# Lifetime Maximization by Cross-Layer Design considering Power Control, MAC, Routing in Sensor Networks

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**Summary**
We consider the cross-layer design considering physical layer, MAC layer, and network layer to maximize the lifetime of energy-constrained wireless sensor network. Our solution is based on system model that considers reliability as well as physical layer (i.e., power control), data link layer (i.e., link scheduling) and network layer (i.e., routing protocol) jointly. To obtain more energy-efficient solution for lifetime maximization of wireless sensor networks, we enhance existing cross-layer model using energy-efficient MAC protocol and its energy-consumption model.

***Key words:***
*Cross-layer, Lifetime maximization, Multi-hop communication, Energy-efficiency, Sensor networks.*

## 1. Introduction

The design challenges and the importance of cross-layer design in energy-constrained networks were describes in [1]. In an adaptive cross-layer protocol stack, the link layer can adapt rate, power, and coding to meet the requirements of the application given current channel and network conditions. The MAC layer can adapt based on underlying link and interference conditions as well as delay constraints and bit priorities. Adaptive routing protocols can be developed based on current link, network, and traffic conditions [1].

Cross-layer design jointing physical layer (i.e., power control), MAC layer (i.e., link schedule) and network layer (i.e., routing protocol) is necessary for lifetime maximization in wireless sensor network. However, the survey from the previous works in section 2, we can know that the cross-layer design considering energy-efficient MAC protocol, which includes routing, link schedule with reliability constraint, as well as transmission power control, does not exist. Therefore, we focus on cross-layer design including those features for lifetime maximization.

The rest of the paper is organized as follows. Some related work is discussed in section 2, and in section 3, we introduce system model, and problem definition of lifetime maximization briefly. In section 4, we show the energy-efficient MAC protocol and its energy consumption model. Then in section 5, we look at the routing and power control algorithm that we use. Then conclusions are drawn in Section 6.

## 2. Related Works

Related works on optimization of different layers of a wireless network for minimizing the total energy consumption and maximizing the network lifetime is as follows. In physical layer, for a given rate vector, power control can be used to conserve energy. And energy-optimal modulation schemes for coded and uncoded systems were studied. In MAC layer, the physical layer results were extended in [2].

In the view of cross-layer, joint scheduling and power control to reduce energy consumption and increase single hop throughput was considered in [3]. Cross-layer design based on computation of optimal transmission power, link schedule and routing flow was described in [4]. The aim of that paper was to minimize the average transmission power over an infinite horizon. Also, the routing flow was computed in an incremental manner: it used the Lagrange multipliers obtained at each step by solving an optimization problem of possibly exponentially complexity in the number of links. Energy-efficient power control and scheduling for QoS provisioning without rate adaptation on links were considered in [5]. Cross-layer design with emphasis on detailed modeling of circuit and transmission energy, and restriction of MAC to variable length TDMA was described in [6]. Joint routing, power control, and scheduling for a TDMA-CDMA network were considered in [7].

The most recent works on lifetime maximization in wireless sensor network are [2] and [8]. Both of [2] and [8]

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are TDMA-based. [8] Investigates the problem of the lifetime maximization in a wireless sensor network under constraint of the target end-to-end transmission success probability, by adopting a cross-layer strategy that considers physical layer (i.e., power control), MAC layer (i.e., ARQ control) and network layer (i.e., routing protocol) jointly. And it develops an optimal routing and power control algorithm that maximizes the network lifetime while keeping the network stable and an alternative heuristic algorithm that has lower and tractable complexity. However, it does not consider adaptive transmission rates or link schedule.

In [2], the problem of computing a lifetime-optimal routing flow, link schedule, and link transmission powers is formulated as a non-linear optimization problem. And it proposes an iterative algorithm that alternates between adaptive link scheduling and computation of optimal link rates and transmission powers for a fixed link schedule. However, it does not consider reliability problem.

## 3. Problem Definition

In this section, we define our system model and the lifetime maximization problem.

### 3.1 System Model

We consider a static network composed of multiple sensor nodes and one sink node for simplicity like [9]. Each sensor node sends its acquired data to the sink node located at the center of the sensor field.

