Minimizing Energy Consumption Through Mobility in Wireless Video Sensor Networks

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***Abstract*—Energy is an important issue in designing wireless sensor networks. Coverage and connectivity are not of less important since they are necessary for the network to be operational. In this work, we consider the case of wireless video sensor networks where some sensors have visual capabilities. We study the benefit of having some mobile nodes able to move in the network field so coverage and connectivity constraints are satisfied while saving energy. We formulated this problem using integer linear programming. We performed several experiments using the CPLEX solver, to get some insight into the contribution of mobility in the context of video streaming. We mainly show that, even if mobility cost is much higher than communication, the latter tends to be predominant in the overall consumed energy as the video session duration increases. Thus, justifying the mobility cost.**

***Keywords*-Video; mobility; optimization; energy saving; topology control;**

I. INTRODUCTION

Recent advances in micro-electronics and wireless communications allow the emergence of wireless sensor networks (WSN) which are currently a hot research area [1]. Research effort in WSN mainly focused on scalar ones with large number of sensors able to sense environmental data (temperature, pressure, location of objects . . .), perform specific processing on them and collaborate to achieve applications' requirements. More recently, the availability of low-cost CMOS cameras and microphones, Wireless Multimedia Sensor Networks (WMSN) [2] gained more interest and research effort. In a WMSN, the scalar WSN is strengthened by introducing the ability of retrieving richer information content through image and video/audio sensors [3][4][5][6]. This can significantly enhance a wide range of applications like object detection, surveillance, recognition, localization, and tracking.

While sensors are small devices mostly running on batteries, the network should operate autonomously for long periods of time in most applications. This is why energy is an important issue in WSN and becomes an important research topic. Other issues such as coverage and connectivity in a WSN are not of less importance. When some areas of the field become uncovered, the mission of the entire network may be affected especially when the uncovered area is security critical. Connectivity, for its part, allows the different sensors to be able to reach each other as well as the sink (central controller or a gateway). Lack of connectivity could create unconnected sets in the network leading to some sensors to be unable to reach the sink.

Due to connectivity and coverage issues, nodes have to be placed carefully when deployed in the network field according to the target application. Good coverage and strong connectivity can be achieved through careful planning of node densities and fields of view so the network topology can be defined before startup [7][8]. However, a sensor network is dynamic by nature since sensors stop working when they exhaust their on-board energy supply. In a dynamic, hostile or hard-to-access environment, there is a need to be able to dynamically redeploy the network such that the application's requirements in terms of coverage and connectivity continue to be met while saving energy. This is what we call On-demand repositioning. In [9] for instance, sensor's ability to move is used to distribute them as evenly as possible in the region so coverage is achieved within the shortest time duration and with minimal overhead. A survey on node placement in WSN can be found in [10].

In this work, we consider a wireless video sensor network (WVSN) where a subset of the nodes are equipped with cameras. We explore the possibility of having locomotion capabilities at some sensors so they are able to move [11]. The aim of this work is to save the overall communication energy in a video session by allowing mobile nodes to move. Even if mobility cost may be higher than communication, moves can be justified by preserving coverage and connectivity in the network. Moreover, moves are generally performed only once, at the beginning of a session, so video applications characterized by their large amount of data can have a small mobility cost as the video duration increases.

Our approach is based on linear programming where we extended the work of [12] so both coverage and connectivity are considered. Additionally, our formulation fits the case of heterogeneous networks where video and scalar nodes coexist. Nodes may have different types of energy supplies (traditional batteries, solar or wind energy, etc.). Energy levels at nodes can be considered in the model so the network lifetime is increased. The paper is organized as follows. Section II summarizes the related work and Section III presents our network model with the different parameters and assumptions made in this work. Our problem formulation is presented in Section IV. Some numerical results are given in Section V. Finally, Section VI concludes and gives some future directions.

II. RELATED WORK

The closest work to ours is the one of Kadayif et al. [12]. An integer linear program is proposed to minimizes energy consumption with the presence of mobile nodes. Our work is an extended version of the linear program they proposed so both coverage and connectivity are satisfied in a heterogeneous WSN. In such a network, nodes may have different type of energy supplies and can have different sensing roles (video/scalar) and capabilities.

