Joint Routing/Encoding-Power for Network Lifetime Maximization in WVSN

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***Abstract*—One of the most important issues, in Wireless video sensor networks (WVSNs), is to achieve an optimal video data encoding through an efficient resource allocation, while maximizing the overall network lifetime. However, the multimedia data is usually voluminous and delivering the compressed video data to the forwarding node poses an emergent demand, to simultaneously optimizing the video encoding and data routing performance in order to maximize the network lifetime. Based on unknown routing matrix, in this paper, we focus on the integration of routing into the analytic model proposed in our previous work. The simulation results show that our proposed solution consumes less than 0.03% of the total battery and ensures a prolongation of the network lifetime compared to the literature approaches.**

I. Introduction

Multimedia sensor networks have been widely regarded as a promising emerging application [14]. Thus, it can take advantages in many applications, such us the smart parking advice systems. According to the research firm *Navigant Research*, such systems are expected to grow rapidly (*i.e.*, up to one million on-street spaces by 2024) [5].

a) Motivations: WMSN should ensure the transmission of multimedia content, implying a high data rates and thus a high bandwidth requirement. To cope with this problem, a multimedia content can be compressed. However, more is the compression level of the multimedia data, less is the number of bits to transmit, and hence large is the distortion. On the other side, if we decrease the level of the compression, the data rate increases.

Thus, two main challenges should be considered: **a)** the encoding of the multimedia content with respect to the desired video quality at the sink and **b)** the reliable routing of the latter, since the choosing routing protocol can highly influence the network lifetime as shown in [13].

In fine, processing and delivery of multimedia content are not independent each other, and their interaction has a major impact on network lifetime.

b) Contributions: Several approaches have been proposed to ensure a power/rate tradeoff for network lifetime maximization. However, the routing issue has been left as a separate field (*i.e.*, the routing matrix was pre-defined and considered as an input), and none of the research works have actually considered an unknown routing matrix.

In this paper, we confine our interest to the integration of the routing issue, based on an unknown routing matrix, in the analytic model proposed in our previous work [12], that ensures a trade-off between the desirable visual quality and the available network's resources. Thus, the main contributions of this paper are:

- we prove that the problem of choosing a single routing protocol among N routing protocols is NP-complete,
- we propose a solution that optimally selects the forwarding nodes,
- we integrate the proposed solution into the analytic model proposed in [12],
- the resolution of the novel optimization problem is distributed and can handle the topology change, in contrast to the approaches proposed in the literature.

In the same context, we have proposed two other solutions that ensure a multipath routing with disjoint paths. The objective of the latter is to cope with both: the huge volume of data rates and link failure, and thus minimize the energy consumption of the intermediate nodes.

Furthermore, we conducted an in-depth simulation analysis of the proposed approaches over two main parameters: battery consumption, and network lifetime. The simulation results show that our proposed solution ensures the convergence of the system, consumes less than 0.03% of the total battery and ensures a prolongation of the network lifetime compared to the literature approaches.

II. Related Work

In this section we outline some of the proposed solution in the literature, which we broadly classify into two categories.

A. Power-Rate-Distortion approaches

Based on the Power-rate-Distortion (P-R-D) model [9], authors in [8] and [1] have proposed a decentralized solution. A mathematical model that considers the encoding powers, and the data distortion was developed. However, authors in [8] did not ensure the convergence for any initial configuration which may lead to no feasible solution.

Through another P-R-D model [17], authors in [7] have proposed a solution, in which the distortion model was considered in the objective function instead of considering it as a constraint. The formulated problem was solved using the

Proximal Point Algorithm. However, the inverse lifetime was computed in a centralized manner by the sink.

In a similar work, an appropriate trade-off between the minimum data distortion and maximum network lifetime was studied in [25], the formulated problem was solved in a distributed manner by primal decomposition. In [24], the authors have proposed a fully distributed solution that jointly optimizes the network coding based multi-path routing. However, both of the aforementioned solutions used the network coding during problem formulation, which requires the decoding and the encoding of the transmitted data at the intermediate nodes resulting in an additional power consumption.

