Locating Base-Stations for Video Sensor Networks

Jianping Pan[†] Y. Thomas Hou[‡] Lin Cai[†] Yi Shi[‡] Sherman X. Shen[†]

[†]Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada
[‡]The Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA, USA

***Abstract*— For a wireless video sensor network (*WiViSeN*) where video nodes have been placed at some strategic locations to capture designated scenes, an immediate challenge is to locate the base-station optimally such that the network lifetime of battery-powered video nodes can be maximized. This paper presents two schemes, one centralized and the other distributed, to obtain the optimal base-station location algorithmically under the proposed definition of topological lifetime. The upper and lower bounds of maximal topological lifetime are derived to enable a quick assessment of energy provisioning feasibility and topology control necessity. In addition, the proposed research provides a foundation to introduce the relay and cluster techniques that can further prolong network lifetime.**

***Index Terms*— Wireless video sensor networks, network lifetime, topology control**

I. INTRODUCTION

Advances in micro-electro-mechanical systems (MEMS) and short-range low-power radios have enabled a quick development and wide deployment of *Wireless Video Sensor Network* (*WiViSeN*s) in recent years. In WiViSeNs, small *video sensor node*s are strategically placed at certain locations to capture designated scenes, as well as other desired inputs such as audio, temperature, motion, and so on. Video nodes may have a limited on-board capacity to process the raw data that they collect. However, the value of the collected data can be significantly magnified if some of these data are transferred back to few specialized nodes with much more sophisticated processing and storage capabilities. These *super* nodes are referred to as *base-station*s, or data *sink*s when video nodes are referred to as data *source*s. In addition, base-stations also serve as the gateway for WiViSeNs to exchange information with other networks such as the global Internet.

WiViSeNs and the-like (*e.g.*, mobile ad hoc networks) have sparked extensive research interests, almost in every layer of the protocol stack [1]-[4], [7] in the last few years. There are research activities in energy conscious sensor media access control (MAC), variable topology routing, localized flow and error control, and even domain-specific application design. Although the traditional computer networks may more-or-less have some similar concerns, the distinct characteristics of WiViSeNs and other variants warrant a revisit of the conventional design wisdom in network architectures, services, and protocols. Nevertheless, these research efforts have been paving the road for a more ubiquitous and efficient deployment of WiViSeNs in the near future.

Energy constraint is a unique feature that further distinguishes WiViSeNs from other wireless or mobile networks. Since it is impractical and sometimes impossible to recharge the battery-powered video nodes economically after they have been deployed, the *utility*, or value, of a WiViSeN heavily depends on how long the network can carry on its mission after being initialized. There are many activities (*e.g.*, sensing, coding, transmitting, and routing data) affecting a video node's lifetime, and among them the communication-related power consumption is the dominant one. In WiViSeNs, once video nodes are placed at strategic locations, they are likely stationary or with very low mobility. But under certain constraints, the base-station can be located flexibly. Since a video node that is close to the base-station consumes less energy than a faraway node when transmitting the same amount of data to the base-station, it reveals an opportunity to prolong a node's lifetime by moving the base-station close to the node. However, it is impossible to have all placed nodes close to the base-station at the same time. Therefore, locating base-station properly becomes a critical task to maximize network lifetime. We refer to this process as *topology control*, and the network lifetime in this context as *topological lifetime* since it is even under the regular MAC and LLC layers.

In this paper, we focus on the topological lifetime of a WiViSeN from the network initialization to a point when it fails to maintain *all* video nodes alive to continue its mission. We first establish a generic system model for WiViSeNs with the definition of topological lifetime. We then construct two schemes to locate base-station optimally. The first scheme is also optimal in computational complexity and assumes that the coordinates of all video nodes are known. When the location information is unavailable, the second scheme locates base-station in a distributed manner by measuring the Arrival of Angle (AoA) of signals among video nodes. The performance evaluation demonstrates the efficacy of topology control as a vital process to maximize network lifetime with regard to a given mission and a certain amount of initial energy. This work also provides a foundation to introduce the relay [6] and cluster techniques that can further prolong network lifetime.