In this work, we take into account the MAC protocol contention of not only the linear network but the whole network surrounding the path of the linear network. Fig.1 illustrates this and the redundant paths can be modeled as an external traffic load affecting the contention process and consuming energy.

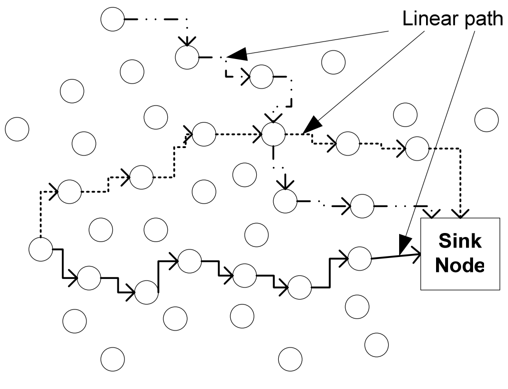

Fig. 1 Multi-paths in sensor networks

Each path of Fig.1 can be approximately by a linear chain in Fig.2

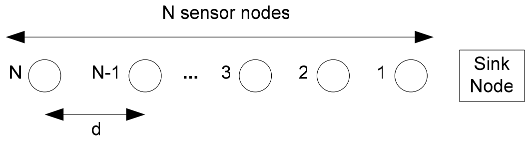

Fig. 2 Linear Topology.

Based on Fig. 2, if medium access control is not assumed, total energy consumption is as follows:

$$E_{MH} = n(k(e_{te} + e_{ta}(d)^{\alpha}) + E_{st}) + (n-1)(ke_{er} + E_{sr} + E_{dec})$$

where $n$ is the number of hops, $k$ is the number of bits transmitted. $e_{te}$ is the energy per bit needed by the transmitter electronics, $e_{re}$ for the receiver electronics, $e_{st}$ and $e_{sr}$ are startup energies, $e_t$, is the power needed to successfully transmit one bit over one meter, $\alpha$ is the path loss exponent. And $E_{st}$ is the energy required for transmitting in single hop, $E_{sr}$ is the energy required for receiving in single hop, and $E_{dec}$ is the energy required for decoding a packet. The encoding of data is assumed to be negligible.

To formulate this linear topology, we think the directed graph representing the sensor network and use the following notation from [2] as follows.

- $\breve{g} = (V, L)$ denote the directed graph representing the network. V is the set of wireless nodes and L is the set of directed links.
- $A \in \mathbf{R}^{|v| X |L|}$ denote the incidence matrix of the graph ğ. We have

  $$A(v, l) = \begin{cases} 1 & \text{if } v \text{ is the transmitter of link } l \\ -1 & \text{if } v \text{ is the receiver of link } l \\ 0 & \text{otherwise} \end{cases}$$

  Let us write

  $$A = A^{+} - A^{-}$$

  such that $A^{+}(v, l), A^{-}(v, l) = 0$ if $A(v, l) = 0$, and $A^{+}$, $A^{-}$ have only 0 and 1 entries.

- The vector $1_t(P^n), 1_r(P^n) \in \mathbf{R}^{|v|}$ as follows:

  $$1_t(P^n) = \begin{cases} 1 & \text{if } (a^{+}_{v})^{T} P_n > 0 \\ 0 & \text{otherwise} \end{cases}$$

  $$1_r(P^n) = \begin{cases} 1 & \text{if } (a^{-}_{v})^{T} P_n > 0 \\ 0 & \text{otherwise} \end{cases}$$

  where and denote he $v$th row of the matrices and, respectively. Thus the vectors give the sets of nods that tranmit and receive data respectively.
- $P^n_l$ and $r^n_l$ denote the transmission power and rate per unit bandwidth, respectively, over link $l$. $P^n$ , $r^n$ $\in \mathbf{R}^{|L|}$ will be used to denote the corresponding vectors for transmission or reception time.
- $P^{max}_l$ be the maximum transmission power of the transmitting node of link $l$. The corresponding vector is $P^{max} \in \mathbf{R}^{|L|}$ .

