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## Serialized optimal relay schedules in two-tiered wireless sensor networks<sup>☆</sup>

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### Abstract

In two-tiered wireless sensor networks (WSNs), sensor nodes (SNs) are scattered in clusters, and are responsible for collecting relevant information from designated areas and transmitting to an application node (AN) in the cluster. The AN then constructs a local-view for the cluster by exploring correlations among information received from nearby SNs, and sends the local-view toward a base-station that creates a global-view for the entire WSN. ANs can also relay local-views for other ANs, if the resultant network lifetime is longer. In this paper, we want to arrange inter-AN relaying optimally, which is an important process in topology control for maximizing the topological lifetime of a WSN with regard to a certain amount of initial energy provisioning. We first propose some criteria on relay candidates preselection, which can considerably reduce the overhead of obtaining an optimal relaying. We then design an algorithm to serialize the parallel relay allocation, so that each AN only needs to have one relaying AN at any time. Finally, we demonstrate the equivalency in network lifetime of the serialized inter-AN relay schedules.

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**Keywords:** Wireless sensor networks; Topology control; Network lifetime; Inter-node relaying; Relay schedule

### 1. Introduction

Wireless sensor networks (WSNs), driven by recent advances in micro-electromechanical system (MEMS) and short-to-medium-range radio technologies, may have a broad and in-depth impact on many aspects of our digitalized and connected society [1,2]. In a two-tiered WSN, small and even tiny sensor nodes (SNs) are scattered in clusters in the lower tier, and are responsible for capturing, encoding, and transmitting relevant information from designated areas. Application nodes (ANs), on the other hand, are responsible for constructing a local-view for the cluster by exploring correlations among information received from nearby SNs. Then, the composite local-view streams are sent from different ANs toward a common

base-station (BS) in the upper tier, where a global-view is created for the entire WSN.

Normally, both SNs and ANs are battery-powered and energy-constrained. Once they are deployed in field, it is unlikely, if not impossible, to recharge them economically. It is also very expensive for them to acquire energy from the environment themselves. A fundamental challenge thereby in WSNs is how to maximize network lifetime with regard to a given sensing mission and a certain amount of initial energy provisioning. When an SN runs out of energy, its AN may still have the capability to construct a comprehensive local-view with the assistance of other related SNs. If the AN is out of energy, from the viewpoint of the BS, the coverage for that cluster is completely lost even when some SNs are still alive, which can jeopardize the entire mission in many cases. Although ANs can have better energy provisioning than SNs, they also consume energy at a much higher rate due to the transmission of streams over greater distances. Here, the energy constraints of ANs are our main concern.

There are many research efforts focusing on media access control (MAC) [3–6], multi-hop routing [7–9], and higher layer issues for WSN and mobile ad hoc networks

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(MANET) [10,11]. For example, an energy-saving MAC scheme can conserve energy by avoiding consistent media sensing and frequent transmission collisions; an energy-aware routing scheme can route packets around dead nodes or nodes that are about to run out of energy, and balance the remaining energy of neighboring nodes. Localized flow, error, and congestion control schemes [12,13] and domain-specific designs [14] are also proposed for WSNs. Nevertheless, most schemes are still within the traditional seven-layer open systems interconnection protocol reference model.

In this paper, we follow another approach and investigate the inter-AN relaying process in topology control, which is designed for maximizing the topological lifetime of a WSN by placing SNs, ANs, and BSs intelligently and by arranging inter-AN relaying optimally. Conceptually, topology control is below the conventional seven-layer protocol stack, and is complementary to other efforts in higher layers when maximizing the overall network lifetime. Energy-constrained topology control is unique for WSNs, where the distances between ANs and the BS, as well as those among ANs, have a dominant impact on the power consumption of each AN and thereby the achievable network lifetime. These distances are considered to be optimal for a WSN when its lifetime is maximized under the process of topology control.

Our contributions in this paper are twofold. First, we propose some criteria for preselecting inter-AN relay candidates. With the proposed preselection process, we show that the overhead of obtaining an optimal relaying can be reduced considerably. Second, we develop an algorithm to serialize the obtained relay allocation due to its parallel nature. The parallel inter-AN relaying implies that an AN potentially has to send its streams to all other ANs simultaneously, which can cause a major technical challenge to the AN transceiver design. With the proposed serialization algorithm, we transform any parallel relaying allocations to serialized relay schedules, so that each AN only needs to have one relaying AN at any time. We also show that the transform can be executed in a distributed manner and is equivalent in terms of network lifetime;

therefore, the parallel optimal inter-AN relaying still preserves its optimality after the serialization process.

The remainder of this paper is organized as follows. In Section 2, we present the system architecture of two-tiered WSNs, their AN power consumption and energy dissipation models, and the definition of topological network lifetime. We also outline a sample WSN without inter-AN relaying as a baseline for numerical illustrations in the following section. In Section 3, we first propose criteria to preselect relay candidates, and then obtain the parallel optimal relay allocation by formulating and solving a constrained optimization problem. We also show the benefit of having a preselection process. Finally, we develop a serialization algorithm to transform the obtained parallel optimal relaying. Section 4 offers some further discussions and Section 5 reviews related work. Section 6 concludes this paper with issues for future work.

## 2. System model

### 2.1. Two-tiered wireless sensor networks

A two-tiered WSN, as shown in Fig. 1(a), consists of a number of SN/AN clusters and at least one BS. In each cluster, there are many SNs and at least one AN. SNs are responsible for all sensing-related activities: once triggered by an internal timer or an external event, an SN starts to capture live information encoded by the SN and directly transmitted to an AN in the same cluster. SNs are small, low cost, and disposable; they can be densely deployed in a cluster. SNs do not communicate with other SNs in the same or other clusters, and usually are independently operated. ANs, on the other hand, have much more responsibilities than SNs. First, an AN receives raw data from all active SNs in the cluster. It may also instruct SNs to be in sleep, idle, or active state if some SNs are found to always generate uninterested or duplicated data, thereby allowing these SNs to be reactivated later when some existing active SNs run out of energy. Second, the AN constructs an

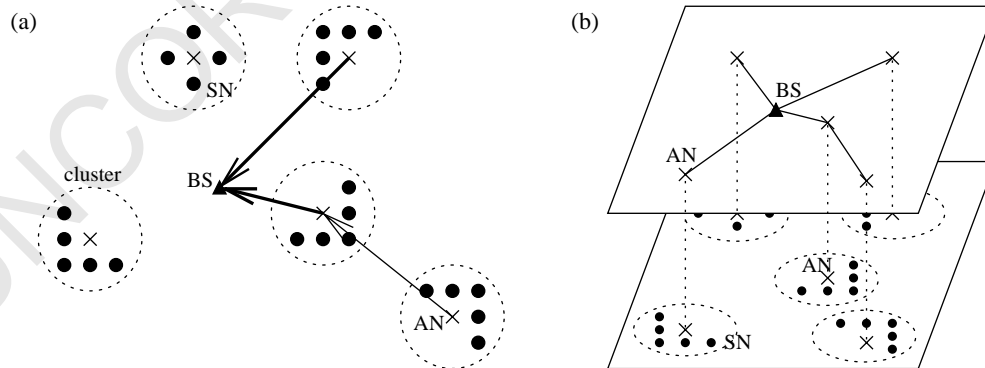


Fig. 1. A two-tiered architecture of wireless sensor networks; (a) physical view, and (b) logical view.

application-specific local-view for the cluster by exploring correlations among data generated by SNs. Excessive redundancy in raw data can be alleviated; the fidelity of captured information will be enhanced. Third, the AN sends the composite stream toward a BS that creates a comprehensive global-view for the entire WSN. ANs can be also involved in inter-AN relaying if such activity is system-feasible, application-acceptable, and energy-favorable.