The remainder of this paper is organized as follows. In Section II, we present the power consumption model for video nodes and define topological lifetime for WiViSeNs. In Section III, we propose two schemes to locate base-station optimally such that the network lifetime can be maximized: one is a centralized *divide-and-conquer* scheme, the other is a

This work has been supported in part by a Postgraduate Scholarship and a Strategic Research Grant from the Natural Science and Engineering Research Council (NSERC) of Canada, and the Woodrow W. Everett, Jr. SCEEE Development Fund in cooperation with the Southeastern Association of Electrical Engineering Department Heads.

0-7803-7954-3/03/$17.00 ©2003 IEEE.

distributed AoA-based scheme. In Section IV, we further discuss the extension and generalization of the proposed schemes to handle a general WiViSeN with an arbitrary network setting and energy provisioning. Section V reviews the related work, and Section VI concludes this paper.

II. SYSTEM MODEL

The communication-related power consumption is found a dominant factor affecting node lifetime, especially when nodes feed live video to base-station during their lifetime in WiViSeNs. Here, we model the power consumption for a video node v_i, which is d_i away from the base-station b, to transmit a video flow at rate r_i to b as $p_t(r_i, d_i) = r_i(\alpha_1 + \alpha_2 d_i^n)$, where n is the path loss exponent, and α_1 and α_2 are the coefficients independent and dependent of d_i, respectively.

Given the initial energy $e_i(0)$, the node lifetime T_i is

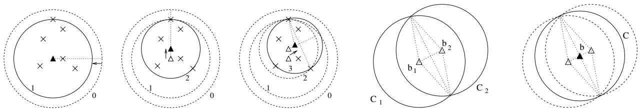
$$T_i = \frac{e_i(0)}{p_t(r_i, d_i)} = \frac{e_i(0)}{r_i(\alpha_1 + \alpha_2 d_i^n)}.$$

We assume that video nodes generate a constant-bit-rate (CBR) flow throughout its lifetime T_i. In Section IV, we will show that our schemes developed in Section III are also applicable when video node v_i generates a variable-bit-rate (VBR) flow at $r_i(t) \geq 0$, as long as $\bar{r}_i = \frac{\int_{T_i} r_i(t)dt}{T_i}$ can be obtained empirically. Our system model is extensible with more sophisticated (*i.e.*, including multi-path and shadowing effects) power consumption and non-linear (*i.e.*, conventional battery) energy dissipation models, as far as $\int_{t=0}^{T_i} p(r_i, d_i)dt \leq e_i(0)$ is always satisfied for node v_i. We do *not* consider inter-node relaying in this paper based on the following reason: this model gives the bounds even when the relaying is undesirable, inefficient, or infeasible. For example, relaying may not be acceptable for some applications where inter-node trustiness is uncertain. Also, relaying may not be attractive when receiving and processing overhead becomes significant. Moreover, relaying simply cannot be supported when low-cost and transmitter-only video nodes are used in WiViSeNs.

For an easy geometrical illustration, we assume that $e_i(0)$ can be allocated proportionally to r_i for v_i. Therefore, we have $T_i = \frac{E_0}{d_i^n}$ if we further assume that α_1 is negligible and $E_0 = \frac{e_i(0)}{r_i \alpha_2}$ for all nodes. The most intuitive definition of network lifetime is that the mission survives only if all video nodes are alive (*i.e.*, the remaining energy $e_i(t) > 0$). The network lifetime under this definition is denoted as $L_N = \min\{T_i\}$ for a WiViSeN (V_N) with N video nodes. The first nodes run out of energy are denoted as *critical* nodes in set V_C.

