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Serialized optimal relay schedules in two-tiered wireless sensor networks☆

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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.

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

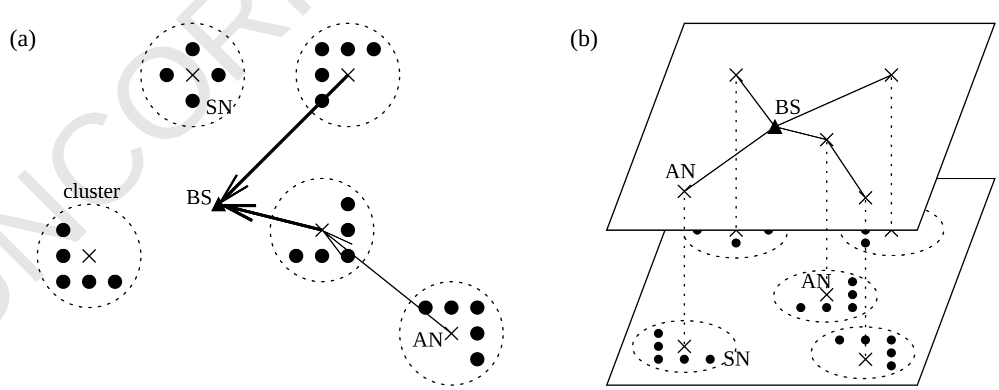

Fig. 1. A two-tiered architecture of wireless sensor networks; (a) physical view, and (b) logical view.

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 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.

Table 1
Notations

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

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

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

where α_1 is a distance-independent term (e.g. the power consumed in transmitter circuit), and α_2 reflects the distance-dependent one. Eq. (1) mainly considers the path loss of exponent n, and usually $2 \le n \le 4$ 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

$$p_r(r) = r\beta. \tag{2}$$

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

$$p_f(r,d) = p_r(r) + p_t(r,d). \tag{3}$$

If an AN generates a stream at $r_0(t)$ itself, relays j bypassing streams at $r_k(t)$, where $1 \le k \le j$, 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

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

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

$$\int_{t=t_0}^{t_0+l} p(t)\mathrm{d}t = e(0), \tag{5}$$

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 $1 \le i \le N$. 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 $1 \le i \le N$, 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

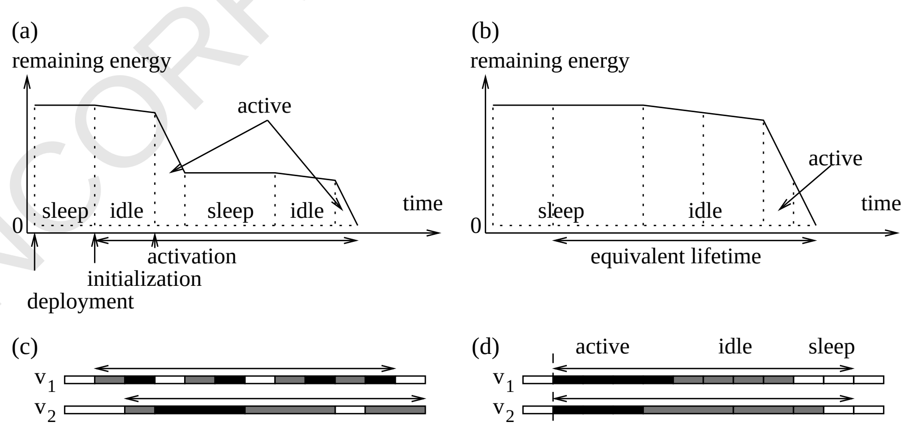

Fig. 2. Activation styles and modes: (a) discrete, (b) continuous, (c) unsynchronized, and (d) synchronized.