The two-tiered architecture of WSNs is motivated by the latest advances in distributed signal processing and source coding [15]. Under this architecture, the goal of lower-tier SNs and their ANs is to *gather data* as effectively as possible; upper-tier ANs and BSs are designed to *move information* as efficiently as possible. As shown in Fig. 1(b), ANs, which extract useful information and construct local-views, are the logical bridge for these two tiers. With this function partition, we can optimize the performance of each tier separately, since they are designed for different purposes and have different concerns. Practically, both SNs and ANs are battery-powered. Although ANs can have more initial energy, they also consume energy at a much higher rate due to the transmission of streams to BSs that are comparatively far away. When an SN runs out of energy, its AN may still have the capability to construct a comprehensive local-view with other correlated SNs; but if the AN runs out of energy, the whole coverage of the cluster will be completely lost from the viewpoint of BSs, even when some SNs in the cluster are still alive. Therefore, we focus on energy constraints of ANs.

Once being deployed, an AN can obtain and report its own location by using an on-board GPS receiver, through triangulation with a few reference points [16], or as instructed by network operators during manual deployment. ANs are in sleep state initially, until they are activated by the on-board wake-up circuit. Then, ANs are instructed with mission schedules, aggregation schemes, and relay routes to accomplish the mission cooperatively with other SN/AN clusters. An SN/AN cluster may undergo the sleep-idle-active cycle repeatedly during its lifetime until the AN exhausts its on-board energy. Once being activated, the AN should feed live local-views or view-changes to other ANs and, eventually, to BSs. According to a specific mission, all ANs can be activated at the same time, or they can be activated independently. The first style is referred to as *synchronized* activation; the second one is *unsynchronized*. An AN can be left in active state once it is activated, or it can be in active and inactive (including sleep and idle) states alternatively. The first mode is referred to as *continuous* activation; the second one is *discrete*. Although different missions can choose different activation styles and modes, from the viewpoint of topological lifetime, an unsynchronized discrete mission can always be converted to an *equivalent* synchronized continuous mission, as soon being discussed in Section 2.2.

Once ANs have been placed, an immediate challenge is to locate BSs so that network lifetime can be maximized

Symbol	Description	
$V_N$	A set of $N$ ANs of a WSN	284
$v_i$	An AN at $(x_i, y_i)$ on a plane	285
$b$	Base station (for notation convenience, $v_0 = b$ )	286
$d_i$	Euclid distance from $v_i$ to $b$	287
$d_{i,j}$	Euclid distance from $v_i$ to $v_j$	288
$r_i(t)$	Data rate generated locally by $v_i$ at time $t$	289
$r_i$	If $r_i(t)$ is time-invariant	290
$r_{i,j}(t)$	Data rate relayed from $v_i$ to $v_j$ at time $t$	291
$p_i(t)$	Power consumption of $v_i$ at time $t$	292
$p_i$	If $p_i(t)$ is time-invariant	293
$e_i(t)$	Remaining energy of $v_i$ at time $t$	294
$e_i(0)$	Initial energy allocation of $v_i$	295
$l_i$	Node lifetime of $v_i$	296
$L$	Network lifetime without relaying	297
$R$	Network lifetime with relaying	298
$RC_i$	Relay candidates set for $v_i$	299
$RR_i$	Parallel relay allocation for $v_i$	300
$\varepsilon$	$e(t=L)$ or $e(t=R)$	301
$\phi_{i,j}$	Energy quota to relay data from $v_i$ to $v_j$ for $R$	302
$RS_i$	Serialized relay schedule for $v_i$	303

even without inter-AN relaying. We assume that ANs can communicate with BSs independently, and that BSs are always reachable for ANs as long as ANs can draw enough transmission power from their remaining energy supply. This property and the characteristics of steady live local-views constructed by ANs, suggest a deterministic MAC scheme such as TDMA employed by ANs. Although an SN, depending on the amount of sensible information available at a certain time, can send raw data in burst to its AN, the aggregated live local-views should be relatively smooth and in low volume, whereas the TDMA scheme can save the extra control overhead and power consumption encountered by contention-based MAC schemes. Our study does not rely on any specific MAC schemes, since topology control is even under the regular MAC layer. After BSs are located, and if inter-AN relaying is desirable, BSs can derive relay schedules, and instruct ANs to communicate cooperatively to achieve a longer network lifetime. Table 1 lists some frequently-used symbols.

## 2.2. Power and energy models

Communication is a dominant source in power consumption for WSNs, where live local-views are transmitted over the air. Thus, we focus on the communication-related activities for battery-powered ANs, since BSs are not energy-constrained. For an AN to transmit a stream at rate  $r$  over Euclid distance  $d$ , its minimal transmitter power consumption is

$$p_t(r, d) = r(\alpha_1 + \alpha_2 d^n), \quad (1)$$

where  $\alpha_1$  is a distance-independent term (e.g. the power consumed in transmitter circuit), and  $\alpha_2$  reflects the distance-dependent one. Eq. (1) mainly considers the path

loss of exponent  $n$ , and usually  $2 \leq n \leq 4$  for free-space and short-to-medium-range radio communications.

For an AN to receive a composite stream at rate  $r$  from other ANs, its power consumption in receiver circuit is

$$p_r(r) = r\beta. \quad (2)$$

For an AN to relay a bypassing stream at  $r$  and to transmit it further over distance  $d$ , its relaying power consumption is

$$p_f(r, d) = p_r(r) + p_t(r, d). \quad (3)$$

If an AN generates a stream at  $r_0(t)$  itself, relays  $j$  bypassing streams at  $r_k(t)$ , where  $1 \leq k \leq j$ , and then transmits an outgoing stream at  $\sum_{i=0}^j r_i(t)$  to another AN or a BS that is  $d$  away, its total communication-related power consumption is

$$p(t) = p_r\left(\sum_{i=1}^j r_i(t)\right) + p_t\left(\sum_{i=0}^j r_i(t), d\right). \quad (4)$$

If the initial energy allocated for the AN is  $e(0)$ , its node lifetime  $l$  is defined by

$$\int_{t_0}^{t_0+l} p(t)dt = e(0), \quad (5)$$

where  $t_0$  is the time when the AN is initialized. Even with a non-linearity model for conventional batteries (e.g. battery lifetime is determined by both battery capacity and discharge current raised to the Peuker constant), as long as we can derive  $l$  from  $e(0)$  and  $p(t)$  empirically, the proposed approaches should still apply in practice.

From the viewpoint of remaining energy, as shown in Fig. 2, an unsynchronized discrete mission can always be converted to an equivalent synchronized continuous mission [17]. For example, Fig. 2(a) represents a discrete mission. If we group all sleep, idle, and active states together, we have Fig. 2(b), which is a continuous mission equivalent in remaining energy. In Fig. 2(c), two ANs,  $v_1$  and  $v_2$ , have unsynchronized activation cycles. However, we can always rearrange the converted continuous missions to make sure that they are synchronized at least once. The convertibility

is due to the additive property of consumed energy, which is the integral of power consumption over time in (5). Therefore, we mainly focus on a synchronized continuous mission, where ANs have constant-rate streams and are activated at  $t_0=0$ . The results can be extended to a general mission with arbitrary activation styles and modes.

### 2.3. Topological lifetime definition

For a WSN of  $N$  ANs placed on a plane, i.e.  $V_N = \{v_i = (x_i, y_i)\}$ , given the initial energy allocation  $e_i(0)$  at  $v_i$ , which generates a stream at rate  $r_i$ , the node lifetime is  $l_i$ . For topology control, our focus is network lifetime ( $R$  or  $L$  for the case with or without inter-AN relaying) from network initialization to a point when the WSN cannot maintain enough ANs alive to continue its given mission. The goal of topology control is to maximize the topological lifetime of a WSN with regard to a certain amount of initial energy provisioning.