III. LOCATING BASE-STATION

In this section, we present two schemes to locate base-station optimally to maximize L_N of a WiViSeN. The first scheme is coordinate-based, which is also optimal in computational complexity. The second scheme is AoA-based, which does not require location information of video nodes. We also obtain some properties on the optimal base-station location and the upper and lower bounds for maximal network lifetime.



(a) existence (b) uniqueness

Fig. 1. Properties of C and b under the L_N definition.

A. Coordinate-based scheme

To maximize $L_N = \min\{T_i\} = \min\{E_0/d_i^n\}$, it is equivalent to minimize $\max d_i$. That is, given $V_N = \{v_i = (x_i, y_i)\}$ on a plane, we should locate the base-station b at (x_0, y_0) such that $\max\{d_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}\}$ is minimized. We first show that such b does exist on the plane.

Lemma 1: For a given V_N, an optimal location for b under the L_N definition does exists deterministically.

The correctness of Lemma 1 can be illustrated through the construction of a circle C with minimal radius r, centered at (x_0, y_0), and enclosing all nodes in V_N on the plane.

Algorithm 1:

1) As shown in Fig. 1(a), there always exists an arbitrary circle C_0 large *enough* to enclose $\forall v_i \in V_N$.
2) Keep center b_0 of C_0 unchanged, and reduce radius r_0 of C_0 until a smaller C_1 crosses a node $v_1 \in V_N$.
3) Move b_1 (or b_0) toward v_1 and keep v_1 being crossed until a smaller C_2 crosses another node $v_2 \in V_N$.
4) If v_1 and v_2 are diameter nodes for C_2, $C = C_2$; exit.
5) Otherwise, move b_2 toward the line (v_1, v_2) and keep both v_1 and v_2 being crossed until a smaller C_3 crosses the third node $v_3 \in V_N$. $C = C_3$; exit. □

The correctness of Algorithm 1 is ensured by the fact that normally on a plane, at most 3 nodes determine a circle. In Fig. 1(a), crosses represent the location of video nodes in V_N, and filled triangles represent the base-station b. Next, we show that such an optimal location exists uniquely.

Lemma 2: For a given V_N, an optimal b location under the L_N definition exists uniquely.

The correctness of Lemma 2 can be proved by showing if there are 2 or more optimal bs, there is a contradiction.

Proof: In Fig. 1(b), without loss of generality, there are 2 optimal locations, b_1 and b_2, corresponding to C_1 and C_2 with the same radius r, respectively. b_1 and b_2 are d away. Since all nodes are enclosed by C_1 and C_2 according to their definition, these nodes should also be enclosed by $C_1 \cap C_2$ which is enclosed by a C centered at the middle point of line segment (b_1, b_2) and with radius $\sqrt{r^2 - (\frac{d}{2})^2} < r$. This is a contradiction according to the definition of C_1 and C_2. ■

Besides the existence and uniqueness properties of b, we can also obtain the upper and lower bounds for L_N. Since $\forall d_i \leq r$ in C and $L_N = \min\{T_i = \frac{E_0}{d_i^2}\}$, we only need to determine the equivalent bounds for radius r.

Theorem 1: For an optimal C, its radius r is bounded by $[\frac{D}{2}, \frac{\sqrt{3}D}{2}]$, where D is the set diameter for V_N.

Proof: i) $r \geq \frac{D}{2}$: This is obvious, since if $r < \frac{D}{2}$, C cannot enclose two nodes that are D away at the same time according

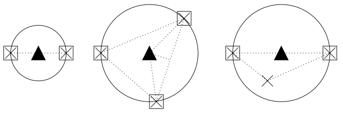


Fig. 2. Optimal base-station location for $N \in \{2,3\}$.

to the definition of set diameter D.
ii) $r \leq \frac{\sqrt{3}D}{2}$: There are two circles C_1 and C_2 enclosing V_N with radius $r = D$ and centered at two nodes v_1 and v_2 that are D away. Similar to the proof of Lemma 2, there is a smaller C enclosing $C_1 \cap C_2$, centered at the middle point of the line segment (v_1, v_2) and with radius $\sqrt{D^2 - (\frac{D}{2})^2} = \frac{\sqrt{3}D}{2}$. ■

With $T_i = \frac{E_0}{d_i^2}$, we have the following corollary for L_N.