Furthermore, all of the aforementioned approaches consider a pre-defined routing matrix.

B. Routing approaches

Authors in [20] have shown that the problem of routing messages, in a wireless sensor network to maximize network lifetime, is NP-hard. Starting from this point they propose a heuristic solution. While in [18] authors have focused on the problem of computing a flow that maximizes the lifetime of the network. However, in these papers the transmission rate on each link is fixed.

In order to meet: delay, packet-loss, energy and memory, authors in [6] have only addressed the routing scheme between the cluster heads and the sink. However, the control packets used in this solution can cause a high overhead. By exploiting the geographic locations and QoS performance of the neighbor nodes, authors in [21] have implemented a localized hop-by-hop routing. The problem was formulated using the multi-objective Lexicographic Optimization (LO) approach.

Nonetheless, the aforementioned routing protocols did not consider at all the encoding power at each node.

To the best of our knowledge, the only work that considered both: **a)** power-rate-distortion optimization, **b)** and routing discovery in WMSNs, was described in [15]. However, the optimization problem does not consider the reception power consumption. Additionally, the routing information are monitored by the sink (*i.e.*, in a **centralized** manner).

III. NP-COMPLETENESS PROOF

Including routing issue leads to the following problem: *how to select the optimal routing path among all available ones?*. The "brute-force" approach is to test all the existing routing paths and then selecting the optimal one with regard to the metric of prolonging the network lifetime. However, including all the existing routing protocols within the same optimization problem can induce a long activity duration implying more energy consumption and hence low network lifetime. To deal with this problem, it is necessary to find a routing protocols execution scheduling in such a way that execution time does not exceed a certain threshold.

Let $\mathcal{P}_1$ be the problem of executing N routing protocols on a single instance of network. Each routing protocol has an execution time denoted t_i. The main objective here is to find a scheduling that minimizes the positive number $L = \sum_{i=1}^{N} t_i$. This function tends to minimize the execution time of the routing protocols.

Theorem 1: The decision problem corresponding to the aforementioned problem is NP-complete.

Proof 1: Let N be the number of the routing protocols, with t_i the execution time of the routing protocol i, and a positive number T. Is there a scheduling such as $L \leq T$?

- Given a solution, it is clear that the time taken to verify whether it is valid or not is $O(N)$.
- The problem, denoted by $\mathcal{P}_2$, that we will reduce to $\mathcal{P}_1$ is *Knapsack problem*, which is defined as the following: A set $S = \{x_1, x_2, x_3, ..., x_n\}$ of n numbers and a positive number y such that: $\sum_{i=1}^{n} x_i = y$, is there $A \subset S$ such that: $\sum_{i=1}^{n} x_i \leq y$?

Let us now construct the polynomial reduction f of the Knapsack problem to our $\mathcal{P}_1$ problem, in such a way that an instance I of Knapsack problem, have a "yes" answer, if and only if $f(I)$, an instance of our problem, has a "yes" answer. Let I be an instance of Knapsack problem. An instance $f(I)$ of our problem can be formulated as the following:

- $N = n + 1$;
- $t_i = x_i$; $\sum_{i=1}^{N} t_i = \sum_{i=1}^{n} x_i + 1$;
- $t_{n+1} = 1$; $\sum_{i=1}^{n+1} t_i = y + 1$.