- $E \in \mathbf{R}^{|L|}$ be such that $E_i$ denotes the initial amount of energy at node *i*.
- $P_{ct}$ and $P_{cr}$ be the power consumption of the transmitter and the receiver circuits at a node, respectively. These values are assumed to be the same across all nodes.
- $G \in \mathbf{R}^{|v| \times |L|}$ denote the link gain matrix of the network. $G_{lk}$ denotes the power gain from the transmitter of link *k* to the receiver of link *l*.
- $s_i$ denotes the rate at which information is generated at node *i*. This information needs to be communicated to the sink. Let $s \in \mathbf{R}^{|v|}$ be the vector whose entries are $s_i$.
- $N_0$ denote the noise power; this is the total noise power over the bandwidth of operation.
- If a node transmit at power *P*, the power consumption in the power amplifier circuit is given by $(1+\alpha)P$. The constant $\alpha>0$ represents the inefficiency of the power amplifier. The power consumption values of the transmitter circuit (other than the power amplifier) and the receiver circuit are modeled as constants $P_{ct}$ and $P_{cr}$, respectively [10].

Using these notations, we can define the network lifetime showed in subsection 3.2.

### 3.2 Network Lifetime

Let $T_v$ denote the lifetime of node *v*, that is the time at which it runs out of energy. Then the network lifetime in Eq. (is the same as the one considered in [2].

$$T_{net} = \min_{v \in V,\ v \neq sink} T_v$$

Then, the problem of maximizing the network lifetime can be written as the following optimization problem [2].

$$\begin{aligned}
&Max. && T_{net}\\
&subject\ to && (1/N)A(r^1 + \dots + r^N) = s\\
& && r^n \succeq 0\\
&\log\left(1+K \frac{G_{lk} P^n{}_l}{\Sigma_{k \neq l} G_{lk} P^n{}_{l} + N_0}\right) && \geq r^n{}_l\\
& && 0 \preceq P^n \preceq P^{max}\\
&(T_{net}/N) \sum_{N=1}^{N}((1+\alpha)A^+ P^n && + P_{ct} 1_t(P^n) + P_{cr} 1_r(P^n)) \quad E
\end{aligned}$$

for all n = 1,…, *N* and $l \in L$.

The constraints are explained below. The first constraint is a set of flow conservation equation. The flow conservation equations are satisfied over each frame. The second constraint ensures the direction of flows – the flow over a directed link can only be from the transmitter to the receiver. The third constraint is a rate constraint over each link. The fourth constraint forces the transmission power to be less than the maximum transmission power at each node. The fifth constrain is an energy conservation inequality. The energy consumed by each node over time $T_{net}$ should be less than or equal to the initial energy at the node.

## 4. MAC Protocol and its Energy Model

In this section, we consider physical layer (i.e. energy consumption minimization) and data link layer (i.e. medium access control) jointly.

### 4.1 MAC Protocol

From [9], among CSMA, S-MAC and nanoMAC, nanoMAC is the best. Therefore, we consider nanoMAC as MAC protocol of our work.

Overview of nanoMAC is as follows. CSMA/CA is a powerful tool for medium access control, so the nanoMAC protocol also implements this feature. Briefly described, nanoMAC is a p-nonpersistent, i.e., with probability *p,* the protocol will act as nonpersistent and with probability 1 -*p* the protocol will refrain from sending even before *CS* and schedule a new time for *CS.* Nodes contending for the channel do not constantly listen for the channel, but sleep until the contention window value is low. Then the node wakes up to sense if the channel is busy for a short but high confidence period before transmitting if the channel is detected vacant. This feature makes the carrier sensing time short, even though the backoff mechanism is binary exponential and saves energy. In the request-to-send (RTS) /Clear-to-send (CTS) frames, nanoMAC does virtual carrier sensing in addition to informing overhearing nodes of the time they are required to refrain from transmission. Virtual carrier sensing enables overhearing nodes to sleep during that period. Unlike S-MAC, IEEE MAC addresses are supported as well as sleep information for virtual clustering and the number of data frames to be transmitted is also included in the RTS and CTS frames.

The data frames carry only temporary, short, random addresses to minimize the data frame overhead. With one RTS/CTS reservation a maximum of 10 data frames can be transmitted using a frame train ideology The idea is similar to message passing in S-MAC, but it is a default characteristic in nanoMAC and the data frames are acknowledged by a single, common ACK frame that has a separate acknowledgement bit reserved for each data frame. The ACK frame is therefore an acknowledgement (ACK) /negative acknowledgement (NACK) combination. In this way only the corrupted frames need to be retransmitted and not the whole packet. When forward error correction (FEC) methods are not used, the frame train method promises to be efficient. If FEC should be used, frames can be made longer. When best utilized, nanoMAC has low overhead even with low data-rate, small frame size applications.