Assuming mobile sinks, [13] considers the case of multiple sink nodes positioning so the network lifetime is maximized. The problem is formulated using a linear programming model. Bredin et al. [14] studied the problem of placing nodes at the network setup time where K-Connectivity is achieved. K-Connectivity implies having K independent paths among every pair of nodes. They formulated the problem as an optimization model where the number of additional nodes required by the K-Connectivity is minimized.

One important concern in nodes placement is field coverage. In [15] the problem of maximum lifetime sensor deployment with coverage constraints is considered and an energy-efficient INformation Gathering (SPRING) algorithm is proposed. Cardel et al. [16] addressed the coverage problem in WSN with adjustable sensing range. Based on the assumption that longer sensing ranges consume more energy, the aim is to give each sensor a coverage radius so the overall consumed energy is minimized while assuring the entire field coverage.

Jaggi et al. [17] considered the problem of maximizing WSN lifetime through activating a minimal set of sensor nodes at any given time while both coverage and connectivity constraints are satisfied. A linear program is formulated and a distributed algorithm for practical use in sensor networks is developed. The WSN considered is composed of static sensors. In this work, however, we aim to find optimal moves of mobile sensors so overall energy in the network is minimized.

III. NETWORK MODEL

We consider a wireless sensor network of N sensor nodes among which some are video sensors located in strategic positions of a two-dimensional grid ($N_1 \times N_2$). All sensor nodes positions are assumed to be known and are given by a boolean matrix P:

$$p_{i,j} = \begin{cases} 1 & \text{if there is a sensor at position } (i,j) \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where $0 \leq i \leq N_1 - 1$ and $0 \leq j \leq N_2 - 1$. This assumes that we consider a WSN with location awareness. Even if only a few nodes have known positions by equipping them with GPS or placing them deterministically, the remainder of nodes positions can be computed from knowledge about communication links [18].

The network is heterogeneous since it contains video and scalar sensors with different energies and processing powers. $c_{i,j,i',j'}$ is the amount of energy needed to transmit a 1-bit message by a sensor located at (i,j) and to be received by the one located at (i',j') and can be estimated using [19]:

$$c_{i,j,i',j'} = \alpha_{i,j}(2 \times E_{elec} + \epsilon_{amp} \times d^2_{i,j,i',j'}) \tag{2}$$

where $d_{i,j,i',j'}$ is the distance between the two sensors located at (i,j) and (i',j') positions, E_{elec} is the dissipated energy by the radio to run the transmitter or the receiver circuitry and ϵ_{amp} is the required energy by the transmit amplifier. We introduced a parameter $\alpha_{i,j}$, $0 \leq \alpha_{i,j} \leq 1$, defined on a per sensor basis in order to individually consider the energy capacities of each sensor node. For instance, a mobile node with solar cells can be assigned an $\alpha_{i,j}$ close to 0 and a node with a low energy level at a given time (possibly with ubiquitous energy) can be assigned an $\alpha_{i,j}$ close to 1. Sensors in the network can have different energy capacities. They can operate on batteries or even use energy extracted from the environment, such as solar energy or vibrations. This does not mean that the energy could become infinite [20] since harvesting energy can not be possible all the time and could be insufficient to provide sensors mobility for instance.

In our network model, some nodes have locomotion capabilities [11] so they are able to move. Their positions can be known thanks to the mobility matrix $B(N_1 \times N_2)$:

$$b_{i,j} = \begin{cases} 1 & \text{if the sensor at location } (i,j) \text{ is mobile} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

To move from point (i,j) to (i',j') in the sensor field, the required energy is noted $m_{i,j,i',j'}$ and assumed to drain much more energy compared to communication cost per bit for the same distances, that is,

$$\forall i,j,i',j' : m_{i,j,i',j'}/c_{i,j,i',j'} = \rho > 1$$

In order to cover a given region or to avoid obstacles, a video sensor with locomotion facility may move mainly as a response to a sink request. However, a video sensor is assumed to stay at its location for the whole session when it begins capturing/transmitting images. Since there is a big amount of data to be transmitted in a video session and assuming that the transportation path is provided from the network layer, a relatively long schedule of messages send/receive can be obtained. We note by L, the number of messages to be transmitted. S and R are the transmission and reception matrices respectively before move where $s_{i,j,l} = 1$ if node at position (i, j) (before moving) sends the l^{th} message to another node and $r_{i,j,l} = 1$ if node at position (i, j) (before moving) receives the l^{th} message from another node. Each sensor node has a radio communication range r_c which is fixed and can not be varied during the video session.