1) We will prove now that $L \leq T$ if and only if there is a set A such that $\sum_{i=1}^{n} x_i \leq y$. Suppose that the subset A such that $\sum_{i=1}^{n} x_i \leq y$ exists. Then, consider a scheduling that executes first the subset A in an arbitrary order, then the $n+1$ routing protocol, afterward the $S-A$ subset. The routing protocols in a subset A ends at y in the worst cases, since $\sum_{i=1}^{n} x_i \leq y$. The y routing protocol ends at $n+1$, and the rest of routing protocols ends at $\sum_{i=1}^{n} x_i + 1$. Thus all routing protocols were executed and thus $L \leq T$. We can conclude that if the Knapsack problem has a solution then $\mathcal{P}_1$ has also.
2) Suppose now that our problem $\mathcal{P}_1$ has a solution, thus we have to prove that the Knapsack problem has also a solution. In order to prove this implication, it is simpler to show its contraposition. In other words, suppose that the Knapsack problem does not have a solution which implies that there is no solution $A \subset S$ such that $\sum_{i=1}^{n} x_i \leq y$. Let A be the subset of the routing protocols executed before the $n+1$ routing protocol, which implies that the execution of A ends at: $E_A = \sum_{i=1}^{n} x_i > y$, by hypothesis. The $n+1$ routing protocol will be executed after and ends at $E_A + 1$, and thus $L > T$. Therefore, if the Knapsack problem has a negative response, then $\mathcal{P}_1$ also. The Knapsack problem is equivalent to our problem, and thus, we can conclude that $\mathcal{P}_1$ is NP-complete.

The NP-completeness of the studied problem led us to develop an heuristic, that takes into account especially the energy consumption since the main objective is to maximize the network lifetime.

IV. NETWORK MODEL

We consider a multimedia sensor network consisting of $\mathcal{N}$ multimedia sensors. These tiny devices have to find the optimal path consuming the minimum energy toward the sink. Thus, our network can be defined as follows:

- An oriented graph $G(\mathcal{V}, L)$, where $\mathcal{V} = \{h_1, \ldots, h_n\}$ is a set of video sensor nodes and $\mathcal{L} = \{l_{ij} \mid h_i, h_j \in \mathcal{V}\}$ is a set of oriented links.
- Two routing matrices a_{il}^{+} and a_{il}^{-} of size $\mathcal{N} * \mathcal{L}$ denote the matrices of outgoing links and incoming links, respectively. Their elements are defined as: a_{il}^{+} (resp. a_{il}^{-} matrix) equals to 1, if a given link l is an outgoing link from i (resp. an incoming link to) and 0 otherwise.
- Then, a general routing matrix a_{il} of size $\mathcal{N} * \mathcal{L}$ can be formulated as the following: $a_{il} = a_{il}^{+} - a_{il}^{-}$.

Note that, each node h generates a multimedia traffic of rate R_h. The generated traffic can be forwarded to the sink using intermediate nodes. Therefore, the flow conservation [8], denoted η_{hi}, at each node must be formulated as follows:

$$\eta_{hi} = \sum_{l \in \mathcal{L}} a_{il} x_{hl} = \begin{cases} R_h & \text{if } i \text{ is the source of the traffic} \\ -R_h & \text{if } i \text{ is the sink} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

where x_{hl} represents the data rate, originated from node h, at link l. Figure 1 shows an example of a directed WMSNs deployed in a region of 50mx50m.

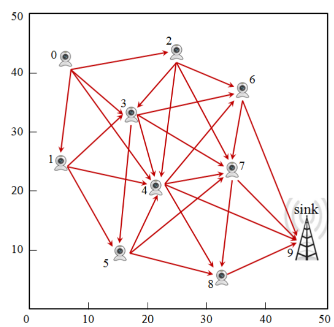

Fig. 1: Example of a WMSN.

V. Theoretical Background

A. Node Power Consumption Model

In this subsection, we formalize the different powers consumed by each node for video coding and data routing.

1) Video coding power consumption: the main objective here is to minimize the video distortion, while considering the encoding power level. Authors in [9] have proposed the following power-rate-distortion (P-R-D) model:

$$D_h = \sigma^2 e^{-\gamma . R_h . P_{sh}^{2/3}}, \tag{2}$$

where σ^2 is the average input variance, D_h is the encoding distortion, and γ is the encoding efficiency coefficient, R_h is the source rate and P_{sh} is the encoding power.