## 4.2 RX/TX Energy Model

In this subsection we briefly describe the theoretical energy consumption of the nanoMAC protocol and the underlying physical layer. First, let's think the case of transmission.

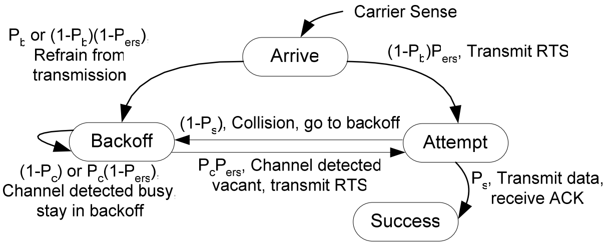

Fig. 3 TX energy model.

The energy consumption model for transmission can be found from Fig. 3. There are four different states: *Arrive, Backoff, Attempt* and *Success.* The *Arrive* state is the entry point to the system for a node getting new data to transmit. To calculate the average energy consumption, we solve a system of equations implied by Fig. 3. Let $E_{tx}$ equal the expected energy consumption by a node with new data at the *Arrive* state until the node reaches the *Success* state. Let *E(A)* equal the average energy consumption on each visit by the node to the *Attempt* state, and let *E(B)* equal the energy consumption on each visit to the *Backoff* state. The average energy consumption upon transmission from the point of packet arrival from the upper layer to the point of receiving an ACK frame is

$$\begin{aligned} E_{TX} = {} & T_{CS} M_{RX} + P_b(T_{bb} + T_r/2)\, M_{Slp} + P_b\, E(B) \qquad (1)\\ & + (1 - P_b)(1 - P_{ers})(T_{bp} + T_r/2)\, M_{Slp} \\ & + (1 - P_b)\, P_{ers}\, E(A) \\ & + (1 - P_b)\, P_{ers}\, (T_{pr} + RTS)\, M_{TX} \\ & + (1 - P_b)(1 - P_{ers})\, E(B). \end{aligned}$$

- $M_{TX}$, $M_{RX}$, and $M_{Slp}$, are transceiver modes TX, RX, and sleep, respectively,
- $T_{CS}$ is the time required for carrier sensing,
- $T_{bb}$ and $T_{bp}$ are incremented and un-incremented backoff times, respectively
- $P_b$ is the probability of finding channel busy during CS,
- $T_r/2$ is the average random delay,
- $P_{ers}$ is the non-persistence value of nanoMAC, and
- $T_{pr}$ and *RTS* are times to transmit a preamble and RTS frame, respectively.

From *E(B)* and *E(A)* we make the same analysis as from the *Arrive* state and solve a system of equations. The term *E(A)* gives a constraint: the probability of no collision with retransmit RTS $P_c \neq 0$ and probability of successful data transmission $P_s \neq 0 \rightarrow G \in\, ]0, \infty[$.

The reception energy consumption model of a packet can be found from Fig.3.

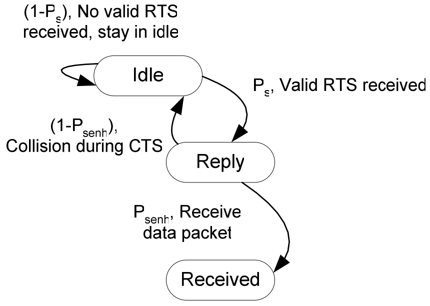

Fig. 4 RX energy model

In Fig. 4, the average receive energy consumption $E_{RX}$ from listening for a transmission to detecting and receiving for a transmission to detecting and receiving a valid packet and being the proper destination can be found to be

$$E_{RX} = E(I) = (\mu + P_s\, \theta)(P_s\, P_{senh})^{-1}. \qquad (2)$$

- *E(I)* is the time incurred in each visit to state *Idle*,
- $\mu$ and $\theta$ are functions of difference probabilities multiplied by times spent in different transceiver modes,
- $P_s$ and $P_{senh}$ are the probabilities of no collision during RTS or CTS, respectively.