Corollary 1.1: $\frac{4E_0}{3D^2} \leq L_N \leq \frac{4E_0}{D^2}$.

Corollary 1.1 can assess whether it is feasible for an initial energy provisioning E_0 to achieve a desired lifetime L of V_N with diameter D. If $L > \frac{4E_0}{D^2} \geq L_N$, E_0 is insufficient or L is infeasible, and V_N should either increase E_0 or decrease D by reducing N. Also, Corollary 1.1 can save unnecessary computation: if $L < \frac{4E_0}{3D^2}$, topology control is trivial by just locating b at the middle point of any two diameter nodes.

Algorithm 2: When $N \in \{2,3\}$, we can locate the optimal b for V_N as Fig. 2 sketches.

- When $N = 2$, the optimal b is at the middle point of the line segment determined by v_1 and v_2, and $r = \frac{D}{2}$.
- When $N = 3$, there are two sub-cases
  1) If v_i $(i = 1,2,3)$ determines an acute or right triangle, the optimal b is at the center of a circle determined by v_i $(i = 1,2,3)$, and $r \leq \frac{\sqrt{3}D}{3}$.
  2) If v_i $(i = 1,2,3)$ determines an obtuse triangle; without loss of generality, let $\angle v_1 v_2 v_3$ be an obtuse angle, then the optimal b is at the middle point of the line segment (v_1, v_3), and $r = \frac{D}{2}$. □

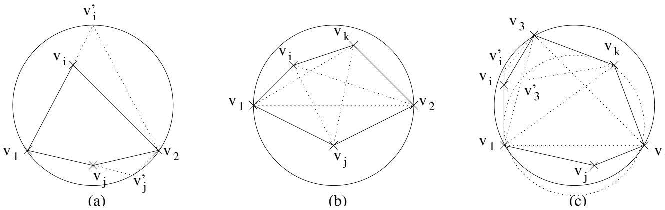
The above construction also gives a tighter upper bound on r, which implies a much tighter lower bound on L_N.

Corollary 1.2: $\frac{3E_0}{D^2} \leq L_N \leq \frac{4E_0}{D^2}$.

Based on Algorithm 2, we can develop a *divide-and-conquer* scheme to locate b recursively for any V_N, since we find that b actually is determined by V_C and $|V_C| \leq 3$ (even if V_N degenerates, it does not affect our scheme; indeed, the degeneracy can speed up the process). Our scheme is based on Welzl's randomized algorithm [5].

Algorithm 3: For a given V_N, we can locate the optimal b with the L_N definition as follows. Initially, $V_{C_N} = \emptyset$.

1) If $|V_{C_n}| = 3$ or $V_n \setminus V_{C_n} = \emptyset$, the optimal b can be located by Algorithm 2 directly; exit.
2) Otherwise, pick any node v from $V_n \setminus V_{C_n}$ and $V_{n-1} = V_n \setminus \{v\}$. Call Algorithm 3 recursively for V_{n-1} with $V_{C_{n-1}} = V_{C_n}$, which returns b_{n-1} for V_{n-1}.
3) With b_{n-1}, if v's lifetime is no less than L_{n-1} for V_{n-1}, v is *not* a critical node for V_n, so that $b_n = b_{n-1}$; exit.
4) Otherwise, v is a critical node for V_n. Call Algorithm 3 recursively for V_n with critical set $V_{C_n} \cup \{v\}$. □



(a) (b) (c)

Fig. 3. Properties of critical nodes.