2) Transmission and reception power consumption: using the power Consumption model presented in [10], the data transmission and reception is formulated, respectively, as:

$$P_{ti} = \sum_{l \in \mathcal{L}} a_{il}^{+} * (\alpha + \beta d_l^{n_p}) * \sum_{h \in \mathcal{V}} x_{hl}, P_{ri} = c^r * \sum_{l \in \mathcal{L}} a_{il}^{-} * \sum_{h \in \mathcal{V}} x_{hl}, \tag{3}$$

where α and β are transmit electronics parameters, d_l is the distance between the transmitter and the receiver, n_p is the path-loss exponent, $\sum_{h \in \mathcal{V}} x_{hl}$ corresponds to the aggregate rate transmitted through link l, and c^r is the radio receiver energy consumption cost.

Then, the total power dissipation at node i can be formulated as:

$$P_i = P_{sh} + P_{ti} + P_{ri} \tag{4}$$

where $P_{sh} = 0$, if i is the sink node (*i.e.*, $i = \mathcal{N}$).

B. Network Power Consumption Model

In this paper, we consider critical applications where the exhaustion of energy of the first node will cause the failure of the whole network. Therefore, and by assuming that each node i has initial energy denoted B_i, the network lifetime T_{net} is defined as:

$$T_{net} = \min_{i \in \mathcal{N}} B_i / P_i. \tag{5}$$

C. Distributed Bellman Ford formulation

Based on the literature, the shortest path represents the minimum-energy routing topology if data is not aggregated [4]. For this reason, we have chosen to implement the distributed Bellman Ford algorithm, that has the following formulation [2]:

$$\mathcal{D}_i = \min_j [d_{ij} + \mathcal{D}_j], \tag{6}$$

where D_i is the shortest distance from node i to the destination and d_{ij} is the distance from node i to j (j is a one-hop neighbor of i, denoted by $Nbrs_i$). The include of the minimum in (6) means that the closest neighbor is selected.

D. Disjoint Paths

The benefits of disjoint path routing are significant for high data multimedia applications [22], it can be used to split the high data over the existing paths or to cope with the links' failure. However, the disjoint paths problem is known to be NP-complete in directed graphs, and can be defined as follows [11]:

Given a directed network $G = (\mathcal{N}, \mathcal{L})$ of $\mathcal{N}$ nodes and $\mathcal{L}$ weighted links. Find k paths $P_1, P_2, ..., P_k$ from $i \in \mathcal{N}$ to the sink node, such that the paths share minimal common links.

VI. Problem formulation

As previously mentioned, we aim to integrate the routing problem into the analytic model proposed in [12] that ensures a trade-off between the desirable visual quality at the sink and the available network's resources.

Before going further let us briefly recall the analytical model proposed in our previous work [12].

a) Literature review: The maximization of the network lifetime can be expressed by minimizing the inverse lifetime given in (5). Let $q = 1/T_{net}$ be the inverse lifetime of the network. However, using q in the problem formulation can not lead to solve this latter in a fully distributed manner.

To cope with this problem, an auxiliary variable, $q_i (\forall i \in N)$, has been introduced and maintained at each individual node i that should be followed by the following constraint: $\sum_{i \in N} a_{il} . q_i = 0$ $(\forall l \in \mathcal{L})$. Firstly, to ensure convexity of the objective function, minimizing q is equivalent to minimize $|N| q^2$, which is equivalent to: $\sum_{i \in N} q_i^2$, using the auxiliary variable q_i. On the other side, we have introduced the following exponents to the corresponding functions (*i.e.*, R_h, x_{hl} and P_{sh}): 2, 2, and 8/3 respectively, with some regular factors (namely δ_r, δ_x and δ_p), to ensure a strict convexity of the problem, more details can be found in [12]. Then, the problem can be formulated as follows:

$$\underset{(q,r,x,P_s)}{\text{minimize}} \sum_{i\in N} q_i^2 + \delta_x \sum_{h,l} x_{hl}^2 + \delta_r \sum_h R_h^2 + \delta_p \sum_h P_{sh}^{8/3}$$
$$\begin{aligned}\text{subject to} &\sum_{l\in\mathcal{L}} a_{il}x_{hl} = \eta_{hi} \quad \forall h\in\mathcal{V}\ \forall i\in\mathcal{N},\\ &\sigma^2 e^{-\gamma R_h P_{sh}^{2/3}} \le D_h \quad \forall h\in\mathcal{V},\\ &P_{sh}+P_{ti}+P_{ri} \le q_iB_i \quad \forall i\in\mathcal{N},\\ &\sum_{i\in\mathcal{N}} a_{il}q_i = 0 \quad \forall l\in\mathcal{L},\\ &x_{hl}\ge 0, R_h \ge 0, P_{sh} > 0.\end{aligned} \tag{7}$$

Let us now introduce the routing constraints to (7):

$$\underset{(q,r,x,P_s)}{\text{minimize}} \sum_{i\in N} q_i^2 + \delta_x \sum_{h,l} x_{hl}^2 + \delta_r \sum_h R_h^2 + \delta_p \sum_h P_{sh}^{8/3}$$
$$\begin{aligned}\text{subject to}\\ &1)\ \sum_{l\in\mathcal{L}} a_{il}x_{hl} = \eta_{hi} \quad \forall h\in\mathcal{V}\ \forall i\in\mathcal{N},\\ &2)\ \sigma^2 e^{-\gamma R_h P_{sh}^{2/3}} \le D_h \quad \forall h\in\mathcal{V},\\ &3)\ P_{sh}+P_{ti}+P_{ri} \le q_iB_i \quad \forall i\in\mathcal{N},\\ &4)\ \sum_{i\in\mathcal{N}} a_{il}q_i = 0 \quad \forall l\in\mathcal{L},\\ &5)\ \mathcal{D}_i = \min_j [d_{ij}+\mathcal{D}_j] \quad \forall i\in\mathcal{N}\ \forall j\in Nbrs_i\\ &6)\ a_{il}^+ = \{0,1\} \quad \forall i\in\mathcal{N}\ \forall l\in\mathcal{L},\\ &7)\ a_{il}^- = \{0,1\} \quad \forall i\in\mathcal{N}\ \forall l\in\mathcal{L},\\ &8)\ x_{hl}\ge 0, R_h\ge 0, P_{sh}>0.\end{aligned} \tag{8}$$

The first constraint reflects the flow conservation maintained at each node. The second constraint ensures the respect of the desired video quality. The third constraint presents the network lifetime with respect to the minimum node lifetime. The fourth constraint ensures the convergence of the system. The fifth constraint presents the shortest path from i to the destination going through the best neighbor. The sixth and seventh constraints present the indicators of the sender and the receiver, respectively. The rest of constraints ensures that all the variables remain positive.

VII. Distributed resolution

In this section we present the resolution of Problem (8). Due to the rich structure of this problem, a decomposition approach can be applied. Firstly, a primal decomposition with respect to the coupling variables (a_{il}^+, a_{il}^-) is required. Then, the dual problem can be formulated with respect to the coupling constraints (1), (2), (3) and (4). Finally, the original optimization problem (8) can be decomposed into two subproblems as follows:

$$\begin{aligned}&\textbf{P1:}\underset{(q,r,x,P_s)}{\min} \sum_{i\in N} q_i^2 + \delta_x \sum_{h,l} x_{hl}^{\alpha_x} + \delta_r \sum_h R_h^{\alpha_r} + \delta_p \sum_h P_{sh}^{\alpha_p}\\ &\text{subject to } (1),(2),(3),(4),(8).\\ &\textbf{P2:}\underset{(a_{il}^+,a_{il}^-)}{\min}\ U^*(a_{il}^+, a_{il}^-)\\ &\text{subject to } (5),(6),(7).\end{aligned} \tag{9}$$

Note that, the resolution of the **P1** problem is achieved if and only if the coupling variables (a_{il}^+, a_{il}^-) are fixed, since these two matrix are needed in the first, third and fourth constraints that are attached to the **P1** problem. However, a_{il}^+ and a_{il}^- are updated through **P2**, thus, $U^*(a_{il}^+, a_{il}^-)$ aims to minimize the number of paths and can be viewed as the optimal value for the resolution of **P1**.