For reception, the constraint $P_s\, P_{senh} > 0 \rightarrow G < \infty$ is introduced. From the evaluation results in [9], the average energy per useful bit on transmission and reception of the 3 MAC protocols, we can know that nonpersistent CSMA transmission energy consumption is the highest and about 40% higher than with nanoMAC, but only 7% higher than with S-MAC. On the other hand, S-MAC receive energy consumption is the highest of the 3 protocols. NanoMAC reception consumes less than 2/5 of the energy in reception per useful bit compared to S-MAC. Therefore, we select nanoMAC as MAC protocol for energy-efficiency.

## 4.3 Minimization of the Energy Consumption

We follow optimal and suboptimal retry limit algorithm for reliability using retransmission in [8]. Those algorithms are as follows.

They first assume that a routing path and a transmission power level are given, and develop the optimal retry limit control scheme that allocates the retry limit to each link over the path such that the total energy consumption can be minimized while the reliability constraint is met.

Since there is no interference from other node's transmission, the transmission failure can occur only due to channel errors, which depends on the transmission power, channel gain, and receiver noise condition. The channel gain, normalized by the noise power, between two nodes is given by

$$g = c \cdot \quad d^{-k}, \qquad (3)$$

where $d$ is the distance between two nodes, $k$ is the path loss exponent, and $c$ is a constant. Then, the probability of successful packet delivery (i.e. per-hop success probability) as a function of transmission power $P^{\mathrm{tx}}$, which is given by $f(gP^{\mathrm{tx}})$.

Let $M_i$ denote the retry limit (including the first transmission and $M_i - 1$ retransmissions) at the $i$-th link. Then, the average probability of delivering a packet successfully is given by

$$P_s(g_i,M_i) = 1 - (1 - f(g_iP^{\mathrm{tx}}))M_i \qquad , (4)$$

and the average number of the total transmissions at the $i$-th link is given by

$$N_i\,(g_i,M_i) = \{1 - (1 - f(g_iP^{tx}))M_i\} \,/\, f(g_iP^{tx}) \qquad . (5)$$

The problem of the total energy consumption minimization under the reliability constraint can be formulated as follows:

$$\min \ \sum_{i=1}^{H}(E^{\mathrm{tx}} + E^{\mathrm{rx}} \cdot 1(i < H))N_i\,(g_i,M_i) \qquad (6)$$

$$\text{subject to} \ \prod_{i=1}^{H}P_s(g_i,M_i) \geq Q_s\,,\ M_i \in \{1,\,2,\,\cdots\},$$

where $H$ denotes the number of links over the path, $1(A)$ an indicating function that becomes 1 if condition $A$ is met, and $Q_s$ the target end-to-end success probability. Note that the energy consumed by the sink node for reception is excluded in (6), as the sink node is usually mains-powered, and hence its energy consumption is not of our concern.

In [8], the energy consumption for the transmission is assumed to be given by

$$E^{tx} = E^{elec} + P^{tx} / R\,, \qquad (7)$$

where $E^{elec}$ denotes the energy consumption of the electronic circuitry, $P^{tx}$ denotes the transmission power, and $R$ is the transmission rate in packets per second. And they assume that the energy consumption for packet reception is fixed at $E^{rx}$. Moreover, they ignore the energy consumption in the sleeping state and ACK packet. However, for more detailed modeling, we use the energy consumption model in subsection 4.2 instead of their energy model. Then the problem of the total energy consumption minimization under the reliability constraint can be formulated as follows:

$$\min \ \sum_{i=1}^{H}(E^{\mathrm{tx}} + E^{\mathrm{rx}} \cdot 1(i < H))N_i\,(g_i,M_i) \qquad (8)$$

$$\text{subject to} \ \prod_{i=1}^{H}P_s(g_i,M_i) \geq Q_s\,,\ M_i \in \{1,\,2,\,\cdots\},$$