The finiteness of the recursive Algorithm 3 relies on the fact that for each recursion, the problem size is reduced, either by a smaller V_n in Step 2) or by a larger V_{C_n} in Step 4). With the termination condition in Step 1), the algorithm should finishes in finite steps. The correctness of Algorithm 3 relies on Algorithm 2 and the comparison in Step 3), which are intuitive and straightforward. Since $|V_C| \leq 3$, the probability of the chosen $v \in V_N$ being a critical node is $p_N \leq \frac{3}{N}$. Let the time complexity of Algorithm 3 for V_N with an empty initial V_{C_N} be $O_{0,N}$. We have

$$O_{i,n} \leq O_{i,n-1} + O(1) + \frac{3-i}{n-i} O_{i+1,n}, \tag{1}$$

where $O_{i,n}$ is the time complexity when there are i known critical nodes among n total nodes and $0 \leq i \leq 3$. $O_{3,\cdot} = O(1)$ if Step 1) is an $O(1)$ operation. The first term in (1) is for Step 2), the second term is for Step 3) and other constant overhead per recursion, and the last term is for Step 4 after v is identified as a critical node. Therefore, $O_{0,N} \sim O(N)$. Actually, this is the least achievable complexity for any algorithms since at least each node should be examined once to determine whether it is critical or not.

B. AoA-based scheme

Although Algorithm 3 is optimal in computational complexity, it requires the coordinates of all video nodes, which may not be feasible in some circumstances. For instance, when the on-board GPS receiver is unavailable, the distance measurement between nodes requires node synchronization, which may not be always achievable in WiViSeNs. On the other hand, the incoming directions or angles of pilot signals from other nodes can be measured without synchronization. Therefore, we can propose a distributed scheme to locate the optimal b based on the measurements of Arrival of Angle (AoA) and without any explicit knowledge of node coordinates. An overviews of AoA measurement methodologies can be found in [8], [9].

Similar to Algorithm 3, to locate the optimal b, we need to identify the critical node set $V_C \in V_N$. First, we derive some properties of V_C in the AoA context.

Property 1: All critical nodes in V_C are hull nodes of V_N.
Proof: Without loss of generality, a critical node v is crossed by a C enclosing all nodes in V_N. Therefore, all nodes in $V_N \setminus \{v\}$ are on the one side of the tangent line to C at v. According to the definition, v is a hull node of V_N. ■

Property 2: For any two critical nodes v_1 and v_2, the line (v_1, v_2) separates $V_N \setminus \{v_1, v_2\}$ into two subsets V_1 and V_2. If both V_1 and V_2 are nonempty, for any two nodes $v_i \in V_1$ and $v_j \in V_2$, $\angle v_1 v_i v_2 + \angle v_1 v_j v_2 \geq \pi$.

Proof: Since all nodes in V_N are enclosed by C determined by v_1 and v_2 along with other critical nodes. As Fig. 3(a) shows, $\angle v_1 v_i v_2 \geq \angle v_1 v'_i v_2$ and $\angle v_1 v_j v_2 \geq \angle v_1 v'_j v_2$, *i.e.*, $\angle v_1 v_i v_2 + \angle v_1 v_j v_2 \geq \angle v_1 v'_i v_2 + \angle v_1 v'_j v_2 = \pi$. ■

V_C can be determined in two steps based on the properties. *Step* 1: each node checks if it satisfies Property 1. This step can eliminate all non-hull nodes. The procedure of Step 1 is straightforward. If a node v_i can find another v_j such that all other nodes in V_N are on one side of the line determined by v_i and v_j, both v_i and v_j are hull nodes. If such v_j does not exist for v_i, v_i is not a hull node and will not participate in Step 2. Although the total computational complexity to identify the hull nodes is even higher than that to identify the optimal base-station using Algorithm 3, all nodes can execute Step 1 simultaneously and the computations are distributed.

Denote V_H as the hull node set identified by Step 1 . If $|V_H| = 2$, both hull nodes are critical. If $|V_H| = 3$, the hull nodes having an acute view angle to the other 2 nodes are critical. For $|V_H| \geq 4$, we have following two cases.