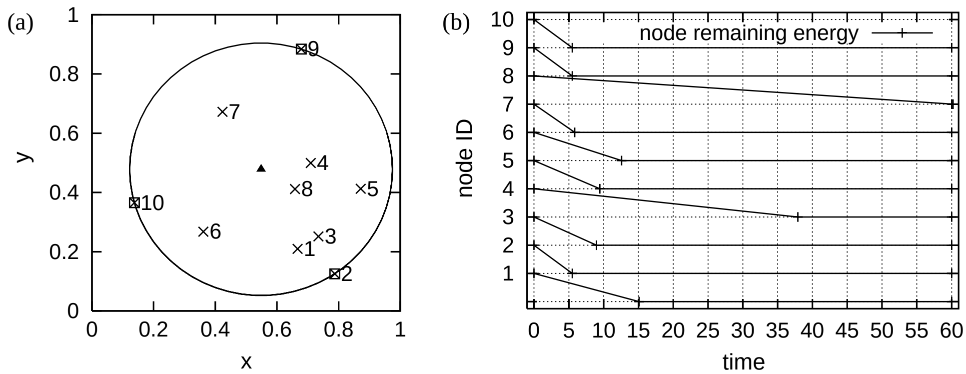

Fig. 3. Normalized *N-of-N* lifetime without inter-AN relaying; (a) optimal b for $N=10$, and (b) node energy and lifetime.

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 $\nu_1 \in \nu_C$, assume there is a non-critical AN $\nu_2 \in V_N/\nu_C$ between ν_1 and b. ν_2 can be a relay candidate for ν_1, if ν_2 has energy left when ν_1 runs out of energy, i.e. $e_2-(e_1p_2)/p_1>0$. As shown in Fig. 4(a), ν_2 relays x portion of the data generated by ν_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 ν_1 and

$$p_2(x) = (r_1x + r_2)d_2^2$$

at ν_2. For ν_1, its node lifetime with relaying is $l_1(x)=e_1/p_1(x)$, and for ν_2, $l_2(x)=e_2/p_2(x)$. By increasing x from 0 to 1, or ν_2 relays more data for ν_1, $l_2(x)$ is reduced. This process stops either $x=1$ or $l_2(x)=l_1(x)$. In the former case, ν_2 still has energy left when ν_1 is out of energy. In the latter one, ν_2 cannot relay more for ν_1, otherwise ν_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 $d_2 \le (\sqrt{2}-1)d_1$, ν_1 should use ν_2 as its full relay, i.e. $x=1$. When $(\sqrt{2}-1)d_1 \le d_2 \le d_1$, the optimal x decreases gradually. When $d_2=d_1$, $x=0$; i.e. ν_2 is no longer a relay candidate for ν_1, since they are the same distance away from b. In Fig. 4(b), p_1 and p_2 are the power consumption of ν_1 and ν_2 without relaying, respectively. To minimize the power consumption at ν_1,

$$\begin{cases} x = 1 \\ \rho = \sqrt{2}-1 \end{cases} \tag{6}$$

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 ν_1 and ν_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