According to the *criticality* of a specific mission, we have the most stringent definition of topological lifetime for a WSN: *N-of-N* lifetime ( $L_N$ ); i.e. mission fails if any AN runs out of energy, or  $L_N = \min\{l_i\}$  for  $1 \leq i \leq N$ . The first ANs that run out of energy are denoted as *critical nodes* in  $v_C$ . Maximizing the topological lifetime  $L_N$  is equivalent to maximizing  $\min\{l_i\}$  for  $1 \leq i \leq N$ , where  $\min\{l_i\}$  is the lifetime of the critical ANs. Fig. 3 shows a sample WSN of  $N=10$  ANs (identified by numbered crosses in Fig. 3(a)) scattered in a unit square, and the BS  $b$  (filled triangle) has been located optimally without inter-AN relaying. We assume that ANs are homogeneous with unit initial energy and produce streams at a unit rate. The cases with heterogeneous ANs are discussed in Section 4. For an ease illustration, we assume that  $n=2$  and  $\alpha_1=0$  in (1). As we shall see,  $b$  locates at the center of a circle  $C$  with minimum radius, crossing all critical ANs  $v_C = \{v_2, v_9, v_{10}\}$ , and enclosing all non-critical ANs. In this case,  $\max L_N = 5.504$  normalized unit time without inter-AN relaying. Fig. 3(b) shows the remaining energy and node lifetime

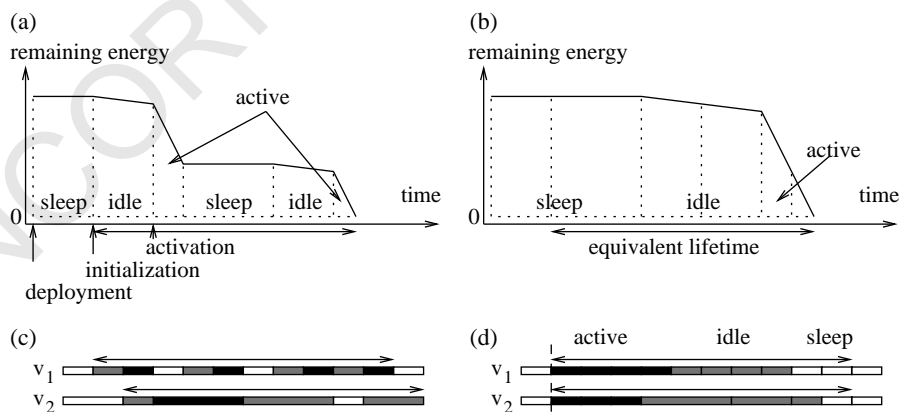


Fig. 2. Activation styles and modes: (a) discrete, (b) continuous, (c) unsynchronized, and (d) synchronized.

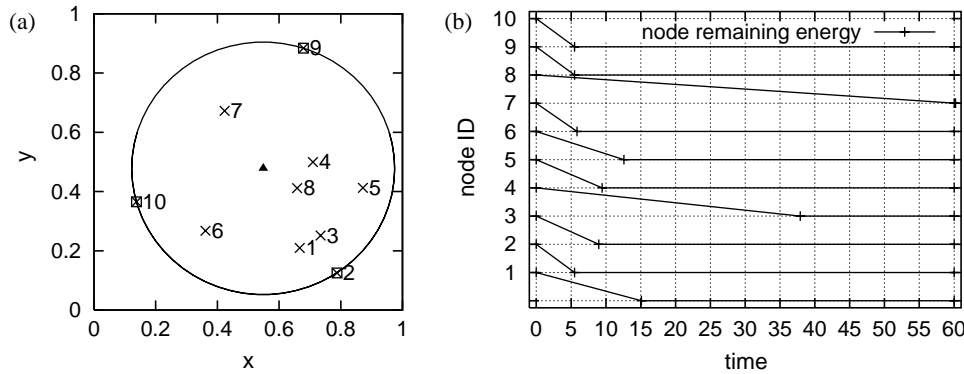


Fig. 3. Normalized  $N$ -of- $N$  lifetime without inter-AN relaying; (a) optimal  $b$  for  $N=10$ , and (b) node energy and lifetime.

for each AN. When critical ANs are out of energy, many non-critical ANs still have considerable energy left to keep them alive for a while.

### 3. Serialized optimal inter-AN relaying

With the determined BS location, we can further prolong network lifetime if inter-AN relaying is application-acceptable and energy-favorable. Here, we first define *relay candidates* for a given AN. We then obtain a parallel optimal allocation through Linear Programming. Finally, we introduce an algorithm to convert the parallel relaying, which requires an AN to potentially communicate with all of its relays simultaneously, to a serialized relay schedule, with which an AN only needs to have one relaying AN at any time.

#### 3.1. Relay candidates selection

As discussed in Section 2.3, critical ANs run out of energy first. To further prolong network lifetime, it is necessary to find relay candidates for critical ANs first.

##### 3.1.1. One-dimension relaying

For a critical AN  $v_1 \in v_C$ , assume there is a non-critical AN  $v_2 \in V_N/v_C$  between  $v_1$  and  $b$ .  $v_2$  can be a relay candidate for  $v_1$ , if  $v_2$  has energy left when  $v_1$  runs out of energy, i.e.  $e_2 - (e_1 p_2)/p_1 > 0$ . As shown in Fig. 4(a),  $v_2$  relays  $x$  portion of the data generated by  $v_1$ . Here, we assume that relaying is always favorable, i.e.  $\beta = 0$  in (3). The communication-related power consumption is

$$p_1(x) = r_1[x(d_1 - d_2)^2 + (1 - x)d_1^2]$$

at  $v_1$  and

$$p_2(x) = (r_1 x + r_2)d_2^2$$

at  $v_2$ . For  $v_1$ , its node lifetime with relaying is  $l_1(x) = e_1/p_1(x)$ , and for  $v_2$ ,  $l_2(x) = e_2/p_2(x)$ . By increasing  $x$  from 0 to 1, or  $v_2$  relays more data for  $v_1$ ,  $l_2(x)$  is reduced. This process stops either  $x = 1$  or  $l_2(x) = l_1(x)$ . In the former case,  $v_2$  still has energy left when  $v_1$  is out of energy. In the latter

one,  $v_2$  cannot relay more for  $v_1$ , otherwise  $v_2$  is out of energy first.

Fig. 4(b) plots the optimal  $x$  as a function of  $\rho = d_2/d_1$ . If  $p_1(x) = p_2(x)$ , i.e.

$$x(d_1 - d_2)^2 + (1 - x)d_1^2 = (1 + x)d_2^2,$$

or

$$d_1^2 - 2xd_1d_2 - d_2^2 = 0.$$

When  $x = 1$ ,

$$d_1^2 - 2d_1d_2 - d_2^2 = 0,$$

or

$$\rho^2 + 2\rho - 1 = 0.$$

Hence,  $\rho = \sqrt{2} - 1 \approx 0.414$  when the optimal  $x$  becomes 1.