Case 1: if $|V_C| = 2$, these two critical nodes must be diameter nodes of C. We have 2 sub-cases if we choose any 2 nodes in V_H:

- all chosen nodes are critical: *i.e.*, view angles from all other V_H nodes to these 2 chosen nodes are obtuse, *e.g.*, $\angle v_1 v_{i,j,k} v_2 > \frac{\pi}{2}$ in Fig. 3(b);
- at least one chosen node is uncritical: *i.e.*, at least one view angle from an unchosen critical node to these 2 chosen nodes is acute, *e.g.*, $\angle v_1 v_2 v_{i,j,k} < \frac{\pi}{2}$ in Fig. 3(b).

Case 2, if $|V_C| = 3$, these three critical nodes determine an acute or right triangle. There are 2 sub-cases if we choose 3 nodes in V_H:

- all chosen nodes are critical: *i.e.*, the sum of the view angle from any unchosen node and the view angle from 1 of these 3 chosen nodes to 2 remaining chosen nodes which determine a line that separates these 2 viewing nodes is greater than π, *e.g.*, $\angle v_1 v_2 v_3 + \angle v_1 v_i v_3 > \angle v_1 v_2 v_3 + \angle v_1 v'_i v_3 = \pi$ in Fig. 3(c).
- at least one chosen node is uncritical: nevertheless, these 3 nodes can determine a circle C'. According to the uniqueness of C, C' cannot enclose all V_N nodes; otherwise, these 3 nodes are indeed critical. In addition, C' cannot enclose all V_H nodes, since no V_N nodes can be outside of V_H nodes. Without loss of generality, let v_h be such a node outside C'. Therefore, at least for v_h, the sum of the view angle from v_h and the view angle from 1 of these 3 chosen nodes to 2 remaining chosen nodes which determine a line that separates these 2 viewing nodes is less than π, *e.g.*, $\angle v_1 v_3 v_k + \angle v_1 v_2 v_k < \angle v_1 v'_3 v_k + \angle v_1 v_2 v_k = \pi$ in Fig. 3(c).

Step 2: each hull node has the following procedure to determine whether it is a critical node when $|V_H| \geq 4$:

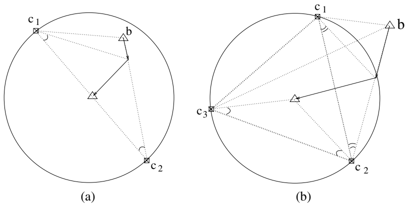
1) Each node measures the directions to all other nodes in V_H, and calculates the view angles to any pair of nodes.
2) Each node reports to all other nodes in V_H the measured view angles to other node pairs.

TABLE I

ALGORITHM FOR STEP 2

```
1   $V = V_H \setminus \{v_0\}$
2   for all $v_i \in V$
3     find $v_j \in V_H \setminus \{v_0, v_i\}$ with min$\angle v_0 v_j v_i$
4     if $\angle v_0 v_j v_i > \pi/2$
5       $v_0 v_i$ are diameter of $C$, return
6     if ch$(v_0, v_i)$=ch$(v_0, v_j)$=ch$(v_i, v_j)$=1
7       $v_0, v_i, v_j$ are critical, return
8     else $V = V \setminus \{v_i, v_j\}$
9   $v_0$ is uncritical, return

10  Procedure ch$(v_1, v_2)$
11  for all $v_a \in V_H \setminus \{v_1, v_2\}$
12    if $\angle v_1 v_2 v_a < \pi$ add $v_a$ into $V_1$
13    else add $v_a$ into $V_2$
14  if $V_1$ or $V_2$ is empty, return(1)
15  for all $v_a \in V_1$
16    for all $v_b \in V_2$
17      if $\angle v_1 v_a v_2 + \angle v_1 v_b v_2 < \pi$, return(0)
18  return(1)
```

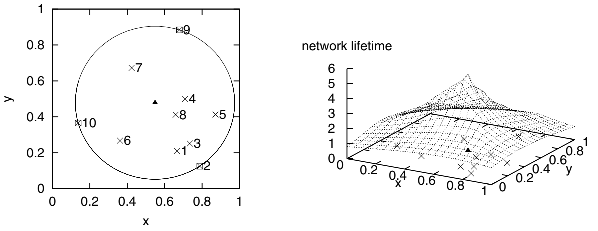


(a) (b)

Fig. 4. Migrating base-station to the optimal position.