$$\begin{cases} x = 1 \\ \rho = \dfrac{1}{3} \end{cases} \tag{7}$$

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

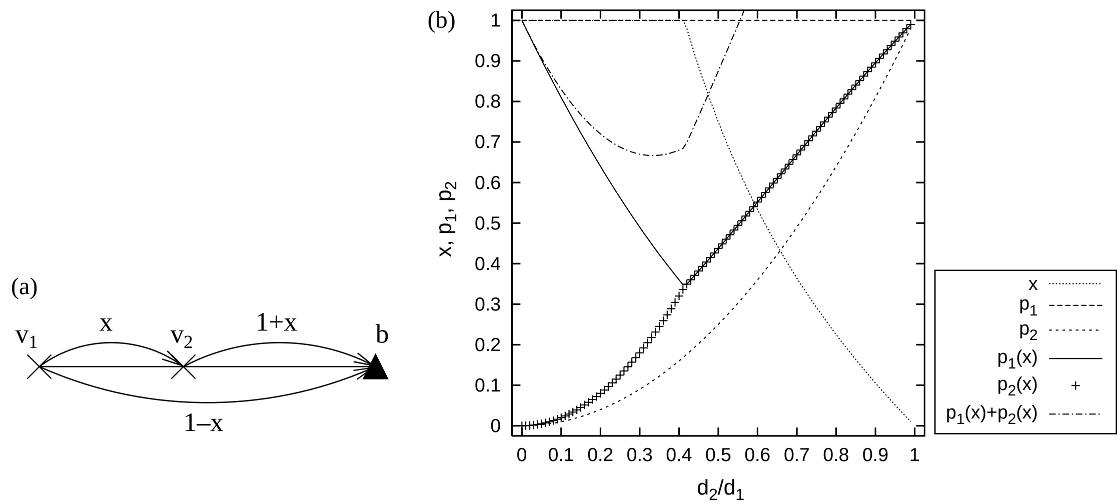

Fig. 4. Relay ratios in one-dimension relaying; (a) relay routes, and (b) relay ratio x vs. $\rho = d_2/d_1$.

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)

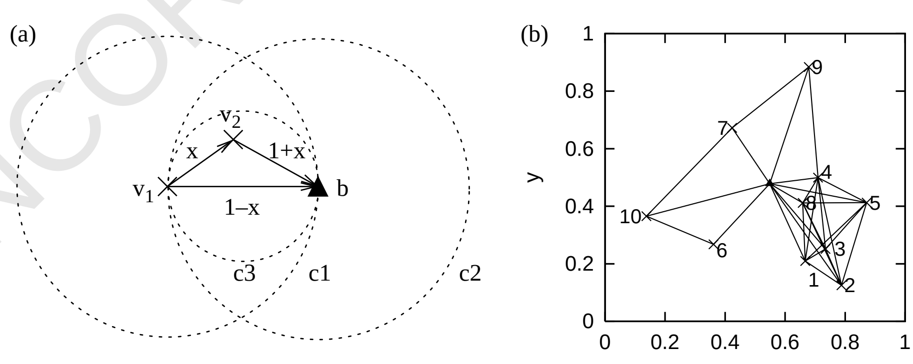

Fig. 5. Relay criteria and routes in two-dimension relaying; (a) relay candidate criteria, and (b) possible relay routes.

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 `c1` and `c2`.

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 $\{v_1^r, v_2^r, \ldots, v_m^r\}$, and v has its own relay candidates $\{v_1^t, v_2^t, \ldots, v_n^t\}$. 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,

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

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 ε 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

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

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

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

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.

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

with the following constraints at each AN v_i

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

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 `c2`, 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	ε_i	p_i	l_i
1	1	–			1.386				0			0	1	≈0	≈0.119	≈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

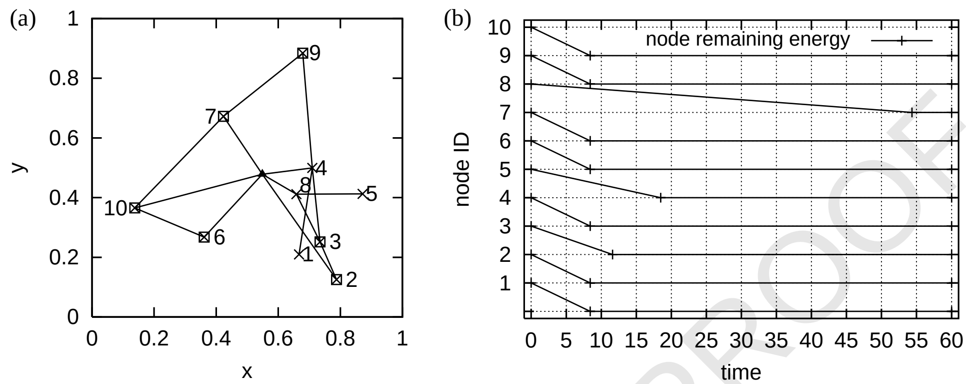

Fig. 6. Parallel relay allocation; (a) optimal relay routes, and (b) node energy and lifetime.

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. $\{v_2,v_9,v_{10}\}$, now have a longer lifetime by transmitting a portion of their data to nearby ANs, at the cost of other ANs such as $\{v_1,v_4,v_8\}$ 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, 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),

Table 4
Compatison on linear programming overhead

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

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

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

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 ν_i transmits a stream at rate r_1 to its relay node ν_1, r_2 to ν_2, and so on. e and ε have the same definition as that in Section 3.2. Throughout network lifetime R, the energy allocation (or *quota*) for ν_k at ν_i is

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

where $p_{i,k}$ is the power for ν_i to send a stream at r_k to ν_k.