As shown in Fig. 4(b), when  $d_2 \leq (\sqrt{2} - 1)d_1$ ,  $v_1$  should use  $v_2$  as its full relay, i.e.  $x = 1$ . When  $(\sqrt{2} - 1)d_1 \leq d_2 \leq d_1$ , the optimal  $x$  decreases gradually. When  $d_2 = d_1$ ,  $x = 0$ ; i.e.  $v_2$  is no longer a relay candidate for  $v_1$ , since they are the same distance away from  $b$ . In Fig. 4(b),  $p_1$  and  $p_2$  are the power consumption of  $v_1$  and  $v_2$  without relaying, respectively. To minimize the power consumption at  $v_1$ ,

$$\begin{cases} x = 1 \\ \rho = \sqrt{2} - 1 \end{cases} \quad (6)$$

and  $\min p_1(1) = [(2 - \sqrt{2})d_1]^2$ . When  $x = 1$ , to minimize the total power consumption  $p_1(x) + p_2(x)$  at  $v_1$  and  $v_2$ ,

$$p_1(1) + p_2(1) = (d_1 - d_2)^2 + 2d_2^2 = 3\left(d_2 - \frac{d_1}{3}\right)^2 + \frac{2d_1^2}{3},$$

i.e.  $\min\{p_1(1) + p_2(1)\} = 2d_1^2/3$  when

$$\begin{cases} x = 1 \\ \rho = \frac{1}{3} \end{cases} \quad (7)$$

Eqs. (6) and (7) can be used to locate the *best* relay for an AN to minimize its own or the total power consumption for the AN and its relay, respectively. These equations can also be

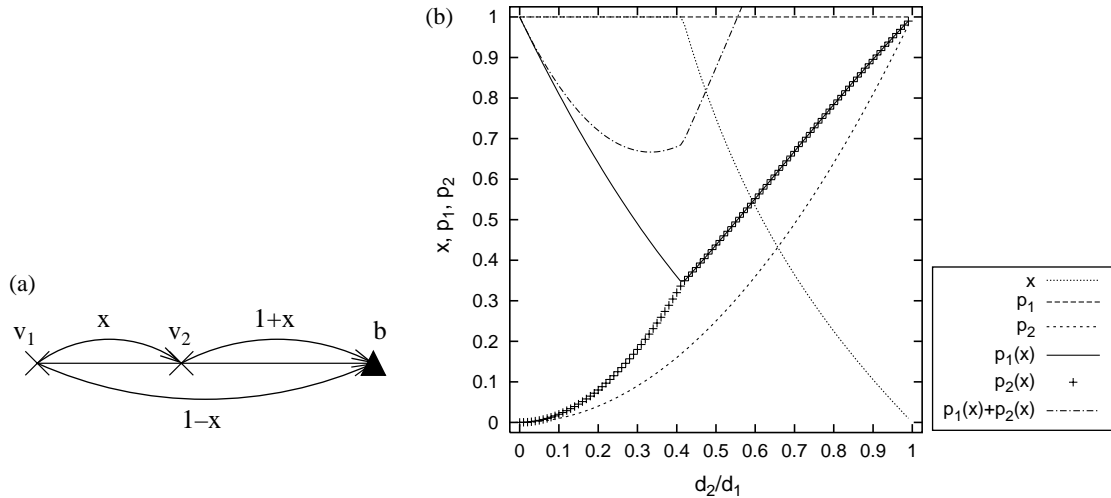


Fig. 4. Relay ratios in one-dimension relaying; (a) relay routes, and (b) relay ratio  $x$  vs.  $\rho = d_2/d_1$ .

used to assist the SN/AN cluster placement process when dedicated relay nodes are introduced to further increase the network lifetime for a deployed WSN.

3.1.2. Two-dimension relaying

Unfortunately, determining relay routes and data ratios on a plane becomes much more complicated. We will use Linear Programming (LP) to obtain the two-dimension relay allocation. Since there are in total  $N^2$  possible relay routes, the computational complexity may become an obstacle when  $N$  is large. Therefore, we shall develop some criteria to preselect the relay candidates for an AN, so that the LP complexity is affordable.

Consider a homogeneous WSN of ANs with unit  $r$  and  $e$ , as shown in Fig. 5(a), there are several possible criteria for an AN  $v_1$  to choose its relay candidate  $v_2$ .

- (c1) Closer to  $v_1$  than  $b$ :  $v_1$  does not choose an AN which is indeed farther away from  $v_1$  than  $b$ ; i.e.  $d_1 > d_{1,2}$  is required for  $v_2$  to be a relay candidate for  $v_1$ .
- (c2) Relay toward  $b$ :  $v_1$  does not choose an AN which is farther away from  $b$  than  $v_1$ ; i.e.  $d_1 > d_2$  is required for  $v_2$  to be a relay candidate for  $v_1$ .

- (c3) Energy conservativeness: optionally,  $v_1$  does not choose  $v_2$  as its relay if the energy saving at  $v_1$  cannot compensate the extra overhead ( $\hat{p}_2$ ) at  $v_2$ ; i.e.  $p_1 - p_{1,2} > \hat{p}_2$  is required for  $v_2$  to be a relay candidate for  $v_1$ .

The first criterion (c1 in Fig. 5(a)) excludes any ANs that are actually farther away to reach for  $v_1$  than to  $b$ . The second criterion (c2) excludes any ANs that are farther away from  $b$  than  $v_1$ : since under the  $e$  and  $r$  assumptions, they are more critical than  $v_1$ . The last criterion (c3) is optional and only applicable when ANs need to conserve total energy consumption as well. c1 and c2 do not alter the optimality of network lifetime for homogeneous WSNs, but c2 has such potential when the initial energy and data rate among ANs are significantly different. When preselecting relay candidates, which criteria are used to filter out bad relays depends on specific applications. Here, we adopt c1 and c2.

Table 2 outlines an algorithm in Tcl-like pseudo code to preselect relay candidates and form relay routes for WSNs. Initially, the relay candidate set RC is empty (line 1), and a non-relayed set NR is built (line 3) and then sorted (line 4)

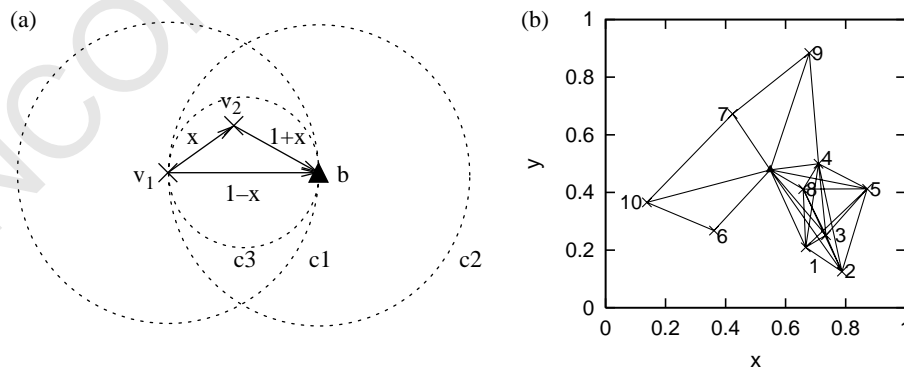


Fig. 5. Relay criteria and routes in two-dimension relaying; (a) relay candidate criteria, and (b) possible relay routes.

Table 2  
Algorithm to preselect relay candidates

1	set RC NULL
2	foreach v in VN
3	lappend NR {v dv}
4	set NR [lsort -index 1 NR]
5	while NR
6	set v [lindex NR 0 1]
7	foreach r in RC
8	if r(R(v))
9	lappend RR_v {v r 0}
10	set NR [lrange NR 1 end]
11	lappend RC v

by the distance between ANs and the BS. For the first AN  $v$  (line 6) in NR, we examine whether there is a relay candidate  $r$  for this AN in RC (line 8) according to the chosen criteria  $\mathcal{R}$ . If so, the relay route  $\{v r 0\}$  is added to the relay route set RR. After all ANs in RC have been examined,  $v$  is removed from NR (line 10) and added to RC (line 11). When NR becomes empty, RR contains all possible relay routes under the chosen criteria. Since there are  $N$  ANs, and each AN can be a relay for other ANs, the time complexity for this algorithm is  $O(N^2)$ . However, it is much better to have this preselecting process, instead of leaving the complexity for LP, as we shall see soon. Fig. 5(b) gives all possible relay routes for the sample WSN with the chosen criteria  $c_1$  and  $c_2$ .

After obtaining the possible relay routes, we need to determine the amount of data relayed through each route, as we did with the relay ratio  $x$  in Section 3.1.1. The relay routes and their data rate are referred to as a feasible relay rate allocation. The allocation is optimal if network lifetime can be maximized with such an inter-AN relaying arrangement.

### 3.2. Parallel relay routes

To obtain an optimal relay allocation, we first assume that an AN has the capability to transmit data to multiple relay candidates simultaneously (or *parallel* relaying).

