} \ge 0, \quad i,j = 1,\cdots,N\}$, $\{W_{ii} = 0, \quad i = 1,\cdots,N\}$, and $\{W_{Nj} = 0, \quad \forall j \in \mathcal{M}_N\}$. From the above formulation we see that the optimization problem is convex over W_{ij} or b_{ij} individually (if we relax the original b_{ij} and W_{ij} to take real values), but not jointly convex over W_{ij} and b_{ij}. However, if we replace b_{ij} with $\frac{\nu W_{ij}}{Bt_{ij}}$, the problem becomes

$$\begin{array}{ll} \min & \sum_{i=1}^{N-1}\sum_{j\in\mathcal{M}_i}\epsilon_{ij} \\ \text{s. t.} & \sum_{i=1}^{N-1}\sum_{j\in\mathcal{M}_i}t_{ij} \le T-(N-1)T_{tr} \\ & \sum_{j\in\mathcal{M}_i}W_{ij}-\sum_{j\in\mathcal{N}_i}W_{ji}=R_iT, \quad i=1,\cdots,N \\ & \frac{\nu W_{ij}}{C_{ij}B}\le t_{ij}\le\frac{\nu W_{ij}}{2B}, \quad j\in\mathcal{M}_i, \quad i=1,\cdots,N-1 \end{array}, \tag{7}$$

where

$$\epsilon_{ij} = x_{ij}\left(2^{\frac{\nu W_{ij}}{Bt_{ij}}}-1\right)Bt_{ij}+y_{ij}Bt_{ij}+z_{ij}. \tag{8}$$

Proving the convexity of the function ϵ_{ij} over W_{ij} and t_{ij} is equivalent to proving the convexity of the function $f(W,t) = t2^{\frac{AW}{t}}$ over W and t where A is a constant, when we remove all the linear terms. For function $f(W,t)$, the Hessian matrix is given by

$$\mathbf{H} = \begin{bmatrix} (\ln 2)^2 2^{AW/t}A^2/t & -(\ln 2)^2 2^{AW/t}A^2W/t^2 \\ -(\ln 2)^2 2^{AW/t}A^2W/t^2 & (\ln 2)^2 2^{AW/t}A^2W^2/t^3 \end{bmatrix}.$$

For a matrix in the form of $\begin{bmatrix} a & b \\ b & c \end{bmatrix}$ with $a > 0$, it is positive semi-definite as long as we have $b^2a^{-1} - c = 0$ according to Schur's complement condition [14]. Since the Hessian matrix $\mathbf{H}$ has the above property, we can claim that $\mathbf{H}$ is positive semi-definite or equivalently, $f(W,t)$ is convex over W and t. Therefore, we proved that ϵ_{ij} is convex over W_{ij} and t_{ij} when both of the variables take real values. Since here b_{ij}'s and W_{ij}'s are again integer variables, relaxation methods similar to the ones discussed in [12] can be used to solve this problem efficiently.

We take the same string topology example as in Section III-A, where we have $R_1 = 60$ pps, $R_2 = 80$ pps, and $R_3 = 20$ pps. When the circuit energy consumption is included, the optimal routing, scheduling, and modulation constellation size b are listed in Fig. 5, where the number above each link is the time slot length assigned to that link and the number below each link is the optimal constellation size used for that link. The network energy consumed within each period T is 0.022 J, while the network energy consumed without link adaptation (as shown in Fig. 4 (d)) is 0.081 J. We see that about 73% energy savings is achieved when we include the link adaptation in the optimization model. Meanwhile, direct transmissions combined with multihop routing are shown to be optimal in this case compared with pure single-hop transmissions as shown in Fig. 4 (d). The reason why multihop routing becomes more efficient is that link adaptation reduces the transmission time for each hop by using higher constellation sizes such that the extra circuit power consumption in the relay nodes is reduced.

V. Delay performance and scalability issues

The energy-minimization models proposed in previous sections solve for the optimal time slot assignment for each active

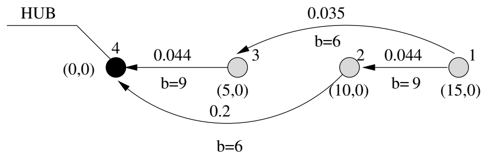


Fig. 5. Minimizing total energy consumption, $R_1 = 60$ pps, $R_2 = 80$ pps, $R_3 = 20$ pps

link. The scheduling order of the slots has no effect on the energy consumption. However, different scheduling orders can lead to different network delays. The details are omitted here due to the space limitations and are fully addressed in [19].

For large networks, we can reduce the computation complexity by dividing the whole network into clusters where each cluster has one master node that collects all the information within the cluster. Therefore, the optimal routing and scheduling problem can first be solved for the network of the master nodes according to the amount of traffic they collect individually. Then the optimal time slot assigned to each master node can be further allocated within the cluster by solving the optimization problem locally. Obviously this strategy can be applied to the case with more than two levels of node clustering.

VI. Conclusions

We show that joint optimization across routing, MAC, and link layers which also takes into account hardware constraints is feasible and beneficial. The problem can be efficiently solved using convex optimization methods. The results show that significant energy savings is possible compared with traditional MAC and routing schemes that are based on layered approaches. We also show that when only the transmission energy is considered, multihop routing saves energy. However, when the circuit processing energy is included, single-hop transmissions may be more efficient than multihop routing schemes. Link adaptation is shown to be able to further improve the energy efficiency when jointly designed with MAC and routing. Numerical examples show that significant energy savings is possible when link adaptation is included in the design model. In addition, link adaptation may reduce the transmission time in relay nodes by using higher constellation sizes such that the extra circuit energy consumption is reduced. As a result, multihop routing may become more energy-efficient than single-hop transmissions when link adaptation is used.

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