$$\begin{aligned}
\text{where } E_{TX} = {} & T_{CS}\,M_{RX} + P_b(T_{bb} + T_r/2)\ M_{Slp} \\
& + P_b\ E(B) \\
& + (1 - P_b)(1 - P_{ers})(T_{bp} + T_r/2)\ M_{Slp} \\
& + (1 - P_b)\ P_{ers}\,E(A) \\
& + (1 - P_b)\ P_{ers}\ (T_{pr} + RTS)\ M_{TX} \\
& + (1 - P_b)(1 - P_{ers})\ E(B)
\end{aligned}$$

$$\text{and } E_{RX} = E(I) = (\mu + P_s\,\theta)(P_s\,P_{senh})^{-1}.$$

If $M_i$ can have continuous values, the problem in (5) can be transformed into the standard convex optimization problem. Then, it is not difficult to solve the problem because there are many efficient algorithms available for solving convex optimization problems. However, as $M_i$ should be an integer, the problem in (8) is a non-linear integer programming problem. Unfortunately, the integer programming problem is NP-complete [11]. So they develop a suboptimal algorithm that can possibly perform close to the optimal solution but has a lower complexity in computation.

They first define an incremental gain that can be obtained by increasing power level, and devise a new algorithm based on it. Specifically, we introduce the incremental ratio $\varphi_i$ of the per-hop success probability contributed by the retry limit increment at the $i$-th hop, i.e.,

$$\varphi_i = P_s(g_i,\,M_i + 1) \,/\, P_s(g_i,M_i). \qquad (9)$$

Then we consider a *greedy retry limit allocation* (GRLA) algorithm that increases the retry limit with the highest increment, as outlined below:

1) Allocate the lowest retry limit to all links, i.e., $M_i \leftarrow 1$ for $i = 1,\,2,\,\cdots,H$.
2) Increase by one the retry limit of the link that has the highest value of $\varphi_i$, $i = 1,\,2,\,\cdots,H$, i.e., $M_i{*} \leftarrow M_i{*} + 1$ for $i{*} = \arg\max_i \varphi_i$.
3) Repeat the above process until the end-to-end success probability becomes equal to or larger than the target value.

## 5. Routing and Power-Control Algorithm

In this section, we consider physical layer (i.e. power control) and network layer (i.e. routing) jointly.

In routing algorithm, if all the packets were routed through the path with the minimum energy consumption, the batteries of the sensor nodes along that path would be drained out quickly. In order to maximize the network lifetime, the routing algorithm needs to route the packets such that the energy consumption is balanced among the multiple paths. To realize this, we use the cost-based routing and power control algorithm, called *cost-based routing and power-control* (CRPC) algorithm, with lower and more traceable complexity than optimal algorithm in [8]. The CRPC algorithm first determines the transmission power as follows: For each transmission power level, we perform the retry limit allocation algorithm and calculate the energy consumptions of sensor nodes. The transmission power is set to the level that minimizes the average energy consumptions. Then, the CRPC algorithm performs the cost-based routing algorithm as follows.

They define the link cost function as the ratio of the required transmission energy for a packet transmission to the remaining energy, similar to the case in [4]. Specifically, they define the link cost of the link originated from node $i$ on the $p$-th path of node $s$ as follows:

$$LC_{spi} = (E^{\mathrm{tx}}_{spi} + E^{\mathrm{rx}}_{spi}) / (\check{E}_i / E_i)^{w}, \tag{10}$$

where $\check{E}_i$ denotes residual energy, and $w$ is a weighting exponent on the remaining energy. Note that the residual energy is normalized by the initial energy because sensor nodes can have different initial energy levels. The path cost is calculated as the sum of all the link costs along the path. The sink node determines the cost for all the paths and then selects the path with the least cost for each sensor node.

The path selection requires an additional knowledge on the residual energy of each sensor node. In order to support this, we arrange the sink node to estimate the residual energy of all the sensor nodes based on the energy consumption determined by the retry limit allocation algorithm. As mentioned earlier, the sink node periodically broadcasts the routing information via the control packet.

## 6. Conclusion

To maximize the lifetime of energy-constrained wireless sensor network, we propose cross-layer system model for wireless sensor network considering reliability constraint as well as physical layer (i.e., power control), MAC layer (i.e., energy-efficient MAC) and network layer (i.e., routing protocol) jointly. Our approach is to improve existing system model considering reliability constraint, using power-efficient MAC and TX/RX energy model considering sleep state. It can help to maximize the lifetime of wireless sensor networks.

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