A. P2 resolution

Next, we discuss how to update the coupling variable (a_{il}^+, a_{il}^-), based on the distributed Bellman Ford method. The path discovery steps are executed according to the following:

1) Neighboring discover: In this phase each video sensor node $i\in\mathcal{V}$ broadcasts a HELLO message in order to have the geometric coordination of its neighbors, and updates its neighboring table. At the end of this phase, each node i will construct its routing matrices (*i.e.*, a_{il}^+ and a_{il}^-), as well as the the routing matrices of the outgoing and incoming links of its one-hop neighbors $j \in Nbrs_i$ (*i.e.*, a_{jl}^+ and a_{jl}^-, respectively).

2) Path establishment: After the neighboring discover phase, each sensor node i initiates the Bellman Ford algorithm by sending $d_{ij}+\mathcal{D}_i$, where $\mathcal{D}_i = 0$ if i is the source and $\mathcal{D}_i = \infty$ otherwise. At the reception of a such message each node $j \in Nbrs_i$ checks if $\mathcal{D}_j > d_{ij}+\mathcal{D}_i$. If "yes" j proceeds as follows:

- Set $\mathcal{D}_j = d_{ij}+\mathcal{D}_i$,
- send the estimate $d_{jk}+\mathcal{D}_j$ to each sensor node $k \in Nbrs_j$,
- the operation continues until the sink node.

3) Path confirmation: At the end of the Path establishment phase, the sink node should maintain the shortest distance from each node to the latter as well as the latest node through which it has received this distance. Then, in the path confirmation phase the sink node sends a *pathConf* message through the inverse path.

4) Disjoint Path: In order to construct multi-paths, the sink node instead of maintaining only the shortest distance from each node to the latter, it maintains the two or three shortest distances paths. On the other hand, to ensure a disjoint paths and avoid to have paths with shared node, we limit each node to accept only one message from an intermediate node with a given sequence number. Thus, nodes that receives more than one message, maintains the one with the minimum cost and ignores the rest.

B. P1 resolution

Lagrangian Dual based methods [19] can be used to solve a **P1** problem. Thus, it can be written as below:

$$\begin{aligned}&L(R,x,P_s,q,u,v,\lambda,w) =\\ &\textstyle\sum_{i\in\mathcal{N}} q_i^2 + \delta_x \sum_{h,l} x_{hl}^{\alpha_x} + \delta_r \sum_h R_h^{\alpha_r} + \delta_p \sum_h P_{sh}^{\alpha_p} +\\ &\textstyle\sum_{h\in\mathcal{V}}\sum_{i\in\mathcal{N}} u_{hi}\left(\sum_{l\in\mathcal{L}} a_{il}.x_{hl} - \eta_{hi}\right)\\ &+\textstyle\sum_{h\in\mathcal{V}} v_h \left(\dfrac{\ln(\sigma^2/D_h)}{\gamma P_{sh}^{2/3}} - R_h\right)\\ &+\textstyle\sum_{i\in\mathcal{N}} \lambda_i \left(P_i - q_iB_i\right)\\ &+\textstyle\sum_{l\in\mathcal{L}} w_l \left(\sum_{i\in\mathcal{N}} a_{il}q_i\right)\end{aligned} \tag{10}$$

Notation	Description	Value
σ^2	Variance of video encoder	3500
γ	Encoding efficiency coefficient	55.54 $W^{3/2}Mb^{-1}s^{-1}$
B_i	Initial energy at each nodes	5.0 MJ
$\delta_x, \delta_r, \delta_p$	Regularization factors	0.2
ρ	step size parameter	0.15
D_h	Distortion of an encoding frame	100
α	Energy cost of the transmit electronics	0.5 JMb^{-1}
β	Coefficient term of the transmit amplifier	$1.3e^{-8}$ $JMb^{-1}m^{-4}$
n_p	Path loss exponent	4
c^r	Energy consumption cost of radio receiver	0.5 JMb^{-1}

TABLE I: Configuration of model parameters in a WVSN [8]

For any $h \in \mathcal{V}$, $i \in \mathcal{N}$, and $l \in \mathcal{L}$, and where u_i, v_h, $\lambda_{h,i}$, w_l are the Lagrange multipliers.