Assume AN  $v$  relays for ANs  $\{v_1^r, v_2^r, \dots, v_m^r\}$ , and  $v$  has its own relay candidates  $\{v_1^t, v_2^t, \dots, v_n^t\}$ .  $v$  generates a bit-stream at rate  $r$  itself, and relays for  $v_i^r$  at  $r_i^r$ . It then transmits an outgoing stream at  $r_j^t$  to its relay candidate  $v_j^t$ . Therefore,

$$\sum_{i=1}^m r_i^r + r = \sum_{j=1}^n r_j^t, \quad (8)$$

i.e. the rate of incoming streams plus the rate of self-generated stream should equal to the rate of outgoing streams, as all local-views should be sent to the BS (aggregation is application-specific and not considered here). This property is referred to as *flow conservation*.

Let  $e$  be the initial energy that  $v$  has, and  $\varepsilon$  be the remaining energy that  $v$  has when the WSN fails to carry on its mission.  $e - \varepsilon$  is the energy to receive flows from  $v_i^r$  at  $r_i^r$

and to transmit flows to  $v_j^t$  at  $r_j^t$  throughout network lifetime  $R$ . Let  $p_i^r$  and  $p_j^t$  be the power consumption at  $v$  to receive and transmit these flows, respectively. We have

$$R \left( \sum_{i=1}^m p_i^r + \sum_{j=1}^n p_j^t \right) + \varepsilon = e. \quad (9)$$

This property is referred to as *energy conservation*. When the network fails to carry on its mission, the remaining energy  $\varepsilon \geq 0$ . This equation can be further rewritten as

$$\frac{\sum_{i=1}^m p_i^r + \sum_{j=1}^n p_j^t}{e} + s = \frac{1}{R}, \quad (9)$$

where  $s = (\varepsilon/eR) \geq 0$  is treated as a *slack* variable.

Now, we can formulate a constrained optimization problem with the objective of maximizing the network lifetime  $R$ , i.e.

$$\min \frac{1}{R} = \frac{\sum_{j=1}^m p_{j,1}^r + \sum_{k=1}^n p_{1,k}^t}{e_q} + s_1 \quad (10)$$

with the following constraints at each AN  $v_i$

$$\text{ST} \begin{cases} \sum_{j=1}^m r_{j,i}^r + r_i - \sum_{k=1}^n r_{i,k}^t = 0 \\ \frac{\sum_{j=1}^m p_{j,i}^r + \sum_{k=1}^n p_{i,k}^t}{e_i} + s_i - \frac{1}{R} = 0 \end{cases}, \quad (11)$$

where  $r_i$  and  $e_i$  are the data rate and initial energy that  $v_i$  generates and carries, respectively. In this formulation, we have  $N$  flow conservation constraints and  $N$  energy conservation constraints, i.e.  $2N$  constraints in total (term  $1/R$  can be removed from (11) by linking energy constraints at any two nodes, which results an equivalent standard LP formulation with  $2N - 1$  resultant constraints in total, and can be solved by applying regular LP-solving techniques).

If we did not preselect relay candidates in Section 3.1, we have  $N^2$  relay routes (including the final routes to the BS). These variables will add considerable computational overhead when we solve this problem. In other words, the problem formulation has a high complexity, despite the fact that LP itself is expensive to solve in time complexity. Since we cannot reduce the number of constraints, we try to reduce the number of total variables (routes). According to  $c_2$ , if  $v_i$  chooses  $v_j$  as its relay,  $v_j$  should not choose  $v_i$  as its relay, since it is energy-inefficient to *bounce* traffic between AN/BSs; i.e. there are at most  $(N(N+1))/2$  preselected relay routes. With the criteria adopted in Section 3.1.2, we can further reduce the number of considered routes, as we shall see shortly.

Table 3 gives the optimal relay rate allocation with the preselected relay candidates. Blank entry in  $r_{i,j}$  denotes the routes not in the RR set, and 0 denotes the routes in the RR set but not in the optimal relay allocation set. Since self-relay is not energy-conscious, it is denoted by—in Table 3. Positive  $r_{i,j}$  is the actual relay allocation when network

Table 3  
Relay routes and rate allocation  $r_{i,j}$

$i$	$r_i$	$r_{i,1}$	$r_{i,2}$	$r_{i,3}$	$r_{i,4}$	$r_{i,5}$	$r_{i,6}$	$r_{i,7}$	$r_{i,8}$	$r_{i,9}$	$r_{i,10}$	$r_{i,b}$	$e_i$	$\varepsilon_i$	$p_i$	$l_i$
1	1	–			1.386				0			0	1	$\approx 0$	$\approx 0.119$	$\approx 8.420$
2	1	0	–	0.386	0	0			0			0.164	1	0	0.119	8.420
3	1	0		–	1.386				0			0	1	0.033	0.086	11.609
4	1				–				0			4.501	1	0	0.119	8.420
5	1	0.386		0	0.506	–			1.107			0	1	0.065	0.054	18.475
6	1						–					1.495	1	0	0.119	8.420
7	1							–				2.230	1	0	0.119	8.420
8	1								–			1.107	1	0.100	0.018	54.359
9	1				0.222			0.778		–		0	1	0	0.199	8.420
10	1						0.495	0.452			–	0.053	1	0	0.119	8.420

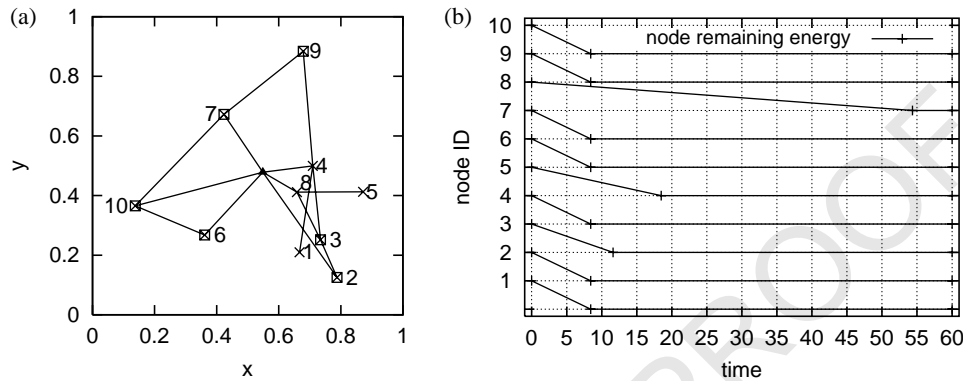


Fig. 6. Parallel relay allocation; (a) optimal relay routes, and (b) node energy and lifetime.

lifetime is maximized. A quick statistics can tell that among all 100 relay routes, there are 29 preselected relay routes, and LP finally chooses 16 optimal relay routes, which are shown in Fig. 6(a), for the maximized network lifetime of 8.420 unit time. ANs with the shortest lifetime in Fig. 3(b), i.e.  $\{\nu_2, \nu_9, \nu_{10}\}$ , now have a longer lifetime by transmitting a portion of their data to nearby ANs, at the cost of other ANs such as  $\{\nu_1, \nu_4, \nu_8\}$  having a shorter lifetime, as shown in Fig. 6(b).

Table 4 compares the overhead of the regular LP formulation and the enhanced one with preselected routes. They both have 20 constraints, i.e. one flow and one energy conservation for each AN. For the regular LP formulation,

Table 4  
Comparison on linear programming overhead

	# Constraints	# Variables	# Iterations	Max $R_N$
Regular LP	20	100	55	8.420
Enhanced LP	20	29	21	8.420

Table 5  
Comparison on random optimal base station location with optimal relay allocation

	Random $b$		Optimal $b$	
	Median	Maximum	w/o optimal relay	Optimal $b$ w/optimal relay
L	1.546	5.083	5.504	R = 8.420

there are 100 considered relay routes, while for the enhanced LP, only 29 routes are considered after the preselection process. The number of relay routes is related to the number of total variables in the LP formulation. The more variables, the higher overhead to solve the problem. With the regular LP, it takes 51 iterations to find the optimal allocation, while with the enhanced LP, it only takes 21 iterations. They both obtain the optimal relay allocation with the same network lifetime. With the preselection process, we can considerably speed up the LP problem-solving process, as indicated in Table 4.