3) Each node in V_H examines its criticality using the algorithm in Tab. I. To be a critical node, it can either find another hull node such that they are the diameter of C (Lines 3 to 5); or, it can find other two critical nodes such that the three nodes satisfy Property 2 pairwisely. For the latter case, v_0 arbitrary chooses one node v_i first. Since when there are 3 critical nodes, any critical node must have the minimum view angle to the other two critical nodes. We only need to check if v_0, v_i, and v_j (the one with minimum view angle to $v_0 v_i$,) satisfy Property 2 pairwisely, which is examined with Procedure `ch()`. If and only if they satisfy Property 2 pairwisely, these 3 nodes are the 3 critical nodes. Even if there are more than 3 critical nodes, at least 3 of them can construct an acute or right triangle, so these 3 critical nodes can be identified by the algorithm.

Once the critical nodes are known, they can direct the base-station to its optimal location. If the diameter nodes of C, c_1 and c_2, are known, they report the base-station the angles $\angle c_1 c_2 b$ and $\angle c_2 c_1 b$. The base-station moves toward the node with smaller angle till these two angles are the same. Then, the base-station moves toward the bisector of $\angle c_1 b c_2$ till c_1, c_2, and b are collinear, as shown in Fig. 4(a). If there are 3 critical nodes, c_1, c_2, and c_3, the base-station first communicates with 2 of them and moves to the location where $\angle c_1 c_2 b = \angle c_2 c_1 b$. Then, the base-station moves toward the bisector of $\angle c_1 b c_2$ till $\angle c_3 c_2 b = \angle c_2 c_3 b$, as shown in Fig. 4(b).



(a) optimal b (b) L_N with a random b

Fig. 5. *N-of-N* topological lifetime.

TABLE II
STATISTICS ON NORMALIZED L_N WITH A RANDOM OR OPTIMAL b

	min	mean	median	25%-75%	max	optimal
L_N	0.722	1.788	1.546	1.251-2.123	5.083	5.504

C. Performance evaluation

Fig. 5(a) illustrates the optimal location of b (filled triangle) for a given sample WiViSeN (V_{10}) of 10 nodes (numbered cross) on a unit square, and Fig. 5(b) plots the normalized L_N respect to E_0 with a random location for b. Rectangles in Fig. 5(a) denote the *critical* nodes that run out of energy first with the optimal b and in this example $V_C = \{v_2, v_9, v_{10}\}$.

As indicated by the statistics of L_N with a random or optimal b in Tab. II, topology control is critical to maximize L_N. With a random b, the most-likely $L_N = 1.546$ is much less than the optimal $(L_N)_{\max} = 5.504$. Even with an exhaustive search, due to the search granularity (0.05 in Fig. 5(b)), the numerical *maximal* lifetime is suboptimal.

IV. FURTHER DISCUSSIONS

We have presented in Section III the schemes to locate base-station b optimally for a given WiViSeN to maximize its network lifetime, L_N. During the course, we used the minimal circle for illustrative purpose on a plane, and we assumed a simplified node lifetime model for easy calculation. However, our proposed location-based scheme, using Algorithm 3, does not rely on such a circle, and can be extended with a much more complicated node lifetime model (since Steps 1 and 3 in Algorithm 3 are generic and independent of how to calculate node lifetime). The underlying principle of our scheme is that the optimal base-station location is actually determined by some so-called *critical* nodes. For any given WiViSeNs, the number of *critical* nodes ($|V_C|$) is limited and is relatively small when comparing to the total number of video nodes. Therefore, our *divide-and-conquer* algorithm can determine these *critical* nodes in an efficient and recursive manner.