Finally, we assume that each sensor node is able to sense within a disk of constant radius r_s and introduce the notion of *coverage degree*. Noted d_c, it is the number of redundant sensors that cover a given area. For video sensors, we aim to obtain a *soft* video coverage as opposed to *hard* coverage. a video sensor is able to move when there is another node to replace it even if it is not a video sensor and can not insure the same service degree (rich video capture). Nevertheless, it can contribute in covering the sensor field by sensing other physical (scalar) phenomenon such as movement detection. In a hard video coverage however, a video sensor moves only if there is another video sensor that it is able to replace it in the coverage of a given zone.

Notations and different parameters and variables used in this paper are listed in tables I and II.

TABLE I
NOTATIONS: PARAMETERS

N	number of sensor nodes.
$N_1 \times N_2$	sensor field dimensions.
P	matrix position: $p_{i,j} = 1$ if there is a node at (i, j).
$d_{i,j,i',j'}$	the distance between sensors located at (i, j) and (i', j').
B	mobility matrix: $b_{i,j} = 1$ if node at (i, j) is able to move.
k	number of bits per message.
L	number of messages to send.
S	transmission matrix before move, $s_{i,j,l} = 1$ if node at (i, j) (before moving) sends the l^{th} message, $1 \leq l \leq L$.
R	reception matrix before move: $r_{i,j,l} = 1$ if node at (i, j) (before moving) receives the l^{th} message, $1 \leq l \leq L$.
$\alpha_{i,j}$	weight given to node located at (i, j).
ρ	ratio of mobility to communication per bit cost: $\rho > 1$
C	communication energy matrix: $c_{i,j,i',j'}$ is the required energy to send a 1-bit message by a sensor located at (i, j) and to be received by the another one located at (i', j').
M	mobility energy matrix: $m_{i,j,i',j'}$ is the required energy to move from point (i, j) to (i', j').
r_c	communication radio range of the different sensors.
r_s	sensing (coverage) radius of each sensor.
d_c	required degree of coverage.

TABLE II
NOTATIONS: VARIABLES

$\dot{S}$	sending matrix after move: $\dot{s}_{i,j,l} = 1$ if node at (i, j) (after a move) sends the l^{th} message to any other node, ($1 \leq l \leq L$).
$\dot{R}$	reception matrix after move: $\dot{r}p_{i,j,l} = 1$ if node at (i, j) (after a move) receives the l^{th} message from any other node, ($1 \leq l \leq L$).
Δ	movement matrix: $\delta_{i,j,i',j'} = 1$ if node at (i, j) moves to optimal location (i', j').
SR	send/receive matrix after move: $sr_{i,j,i',j',l} = 1$ if (after move) node (i, j) takes part in the communication of message number l and sends it to a node located at (i', j'), $1 \leq l \leq L$.

IV. PROBLEM FORMULATION

In this section, we present our formulation to the problem of minimizing energy through mobility while preserving connectivity and coverage in our relatively heterogeneous network as described in the previous section. The problem can be formulated as an integer linear program (ILP) as follows:

Minimize

$$\begin{aligned} E &= \sum_{i=0}^{N_1-1} \sum_{j=0}^{N_2-1} \sum_{i'=0}^{N_1-1} \sum_{j'=0}^{N_2-1} \delta_{i,j,i',j'} \times m_{i,j,i',j'} \\ &+ \sum_{i=0}^{N_1-1} \sum_{j=0}^{N_2-1} \sum_{i'=0}^{N_1-1} \sum_{j'=0}^{N_2-1} \sum_{l=1}^{L} sr_{i,j,i',j',l} \times k \times c_{i,j,i',j'} \end{aligned} \quad (4)$$