Table 5 lists the topological network lifetime achieved through random BS location (by exhaustive grid search),

optimal BS location without relaying, and optimal BS location with optimal relay allocation. It shows the substantial efficacy of the proposed topology control approaches. The  $N$ -of- $N$  topological lifetime with inter-AN relaying is denoted as  $R$ , and  $L$  without inter-AN relaying. For the sample WSN, the optimal BS location with optimal relay allocation can improve network lifetime by 445% over the random BS location without relaying, and by 50% over the optimal BS location without optimal relay allocation.

ANs  $\{\nu_2, \nu_4, \nu_6, \nu_7, \nu_9, \nu_{10}\}$  are critical and run out of energy first in the optimal relay allocation of the sample WSN. It is worth pointing out that for non-critical ANs  $\{\nu_1, \nu_3, \nu_5, \nu_8\}$ , their feasible relay allocation can be different from the one shown in Fig. 6(a) and Table 3, unless they become critical nodes themselves. In addition, the optimal relay allocation may not be unique due to different initial LP solutions, but they all give the same network lifetime.

### 3.3. Serialized relay schedule

The *parallel* optimal relay allocation obtained in Section 3.2 requires that ANs always have the capability to transmit data to multiple relaying ANs simultaneously. This requirement can impose a technical challenge to the radio transceiver design when a transmitter can only tune to a specific time slot, frequency band, or code sequence at any time. Therefore, it is necessary to derive a *serialized* relay time schedule, so that an AN transmits its data to exactly one node (AN or BS) at any time. At a predetermined time, the AN switches its time slot, frequency band, or code sequence, and communicates with the next relay node. Since the turnaround operation is also *expensive*, we expect at most one *switch* per each relay node throughout network lifetime.

The proposed serialization algorithm is based on relay *energy* allocation, not relay *rate*, *power*, or *time* allocation. Although energy allocation is an integral of power and time allocations, only energy (data) allocation is an *invariant* during the serialization process, as shown in Fig. 2. In a parallel relay rate allocation, an AN  $\nu_i$  transmits a stream at rate  $r_1$  to its relay node  $\nu_1$ ,  $r_2$  to  $\nu_2$ , and so on.  $e$  and  $\varepsilon$  have the same definition as that in Section 3.2. Throughout network lifetime  $R$ , the energy allocation (or *quota*) for  $\nu_k$  at  $\nu_i$  is

$$\phi_{i,k} = \frac{(e - \varepsilon)p_{i,k}}{p_{i,1} + p_{i,2} + \dots + p_{i,m}}, \quad (12)$$

where  $p_{i,k}$  is the power for  $\nu_i$  to send a stream at  $r_k$  to  $\nu_k$ .

During network lifetime  $R$ , AN  $\nu_i$  has the flexibility to choose which relay to use at a certain time and how long it uses the relay, as long as the flow conservation and the energy quota are both satisfied. For example, once the WSN is initialized,  $\nu_i$  can randomly pick an AN  $\nu_1$  in its relay set, and transmit all data it has, including the data it generates and the data relayed for others, until it exhausts the energy quota  $\phi_{i,1}$  for  $\nu_1$ .  $\nu_1$  will be removed from the relay set. Then,

$\nu_i$  picks another unchosen node  $\nu_2$  in its remaining relay set and exhausts the energy quota  $\phi_{i,2}$  for  $\nu_2$ . This process repeats until the relay set becomes empty. No matter in which order the relay nodes are chosen,  $\nu_i$  always achieves the same node lifetime; therefore, the WSN achieves the same network lifetime.

Table 6 outlines the approach to obtain the serialized relay schedule. Procedure `addr{v dr}` is used when an AN  $\nu_j$ , which  $\nu$  relays data for, changes its data relayed from  $\nu_j$  to  $\nu$  by  $\Delta r$ . If  $\nu$  is the BS, such change has no impact, since  $b$  is not energy-constrained (line 2). Otherwise,  $\nu$  cancels its next switch event (line 4) and sets up a new one (line 9), according to the remaining energy quota of its current relay  $\nu_2$  and the updated outgoing data rate  $r_t$ . This procedure is called for  $\nu_2$  and its current relay recursively.

`switch{v}` determines the actual relay *time* schedule. It is called when the current relay  $\nu_2$  has exhausted its energy quota. Therefore, relay  $\nu_2$  is updated by `addr{v2 -rt}` (line 14) since the data rate from  $\nu$  to  $\nu_2$  drops from  $r_t$  to 0. Then, the next relay node for  $\nu$  is retrieved from the relay list, and a new switch event is set up according to the energy quota for the new relay and the current outgoing data rate of  $\nu$ . For the new relay  $\nu'_2$  and its relays, `addr` is called recursively (line 20) since the data rate from  $\nu$  to  $\nu'_2$  jumps from 0 to  $r_t$ .

Table 6  
Algorithm to calculate relay schedule

1	<code>proc addr {v dr}</code>	981
2	if v = b	982
3	Return	983
4	cancel switch v	984
5	set v2 [lindex EQ_v 0 1]	985
6	set e2 [lindex EQ_v 0 2]	986
7	update e2 in EQ_v	987
8	set rt [expr rt + dr]	988
9	at now + $\frac{e_2}{p(r_t, d_t, r_2)}$ switch v	989
10	addr v2 dr	990
11	Endproc	991
12	<code>proc switch {v}</code>	992
13	set v2 [lindex EQ_v 0 1]	993
14	addr v2 --rt	994
15	set EQ_v [lrange EQ_v 1 end]	995
16	set v2 [lindex EQ_v 0 1]	996
17	set e2 [lindex EQ_v 0 2]	997
18	at now + $\frac{e_2}{p(r_t, d_t, r_2)}$ switch v	998
19	lappend RS {now v v2}	999
20	addr v2 rt	1000
21	Endproc	1001
22	<code>ForEach v VN</code>	1002
23	set ps 0	1003
24	ForEach {v t rr} RR_v	1004
25	set rs [expr ps + pt (rr, dt)]	1005
26	set eq (e - ε) / ps	1006
27	ForEach {v t rr} RR_v	1007
28	lappend EQ_v {v t eq pt}	1008
29	set EQ_v [lsort -ran 1 EQ_v]	
30	set EQ_v [concat { } EQ_v]	
31	ForEach v VN	
32	switch v	

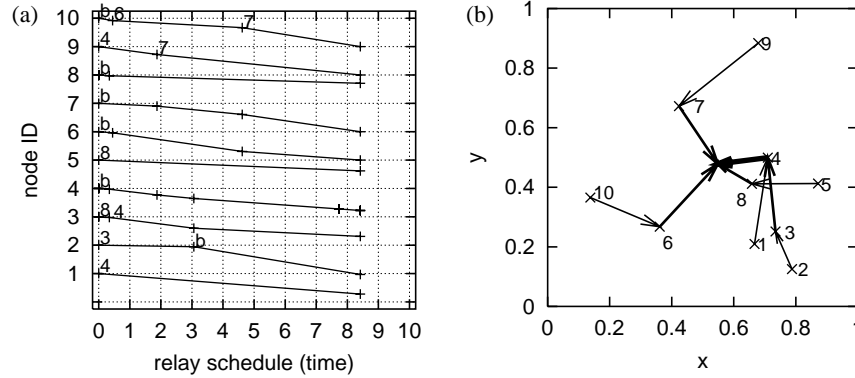


Fig. 7. Serialized relay schedule; (a) relay schedule, and (b) relay snapshot at  $t=2$ .