During network lifetime R, AN ν_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, ν_i can randomly pick an AN ν_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 ν_1. ν_1 will be removed from the relay set. Then, ν_i picks another unchosen node ν_2 in its remaining relay set and exhausts the energy quota $\phi_{i,2}$ for ν_2. This process repeats until the relay set becomes empty. No matter in which order the relay nodes are chosen, ν_j 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 ν_j, which ν relays data for, changes its data relayed from ν_j to ν by Δr. If ν is the BS, such change has no impact, since b is not energy-constrained (line 2). Otherwise, ν 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 ν_2 and the updated outgoing data rate r_t. This procedure is called for ν_2 and its current relay recursively.

`switch{v}` determines the actual relay *time* schedule. It is called when the current relay ν_2 has exhausted its energy quota. Therefore, relay ν_2 is updated by `addr{v2 −rt}` (line 14) since the data rate from ν to ν_2 drops from r_t to 0. Then, the next relay node for ν 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 date rate of ν. For the new relay ν'_2 and its relays, addr is called recursively (line 20) since the data rate from ν to ν'_2 jumps from 0 to r_t.

Table 6
Algorithm to calculate relay schedule

```
1   proc addr {v dr}
2     if v==b
3       Return
4     cancel switch v
5     set v2 [lindex EQ_v 0 1]
6     set e2 [lindex EQ_v 0 2]
7     update e2 in EQ_v
8     set rt [expr rt+dr]
9     at now+e2/p(rt,d_{v,v2}) switch v
10    addr v2 dr
11  Endproc
12  proc switch {v}
13    set v2 [lindex EQ_v 0 1]
14    addr v2 --rt
15    set EQ_v [lrange EQ_v 1 end]
16    set v2 [lindex EQ_v 0 1]
17    set e2 [lindex EQ_v 0 2]
18    at now+e2/p(rt,d_{v,v2}) switch v
19    lappend RS {now v v2}
20    addr v2 rt
21  Endproc
22  Foreach v VN
23    set ps 0
24    Foreach {v t rr} RR_v
25      set rs [expr ps+pt(rr,dt)]
26    set eq (e−ε)/ps
27    Foreach {v t rr} RR_v
28      lappend EQ_v {v t eq·pt}
29    set EQ_v [lsort -ran 1 EQ_v]
30    set EQ_v [concat { } EQ_v]
31  Foreach v VN
32    switch v
```

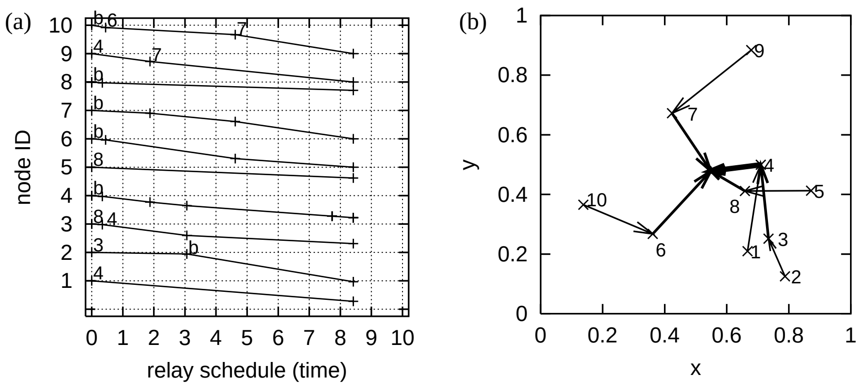

Fig. 7. Serialized relay schedule; (a) relay schedule, and (b) relay snapshot at $t=2$.