subject to

$$\forall i \in 0..N_1 - 1, \forall j \in 0..N_2 - 1, \sum_{i'=0}^{N_1-1} \sum_{j'=0}^{N_2-1} \delta_{i,j,i',j'} = p_{i,j} \quad (5)$$

$$\forall i' \in 0..N_1 - 1, \forall j' \in 0..N_2 - 1, \sum_{i=0}^{N_1-1} \sum_{j=0}^{N_2-1} \delta_{i,j,i',j'} \leq 1 \quad (6)$$

$$\begin{aligned} &\forall i' \in 0..N_1 - 1, \forall j' \in 0..N_2 - 1, \forall l \in 1..L, \\ &\dot{r}_{i',j',l} = \sum_{i=0}^{N_1-1} \sum_{j=0}^{N_2-1} \delta_{i,j,i',j'} \times r_{i,j,l} \end{aligned} \quad (7)$$

$$\begin{aligned} &\forall i' \in 0..N_1 - 1, \forall j' \in 0..N_2 - 1, \forall l \in 1..L, \\ &\dot{s}_{i',j',l} = \sum_{i=0}^{N_1-1} \sum_{j=0}^{N_2-1} \delta_{i,j,i',j'} \times s_{i,j,l} \end{aligned} \quad (8)$$

$$\forall i \in 0..N_1-1, \forall j \in 0..N_2-1,$$
$$(p_{i,j}=1) \wedge (b_{i,j}=0) \Rightarrow \delta_{i,j,i,j}=1 \tag{9}$$

$$\forall i \in 0..N_1-1, \forall j \in 0..N_2-1, \forall l \in 1..L,$$
$$\sum_{i'=0}^{N_1-1}\sum_{j'=0}^{N_2-1} sr_{i,j,i',j',l} = \dot{s}_{i,j,l} \text{ with } d_{i,j,i',j'} \leq r_c \tag{10}$$

$$\forall i \in 0..N_1-1, \forall j \in 0..N_2-1, \forall l \in 1..L,$$
$$\sum_{i'=0}^{N_1-1}\sum_{j'=0}^{N_2-1} sr_{i',j',i,j,l} = \dot{r}_{i,j,l} \text{ with } d_{i,j,i',j'} \leq r_c \tag{11}$$

$$\forall i \in 0..N_1-1, \forall j \in 0..N_2-1,$$
$$\sum_{i''=0}^{N_1-1}\sum_{j''=0}^{N_2-1}\sum_{i'=0}^{N_1-1}\sum_{j'=0}^{N_2-1} \delta_{i'',j'',i',j'} \geq d_c \tag{12}$$

with $(i' \geq i - r_s) \wedge (i' \leq i + r_s) \wedge (j' \geq j - r_s) \wedge (j' \leq j + r_s) \wedge ((i \neq x) \vee (j \neq y))$ where (x, y) is the sink coordinates.

where E is the overall consumed energy including both communication and movement cost and k is the number of bits per transmitted packet. The different joined constraints are explained below:

(5): a sensor node can move to any non-occupied place and a move can only take place from an occupied position in the network [12].

(6): any move to a non-occupied position is performed by only one node ; otherwise this latter stays in its initial position [12].

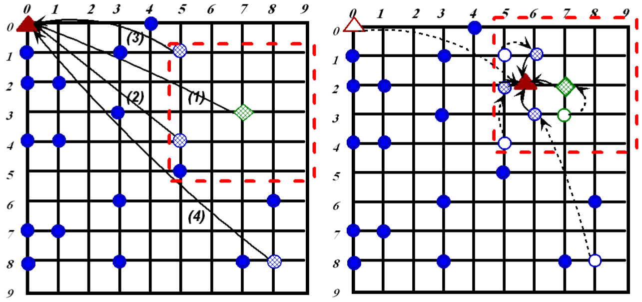
(7) and (8) give expressions of $\dot{S}$ and $\dot{R}$, the emission and reception matrices respectively after move.

(9): a non mobile node located at (i, j) (i.e. $b_{i,j} = 0$) stays at its initial position.

(10) and (11) are the connectivity constraints. A message m is sent by one node and received by only one node (unicast communication). Moreover two nodes can not communicate unless they are in each other radio range. The distance between the two nodes (after move) is less or equal to the communication radio range [12].