Following the subgradient method [3], the different Lagrange multipliers can be iteratively calculated, as follows:

$$\begin{aligned}
u_{hi}^{k+1} &= u_{hi}^k - \theta^k \left(\eta_{hi}^k - \textstyle\sum_{l\in\mathcal{L}} a_{il}.x_{hl}^k\right) \\
v_h^{k+1} &= \max\left\{0, v_h^k - \theta^k \left(R_h^k - \frac{\ln(\sigma^2/D_h)}{\gamma(P_{sh}^k)^{2/3}}\right)\right\} \\
\lambda_i^{k+1} &= \max\left\{0, \lambda_i^k - \theta^k \left(q_i^k B_i - P_{ti}^k - P_{ri}^k\right)\right\} \\
w_l^{k+1} &= w_l^k + \theta^k \textstyle\sum_{i\in\mathcal{N}} a_{il} q_i^k
\end{aligned} \tag{11}$$

Where θ^k represents the step size and given by: $\theta^k = \rho/k^{1/2}$, where $\rho > 0$ and $k > 0$.

All the functions to be minimized are differentiable, and thus, can be computed in one step as follows:

$$q_i^k = \max\left\{\epsilon, \frac{-(\sum_{l\in\mathcal{L}} a_{il}w_l - \lambda_i B_i)}{2}\right\}$$

$$P_{sh}^k = \max\left\{\epsilon, \left(\frac{-3\lambda_h^k + \sqrt{(3\lambda_h^k)^2 + 64\delta_p.v_h^k/\gamma.\ln(\sigma^2/D_h)}}{16\delta_p}\right)^{\frac{3}{5}}\right\}$$

$$R_h^k = \max\left\{0, \frac{{v_h}^k}{2\delta_r}\right\}$$

$$x_{h,l}^k = \max\left\{0, \frac{-\sum_{i\in\mathcal{N}}\left(\lambda_i^k(P_{ti}+P_{ri}) + u_{hi}^k a_{il}\right)}{2\delta_x}\right\}$$

for any $h \in \mathcal{V}$, $i \in \mathcal{N}$, and $l \in \mathcal{L}$.

VIII. Simulation Results

In this section, we evaluate our routing/power-rate trade-off approach,using the topology given in Figure 1, through simulation. The model was implemented using OMNET++ simulator [23], through MiXiM framework [16]. The values of the simulation parameters are presented in Table I.

A. Convergence of the proposed solution

The convergence of the auxiliary variable q_i to a common q, can be observed in figure 2, where we can see that after a 10^{-2} convergence threshold, the system is almost stable. Thus, in the following, we consider the system as completely stable when the maximum variation between the q_i is $T = 10^{-2}$.

B. Optimization cost

In this subsection we analyze the cost of the optimization steps on both energy and duration at each node.

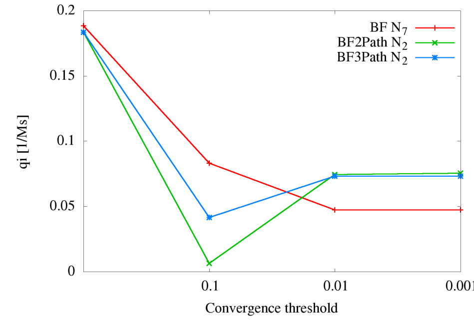

Fig. 2: Auxiliary variables

1) Energy cost: Figure 3 depicts the percentage of battery consumption of the most consumer sensor nodes, namely, node 7, node 2 and node 2 for one path, two paths and three paths, respectively. Thus, it concerns the total energy requirement for the optimization steps of both **P1** and **P2**. We can observe that the *two paths routing protocol* is the least energy applicant routing protocol, even less than the one path routing protocol. This observation can be explained by the fact the one path routing protocol requires much more iterations to converge and thus, it can get to the point of consuming more energy. Even though, we can conclude that the optimization steps including both **P1** and **P2** consume a negligible energy.