Code from line 22 to 28 calculates the energy quota (EQ) for each relay of a given node  $\nu$ , according to the output of the candidate preselection in Section 3.1 and the rate allocation in Section 3.2. When applicable, line 29 randomizes relays in the list, so that it is less likely that multiple ANs choose the same AN as their relay at the same time. Line 30 intentionally prefixes a *dummy* relay at the beginning of the EQ list, so that we can issue a pseudo `switch{v}` at network initialization and switch from the *dummy* relay to a *real* relay in  $V_N$ . Assume that `add{v r}` have the complexity  $O(1)$ , then each `switch{v}` has the complexity  $O(N)$  since a relay path at most has  $N-1$  intermediate relays to  $b$ . Therefore, the total time complexity to obtain the relay schedule is  $O(N|RR|)$ . This schedule can actually be calculated in a distributed manner at each AN, if  $b$  dispatches the energy quota by (1) to ANs directly, unless the relay schedule needs to be coordinated with the mission schedule at  $b$ .

Fig. 7(a) plots the resultant serialized relay schedule. The numbered cross denotes when an AN chooses another node as its new relay, and the unnumbered cross denotes when the AN serves as a relay for other ANs and the incoming data rate changes. For example, at network initialization,  $\nu_{10}$  chooses  $b$  as its relay for 0.446 unit time. When its remaining energy drops to 0.918 unit,  $\nu_{10}$  has used up the energy quota for  $b$  and switches to the next relay  $\nu_6$ . At 4.616 unit time,  $\nu_{10}$  has used up the quota for  $\nu_6$ , and switches to  $\nu_7$  until at 8.420 unit time

the network fails to carry on its mission due to multiple ANs (including  $\nu_{10}$ ) out of energy.

Although AN  $\nu_7$  does not change its relay (the BS) throughout network lifetime, its power consumption also changes due to different ANs using it as their relay. During  $[0, 1.873]$  unit time, no other ANs use  $\nu_7$  as a relay;  $\nu_7$  has the least power consumption for an outgoing stream at 1 unit rate. Then at 1.873 unit time,  $\nu_9$  starts to use  $\nu_7$  as its relay. Therefore,  $\nu_7$  begins to have a higher power consumption (or a quicker drop of its remaining energy) with a two-unit outgoing flow. After 4.616 unit time, both  $\nu_9$  and  $\nu_{10}$  use  $\nu_7$  as their relay.  $\nu_7$  now has the highest power consumption in its lifetime for a three-unit outgoing flow. At 8.420 unit time,  $\nu_7$  exhausts its energy, and at the same time the entire network fails to carry on its mission. Fig. 7(b) gives a snapshot of the relay schedule for the sample WSN at  $t=2.0$  unit time. The arrow of lines shows the direction of relayed flows; the line width implies the data rate. For serialized relaying, at any time,  $V_N$  always forms a tree rooted at the BS.

A certain amount of energy quota allocated for  $\nu_k$  at  $\nu$  represents the amount of data transferred from  $\nu$  to  $\nu_k$ . Since the total energy and energy quota for each relay are identical in either parallel or serialized relaying, the amount of data transferred should also be the same. A formal proof of this equivalency was given in [17]. Therefore, an AN has the same lifetime with parallel or serialized relaying, as shown in Fig. 8(a) for AN  $\nu_7$ . With parallel relaying, the remaining

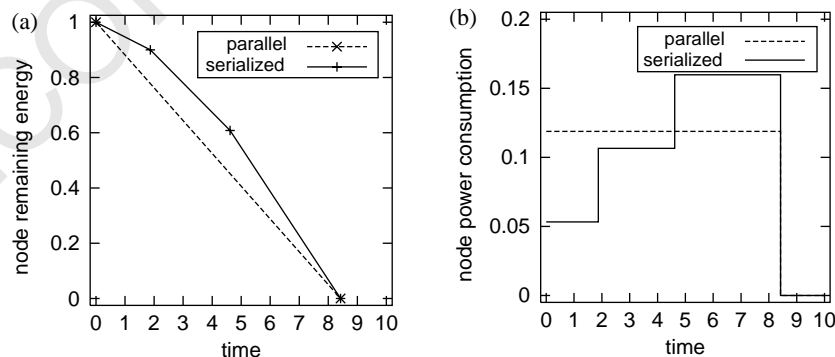


Fig. 8. Equivalency between parallel and serial relay ( $\nu_7$ ); (a) node remaining energy, and (b) node power consumption.

energy at  $\nu_7$  decreases at a constant rate throughout its node lifetime. With serialized relaying, the remaining energy at  $\nu_7$  decreases at different rates according to its current power consumption shown in Fig. 8(b). Although the remaining energy curves for parallel and serialized relaying are different most of the time, they meet again when  $t=R_N$ .

#### 4. Further discussions

We have developed approaches to obtain the optimal relay rate allocation and time schedule if inter-AN relaying is feasible, acceptable, and favorable, in order to maximize the topological lifetime of a WSN with a certain amount of initial energy provisioning. In this section, we further discuss the applicability and extensibility of these proposed approaches in a more practical context.

##### 4.1. Topology control process

Fig. 9 illustrates the relationship among these approaches and their positions in the whole topology control process. Given a geographical coverage  $\mathcal{C}$ , the information source  $\mathcal{S}$ , and the expected network lifetime  $\mathcal{T}$ , the first step is to collocate SN/AN clusters  $\mathcal{V}$  with  $\mathcal{S}$ , which gives a proper coverage [18]. With the incremental cluster grouping techniques, some SN/AN clusters are then grouped into a WSN partition  $V_N$  that is served by a common BS. The BS is then located optimally for a WSN partition so that the network lifetime  $L$ , according to  $N$ -of- $N$  or other lifetime definitions, is maximized even without inter-AN relaying. If  $L \geq \mathcal{T}$ , the topology control process exits with the optimal BS location.

If  $L < \mathcal{T}$ , topology control can either adjust the SN/AN cluster partition, or request more BSs. If inter-AN relaying is application desirable, energy favorable, and most importantly, system feasible, topology control can also invoke the approaches in Section 3.1 to preselect relay candidates. With the LP approach in Section 3.2, network lifetime can be prolonged to  $R$ . If  $R \geq \mathcal{T}$ , this relay allocation is acceptable and will be converted into a serialized relay

schedule, according to the approach developed in Section 3.3. Then, topology control exits with both the optimal BS location and optimal relay schedule.

However, if  $R < \mathcal{T}$ , topology control has to rely on its last two resorts: more BSs or dedicated relay nodes. Although we did not address the node placement and partition problem in this paper, the relay candidacy criteria in Section 3.1 can assist the process of deciding, where to place the additional dedicated relay nodes. It turns out that topology control actually is an interactive process with multiple iterations. During the course of network operation, nodes may fail and be substituted by other nodes, and the mission may get extended. These changes require a revisit of some building blocks in the topology control process depicted in Fig. 9.

##### 4.2. Practical considerations

In the previous discussions, we focused on the distance-related portion of power consumption and its role in topology control. In a practical WSN, other non-distance-related power consumptions may become non-negligible, e.g. the energy consumed within the transmitter or receiver circuit, as well as in the data processing and view composition components. Node homogeneity may not always be guaranteed, especially when we consider the WSN redeployment scenarios (i.e. new nodes join the network long after old nodes have been initialized and activated). Also, transmission power consumption may take a path loss exponent greater than two and include other portions to combat multi-path, shadowing, interference and other effects. A third geometry dimension may be introduced when node elevation varies considerably.

The approaches proposed in this paper are extensible to accommodate these challenges. For the relay candidates selection, instead of the Euclid distance used in criteria  $\{c_1, c_2, c_3\}$  in Section 3.1, we can replace it by: how expensive, in terms of node lifetime, it is for a node to use a relay. For example, a node should not choose the node that is more expensive than  $b$  as its relay. Within this schema, the LP formulation is similar, and we can still obtain the optimal relay allocation. The serialization process is based on the actual energy quota, so it will not be challenged by heterogeneity in practice. ANs count the energy consumed for the current relay, and switch to another relay when the energy quota for the current one has been exhausted, while non-transmission-related energy consumption can be set aside early.