(12) is the coverage constraint. Each position in the field is covered by at least d_c nodes to satisfy the required coverage degree. A node moves to position (i', j') from another one (i'', j'') or it stays at its initial position i.e. $i' = i''$ and $j' = j''$. Position (i, j) must be in the zone covered by the sensor located at (i', j').

Illustrative Example: we consider a field 10×10 where 20 sensor nodes are deployed as depicted by Figure 1(a) with 4 sources (at $(3, 7)$, $(4, 5)$, $(1, 5)$ and $(8, 8)$ willing to transmit one message each to the sink. Taking $r_s = 2$, each sensor node covers in addition to its own position, the 24 neighboring ones: the node located at $(3, 7)$ covers the square area within the dotted boundary as shown in Figure 1. In this sensor field, positions $(0, 8)$ and $(0, 9)$ are not covered. We assume that the communication radio range $r_s = 4$ and that communications are only possible in single hop (there is no underlying routing protocol). All sources can not reach the sink in one hop.



(a) (b)

Figure 1. Illustrative Example: coverage and connectivity constraints

After applying our optimization program, all source nodes as well as the sink move as shown by dashed arrows in Figure 1(b). In this way, the required connectivity is satisfied so all the sources can achieve the sink in one hop. Additionally, the node located at $(3, 7)$ moves to position $(2, 7)$ so the problem of coverage is solved (points $(0, 8)$ and $(0, 9)$ become covered). The consumed energy is also reduced (for one message with 1024 bits, $401mJ$ is consumed instead of $403mJ$).

V. NUMERICAL RESULTS

In order to get some insight into the benefit of mobility to save energy in a WVSN, our formulated problem was coded using AMPL (A Mathematical Programming Language) [21] and solved using the CPLEX solver [22] on NEOS server [23].

We consider the case of a grid of dimension 10×10 where 40 nodes among which a given ratio is assumed to be mobile, are randomly placed. The sink is located at position $(0, 0)$ and depending on the experiment, one to seven sources are randomly chosen in the field. Paths from each source to the sink are generated using MFR (Most Forward within Radius) [24]. Each source is assumed to capture and transmit a 10-second video sequence (*Hall Monitor* [25]). Data packets are assumed to have 1024 bits of payload. Information about paths, amount of data to be transmitted and the size of packets allow us to generate the corresponding communication schedule required as an input of our ILP. For the energy model, we put in equation (2), $E_{elec} = 50nJ/bit$ and $\epsilon_{amp} = 0.1nJ/bit/m^2$.

Figure 2 plots the mobility to the overall consumed energy ratio as a function of video duration for different values of ρ. In this scenario, 20% nodes have locomotion facilities and only one source is transmitting. The overall

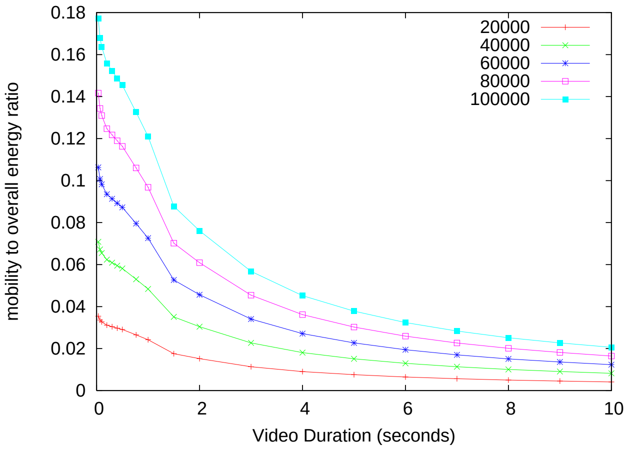


Figure 2. Mobility to overall energy ratio for different values of ρ. One source, 20% of nodes are mobile