In Section II, we adopted a simplified source model by assuming that all video nodes produce CBR streams and are activated at the same time. We can show that as far as the average data rate is obtainable for a node producing a VBR stream, our model and schemes are still applicable, since $p(\bar{r}_i(t), d_i)T = \int_T p(r_i(t), d_i)dt \leq e(0)$ and $r_i(t)$ is a linear factor in $p(r_i(t), d_i)$. When nodes are activated asynchronously (a node is inactive for the time period $[t_1, t_2]$ if $\int_{t_1}^{t_2} r_i(t)dt = 0$ and $r_i(t) \geq 0$), we only need to change our definition on node lifetime slightly to accommodate this generalization, *i.e.*, a node is considered *alive* if there is no need for this node to generates information any more. Therefore, if the remaining energy $e_i(t^*) = 0$ for node v_i at time t^*, and if $r(t) = 0$ for $\forall t \geq t^*$, according to the new definition on node lifetime, the mission continues with an L_N topological network lifetime.

V. RELATED WORK

Energy-saving MAC and routing in sensor networks have attracted many research efforts in recent years [1]. In MAC layer, it is found that for the battery-powered sensor nodes, a contention-based MAC has lower energy efficiency due to communication overheads such as media sensing, collision avoidance, and receiver overhearing. In addition, the multi-hop routing among nodes should be arranged properly to conserve node energy [3], since the transit nodes have to consume extra energy to relay data for other nodes. These efforts focus on the local energy optimization at a node or along a path, which are different from our approach where the global optimization is achieved by locating base-station properly to reduce power consumption for all nodes. Due to the fact that data collected in a sensor network contains considerable redundancy, information fusion or in-network processing also generates many research interests [1].

VI. CONCLUSIONS

In this paper, we have proposed two schemes to optimally locate the base-station for a video sensor network, in order to maximize its topological network lifetime. One is a centralized location-based scheme, which is also optimal in computational complexity. The other is a distributed AoA-based scheme, which is applicable when the location information of sensor nodes is unavailable. We also obtained some properties and derived the upper and lower bounds of maximal topological lifetime. It is shown that topology control is very important for WiViSeNs. In a follow-on report [6], we will further extend these schemes with the relay and cluster techniques.

REFERENCES

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Computer Networks*, 38:393–422, 2002.

[2] W. Heinzelman. Application-specific protocol architectures for wireless networks. *Ph.D. thesis*, MIT, 2000.

[3] R. Ramanathan and R. Rosales-Hain. Topology control of multihop wireless networks using transmit power adjustment. *Proc. IEEE Infocom*, pp. 404–413, 2000.

[4] V. Rodoplu and T.H. Meng. Minimum energy mobile wireless networks. *IEEE J. on Selected Areas in Communications*, 17(8):1333–1344, 1999.

[5] E. Welzl. Smallest enclosing disks (balls and ellipsoids). *Lecture Notes in Computer Science*, 555:359-370, 1991.

[6] Y.T. Hou, Y. Shi, J. Pan, A. Efrat, and S. Midkiff. Maximizing lifetime of wireless video sensor networks through single-session flow routing. *Technical Report,* Virginia Tech, 2003. Available at `http://www.ece.vt.edu/~thou/Research.`

[7] M. Bhardwaj and A.P. Chandrakasan. Bounding the lifetime of sensor networks via optimal role assignments. *IEEE Infocom*, 1587–1596, 2002.

[8] S. V. Schell and W. A. Gardner, "High resolution direction finding," *Handbook of statistics*, 10, Elsevier, pp. 755-817, 1993.

[9] T. S. Rappaport, J. H. Reed, and B. D. Woerner, "Position location using wireless communications on highways of the future," *IEEE Communications Magazine*, 34(10), pp. 33-42, Oct. 1996.