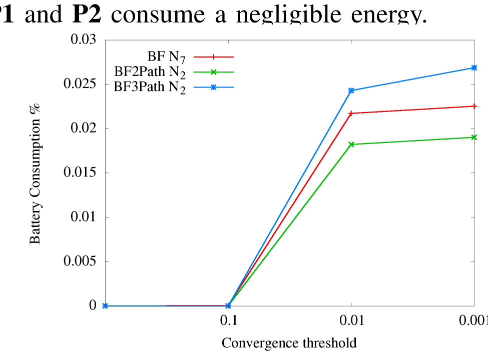

Fig. 3: battery consumption of optimization steps

2) Optimization steps duration: In this stage of evaluation, we present the need in term of duration (in minute) of the optimization steps to converge to the common variable q. Figure 4 presents the optimization steps duration including both: **P1** plus **P2**, for each threshold $T \leq 10^{-3}$ of the last converging nodes (namely, node 7, node 2 and node 2 for one path, two paths and three, respectively). It can be observed that more is the need to gain precision, more is the optimization duration.

C. Node lifetime improvement

The node lifetime can be calculated using the following formula: $T_i = B_i/P_i$.

Figure 5 shows the lowest improvement of nodes lifetime. We can see that with our optimization steps, and by including the routing constraints in the analytical model while imposing a trade-off between P_{sh} and R_h, we have increased the network lifetime by at least 7.72, 12.53 and 11.95 times considering the minimum nodes lifetime (*i.e.*, node 7, node 2

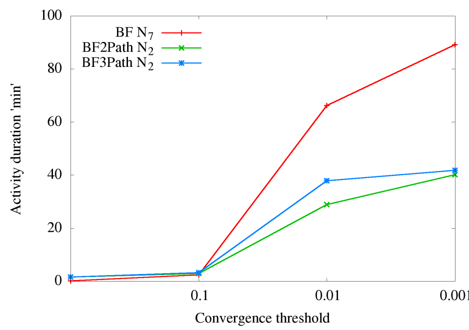

Fig. 4: Optimization duration

and node 2 for one path, two paths and three, respectively). We can also observe that *the two and three paths routing protocols* ensure the hightest network lifetime, since the multimedia content is distributed over the existing outgoing links. And thus, it demonstrates that the proposed design effectively increases the nodes lifetime and thus the network lifetime.

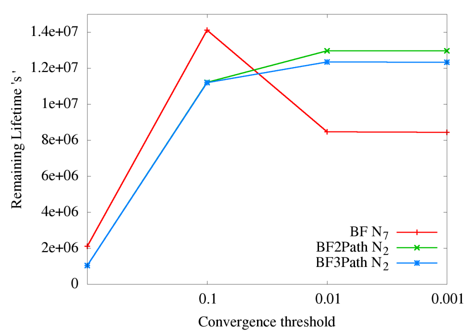

Fig. 5: Remaining lifetime after each convergence threshold

IX. Conclusion

In wireless video sensor networks, the video coding and multimedia content transport are the most energy consuming tasks, and hence impact the overall network lifetime. Thus, both of the processing and delivery of multimedia content should be considered, since their interaction has a major impact on network lifetime.

In this paper, based on our previous study on power/rate tradeoff for network lifetime maximization, we have proposed a novel analytical model for video coding and multimedia content delivery. The optimization problem was solved over a two level optimization. Simulation results approve the effectiveness of the proposed solution, given its minimal requirements in terms of computational power and energy consumption.

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