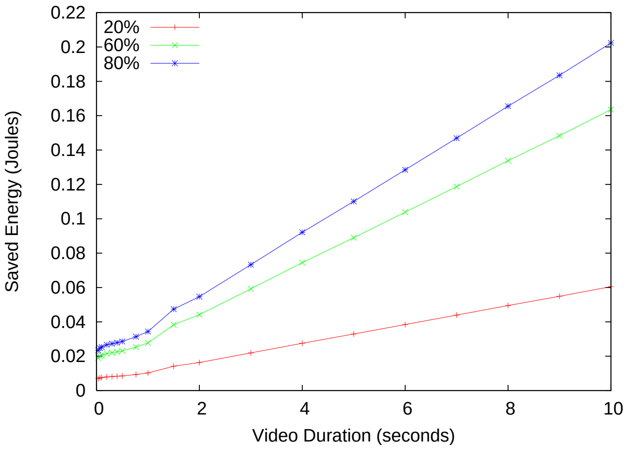


Figure 3. Saved energy as a function of video duration for different densities. $\rho = 1000$

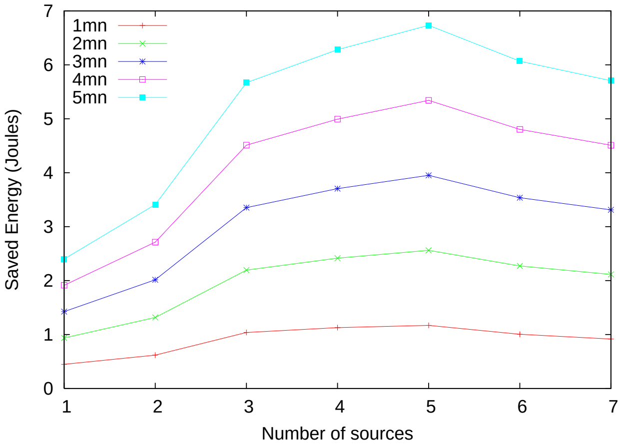


Figure 4. Saved energy as a function of the number of sources. $\rho = 1000$

consumed energy includes energy required by nodes to move to their optimal positions and the consumed energy due to transmitting/receiving data packets. We can see that if we increase ρ (till 100,000) so the mobility cost is much higher than the communication one and even for a small video duration (0.1 second for instance), mobility cost is at most about 18% of the overall consumed energy. It is also to notice that the share of mobility in overall energy consumption decreases with session duration. In fact, the longer the video session, the larger the amount of data to deliver. As a result, the communication cost increases compared the mobility one where moves are performed only once at the beginning of a session. Consequently, mobility is well justified in the context of WMSN characterized by their big amount of data.

In order to assess the gain obtained thanks to nodes mobility, we plot curves of Figure 3 showing the amount of energy (in Joules) saved when applying our optimization problem as a function of video duration for different densities of mobile nodes in the field. We can see that the amount of saved energy is higher for bigger number of mobile nodes. Furthermore, when the video session duration increases, saved energy is also increased. This confirms results obtained and observed in Figure 2. The amount of energy saved allows for augmenting the lifetime of the entire network.

Finally, we varied the number of transmitting sources from 1 to 7 and reported the amount of saved energy for different video streaming durations ranging from 1 to 5 minutes. Figure 4 plots this saved energy and shows, once again, that when increasing the video duration, the saved energy increases. When augmenting the number of sources until 5 sources, we save more energy. However when the number of sources reaches 6, we get less energy saving. This is due to the fact that when increasing the number of sources, some nodes are likely to belong simultaneously to more than one path.

VI. CONCLUSION AND FUTURE WORK

In this work, we formulated the problem of optimal node placement in a WVSN so energy consumption is minimized under coverage and connectivity constraints using ILP. We performed several experiments to get some insight into the benefit of having some mobile nodes in the network in the context of video streaming. We mainly showed that even if mobility cost is much higher than communication, the latter tends to be predominant in the overall consumed energy as the video session duration increases.

Our problem formulation is $O(N_1^2 \times N_2^2 \times L)$ and it is difficult to scale to large sensor networks. We suggest to execute it at the sink for relatively small networks (at the beginning of a video session) and off-line for larger ones for optimal initial deployment. This study allowed us to assess the contribution of mobility in saving energy. Our optimal solution can be used to derive and evaluate the effectiveness of localized and less complex algorithms based on heuristics. Actually, we are developing and evaluating distributed heuristics that approximate the optimal solution.

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