Code from line 22 to 28 calculates the energy quota (EQ) for each relay of a given node v, 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, v_{10} chooses b as its relay for 0.446 unit time. When its remaining energy drops to 0.918 unit, v_{10} has used up the energy quota for b and switches to the next relay v_6. At 4.616 unit time, v_{10} has used up the quota for v_6, and switches to v_7 until at 8.420 unit time the network fails to carry on its mission due to multiple ANs (including v_{10}) out of energy.

Although AN v_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 v_7 as a relay; v_7 has the least power consumption for an outgoing stream at 1 unit rate. Then at 1.873 unit time, v_9 starts to use v_7 as its relay. Therefore, v_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 v_9 and v_{10} use v_7 as their relay. v_7 now has the highest power consumption in its lifetime for a three-unit outgoing flow. At 8.420 unit time, v_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 v_k at v represents the amount of data transferred from v to v_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 v_7. With parallel relaying, the remaining

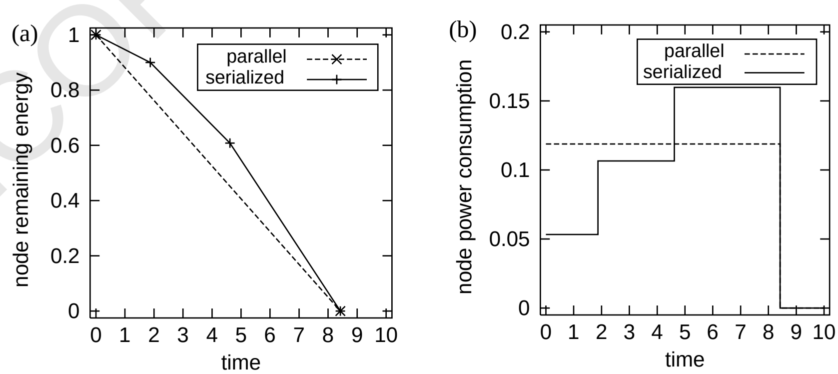

Fig. 8. Equivalency between parallel and serial relay (v_7); (a) node remaining energy, and (b) node power consumption.

energy at v_7 decreases at a constant rate throughout its node lifetime. With serialized relaying, the remaining energy at v_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

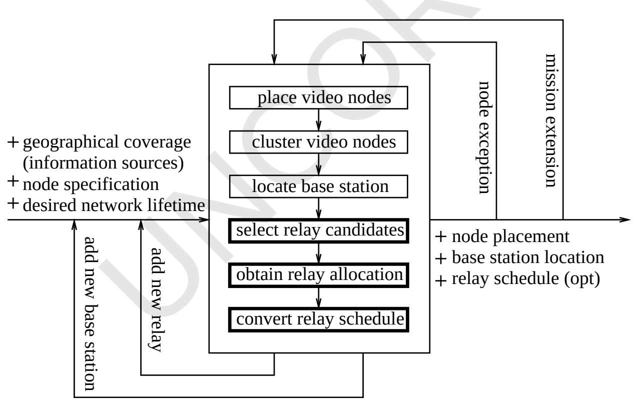

Fig. 9. Topology control iterations for wireless sensor networks.

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 {c1,c2,c3} 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 have certain mobility, and may change its location when some ANs are dead or about to run out of energy. Here, we adopt a two-stage approach: locate the BS first; then arrange inter-AN relaying optimally. Another attempt can allow the BS to change its location while rearranging inter-AN relaying to achieve an even longer network lifetime. At each step, the approaches proposed to obtain the optimal relay arrangement still apply.

5. Related work

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

There are a few lifetime and topology-focused research activities in the literature. The lifetime upper bound of information harvest sensor networks that convey probabilistic data from a point, a line, or an area source is derived in [19]; simulation-based evaluations to validate the tightness of the derived bound are also given there. In [20], the optimal role assignment is further explicitly formulated as a maximal network flow problem, again in data harvest networks. In our context, instead of harvesting from probabilistic information sources, when being activated, WSNs should consistently offer an in-situ, real-time, and steady global-view of the whole network. In [21], a family of flow augmentation algorithms, which redirect data flows among nearby nodes to balance their energy consumption in a distributed but empirical manner, is presented. Our approach is a centralized one due to the application nature 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 cannot 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.

Acknowledgements

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