The proposed approaches on inter-AN relaying arrangement, along with other blocks in topology control such as SN/AN/BS placement and partition, give us the capability to maximize network lifetime *topologically*. Although we assumed that topology control is done before network initialization in this paper, further improvement can be introduced by adaptively updating topology control throughout the entire mission. For example, the BS can

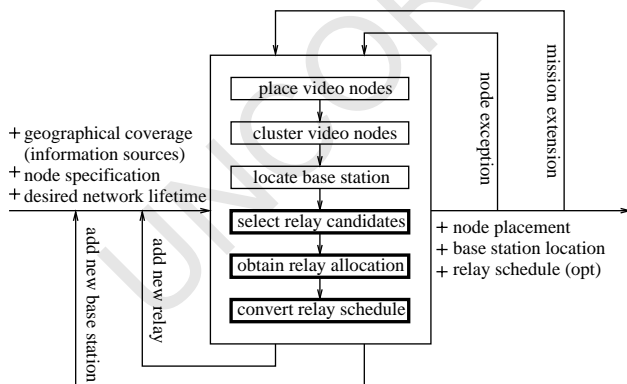


Fig. 9. Topology control iterations for wireless sensor networks.

1233 have certain mobility, and may change its location when  
 1234 some ANs are dead or about to run out of energy. Here, we  
 1235 adopt a two-stage approach: locate the BS first; then arrange  
 1236 inter-AN relaying optimally. Another attempt can allow the  
 1237 BS to change its location while rearranging inter-AN  
 1238 relaying to achieve an even longer network lifetime. At  
 1239 each step, the approaches proposed to obtain the optimal  
 1240 relay arrangement still apply.

## 1241 5. Related work

1242  
 1243  
 1244  
 1245 MANETs and regular WSNs have attracted intensive  
 1246 research interest in recent years. A comprehensive survey on  
 1247 WSNs can be found in [10] and the references therein. The  
 1248 research challenges and directions for MANETs can be  
 1249 found in [11]. Although two-tiered WSNs have many aspects  
 1250 in common with MANETs and regular WSNs, its tiered  
 1251 structure and mission-driven nature bring in some unique  
 1252 characteristics. For example, most research activities in  
 1253 WSNs assume a dense and microsensor deployment.  
 1254 Microsensors have very limited energy provisioning to  
 1255 capture scalar-only data such as temperature and motion  
 1256 triggered by external events. But for a two-tiered WSN, ANs  
 1257 are much more capable than ordinary microsensors (SNs), as  
 1258 they are required to construct and feed live local-views to  
 1259 BSs when they are activated. With the considerable coverage  
 1260 of a single SN/AN cluster, there is no need to have a very  
 1261 dense deployment of SN/AN clusters (generally, SN/AN  
 1262 clusters are placed with the proximity of designated areas).  
 1263 Due to this sparse deployment, the inter-AN distance is  
 1264 comparable with the dimension of coverage, and scalability  
 1265 is manageable even with a few BSs and a certain number of  
 1266 ANs. Based on these facts, the lifetime of an AN is dominated  
 1267 by its distance-related communication power consumption.  
 1268 Therefore, topology control that determines the distance  
 1269 from ANs to BSs and chooses relay candidates according to  
 1270 the inter-AN distance, plays a vital role in maximizing the  
 1271 topological network lifetime of WSNs.

1272 There are a few lifetime and topology-focused research  
 1273 activities in the literature. The lifetime upper bound of  
 1274 information harvest sensor networks that convey probabilistic  
 1275 data from a point, a line, or an area source is derived in  
 1276 [19]; simulation-based evaluations to validate the tightness  
 1277 of the derived bound are also given there. In [20], the  
 1278 optimal role assignment is further explicitly formulated as a  
 1279 maximal network flow problem, again in data harvest  
 1280 networks. In our context, instead of harvesting from  
 1281 probabilistic information sources, when being activated,  
 1282 WSNs should consistently offer an in-situ, real-time, and  
 1283 steady global-view of the whole network. In [21], a family  
 1284 of flow augmentation algorithms, which redirect data flows  
 1285 among nearby nodes to balance their energy consumption in  
 1286 a distributed but empirical manner, is presented. Our  
 1287 approach is a centralized one due to the application nature  
 1288 of WSNs. After the BS is located, if inter-AN relaying is

feasible, we first select relay candidates and then obtain the  
 optimal parallel relay allocation. In contrast to previous  
 work in this area, we further convert the relay allocation to a  
 serialized relay schedule with the equivalent optimality, and  
 allow ANs to choose their relays locally according to *energy  
 quota*. Therefore, an AN only needs to have one relay  
 destination at any time. In some two-tiered WSNs, BSs can  
 further have certain mobility (e.g. mounted on vehicles),  
 and have sophisticated processing and storage capabilities  
 to accommodate the centralized topology control and other  
 functionalities.

Other topology-related research mainly focused on  
 multi-hop routings in WSNs. For example, [22] considered  
 fixed topologies of {4,6,8}-neighbor on a two-dimension  
 plane and 6-neighbor in a three-dimension space, and  
 proposed a power-aware routing scheme to reduce the total,  
 and even the per-node, power consumption. In this paper,  
 we consider an arbitrary node placement on a plane, without  
 any geometrical constraints on the node neighborhood. In  
 practice, the location of SN/AN clusters is determined by  
 specific missions, not by topology control. [23] considered  
 adjusting the transmitter output power to create a desired  
 topology for connectivity and bi-connectivity; it also  
 observed that a poor topology can only offer a small  
 fraction of the achievable lifetime, but they focused on  
 multi-hop networks without any common sinks like those in  
 WSNs. [24] proposed a sparse topology and energy  
 management (STEM) technique that aggressively puts  
 nodes in sleep mode and only wakes them up when they  
 are needed to forward data; it also explored the equivalency  
 of nearby nodes for data forwarding. However, in two-tiered  
 WSNs, due to their application characteristics, once being  
 activated, the already-sparsely-deployed ANs usually can-  
 not be forced into sleep. Otherwise, the designated local-  
 views are lost. [25] proposed a distributed cone-based  
 topological control to maintain the global connectivity with  
 minimum power paths in multi-hop ad hoc networks. [26]  
 considered a distributed algorithm to determine whether a  
 node should be awake or asleep, depending on how many of  
 its neighbors will get benefit and how much remaining  
 energy it has. The focus in these work, i.e. the purpose of  
 topology control, is different from the one that we have in  
 this paper. Instead of minimizing the power consumption  
 for individual nodes or along a forwarding path, we  
 minimize the power consumption of those critical ANs  
 that dominate the lifetime, or utility, of the entire WSN.  
 Overall, the WSNs under our consideration are BS-centric  
 with multi-hop inter-node relaying, where SN/AN clusters  
 with a certain amount of initial energy are sparsely deployed  
 in designated areas without significant redundancy.

## 6. Conclusions

In this paper, we have proposed approaches to obtain the  
 optimal relay allocation to maximize the topological

lifetime of a WSN with a certain amount of initial energy provisioning, when inter-node relaying is application-desirable and energy-favorable. We also converted the parallel relay rate allocation into a serialized relay time schedule so that any node only needs to have one relaying node at any time. Experimental evaluations have demonstrated the efficacy of topology control as a vital process for two-tiered WSNs, and they also validated the optimality of proposed approaches.

For future work, the main focus will be on the other few building blocks in the topology control diagram shown in Fig. 9: node placement and partition techniques, and their impact on the BS location and inter-node relaying arrangement. Others scenarios, such as dynamic deployment and redeployment, as well as hierarchical and heterogeneous WSNs, can also be taken into consideration.

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