Joint Value of Information and Energy Aware Sleep Scheduling in Wireless Sensor Networks: A Linear Programming Approach

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***Abstract*—We consider wireless sensor networks that nodes offload data to a central collector node (sink) via wireless communication. Sensed data are associated with a value, decaying in time. In this scenario, we address the problem of finding the path of sensed data so that the Value of Information (VoI) of the data delivered to a sink is maximized while keeping energy usage as low as possible. Sleep scheduling is a widely used technique in MAC-layer to reduce unnecessary idle energy consumption in WSN; however, when it is carried out without paying attention to network-layer routing, it may adversely affect sensed data value of information. In this paper, we employ linear programming (LP) to establish a paradigm of cross-layer formulation to capture the interplay between scheduling and routing. We propose a bi-objective model of data value of information maximization and energy cost minimization in a WSN. Compared to existing work, our formulation is not only bi-objective which considers both data value of information and energy consumption jointly, but also is more realistic given that it explicitly accounts for different types of signal interference that may affect a wireless transmission.**

I. INTRODUCTION

Wireless sensor networks are communication networks composed of spatially distributed sensors. Mostly sensors are small, lightweight, equipped with a microcomputer, transducer, transceiver, and a limited power source. Potential applications of wireless sensor networks are extensive. The data gathered by them such as temperature, sound, pressure, etc. are used in many applications for scientific, safety, commercial, environmental, security and military needs. Underwater wireless networks (UWNS) are a good example to the importance of such networks. Recent advancement in underwater communications using WSN have brought substantial improvements to underwater monitoring applications in terms of feasibility and cost effectiveness. Nodes are deployed for large areas data sensing coverage and they are able to route sensed data directly or through mobile autonomous underwater vehicles (AUVs) to a data collection center [1]. Vessel Traffic Services (VTS) and Coastal Surveillance (CS) applications such as monitoring of water quality, habitat, oil industry deployments, pollution and climate changes, and telecommunications are just a few applications for these networks [2].

Wireless sensor networks use either acoustic or optical communicating over wireless links with or without using a fixed network infrastructure. Sensor nodes have a limited processing and storage capabilities. They suffer from transmission range limitations as well. Wireless sensor network routing protocols use multi-hop communications to ensure reliability under these conditions.

Sensors use three types of communications: clock-driven, event-driven or query-driven. No matter which type of communication is in use, the main issue has always been the energy consumption. Even though some wireless sensors have been recently developed to scavenge energy from the natural environment, such as solar, heat, or vibration, efficient energy usage is still a primary concern in underwater wireless sensor networks [3]. Moreover, even if sensors become alive again after refilling their energy, temporary failures such as temporally out-of-service of a key node can have negative effect on the quality of service provided as a whole [4]. Sleep scheduling is a key technique which can be employed in WSNs to not only reduce their energy consumption but also allow sensor nodes enough time to recharge the energy [5], it can save energy usage that is due to the idle listening state. Many routing algorithms make the unrealistic assumption that all nodes in WSN are always awake. They do not consider the deployment scenarios where sensor nodes have duty cycle to reduce energy consumption. In these cases, nodes can reduce their energy consumption by putting their radio module to sleep occasionally. For example, if they can predict active cycles of their receiving nodes, they can be awake only when their receiving nodes are awake to receive the data and sleep otherwise [6].

One of the other important factors in the realm of WNS regarding data gathering is value of information (VoI). VoI refers to the profit that the information brings to the user. For example, if an oil leak occurs, as soon as this event is reported to the oil rig company, they can start the repair process to prevent further damages and environmental hazards. Generally, value of data information is considered as the benefits obtained by having that data and responding correspondingly in a timely manner. Moreover, the sooner the company is informed, more cost savings can occur due to dimished need for environmental cleanup. Indeed, value of the data as perceived by the user is under the influence of time. In most situations, the VoI has the highest value at the moment an event is sensed and it typically decays in time [7]. Accordingly, minimizing latency is of great importance for data transmission in WSN. Minimizing data latency can be achieved through minimizing the number of hops between the source node which have sensed the data from the environment and the destination node. Preventing a signal interference between nodes is another approach due to the packet drops. Once a packet is dropped, it should be re-generated and re-transmitted which in turn prolongs the process of reporting information to the user. Finally, designing multihop routing protocols by foreseeing nodes' sleep scheduling can reduce data latency as well as energy consumption.

The rest of the paper is organized as follows. Section 2 defines the problem statement in detail. In Section 3, we present an ILP formulation for jointly sleep scheduling and routing in WSN. Section 4 presents the performance evaluation of the proposed model. Section 5 reviews related works while Section 6 concludes the paper.

II. PROBLEM DEFINITION

We consider a sensor network consists of a set of S (sensor) nodes $s_1, ..., s_N$ and a central sink node which perform sensing (e.g., taking videos). Nodes are static and uniformly dispersed in the environment. They are assumed to know their locations either through manual deployment or by leveraging localization techniques.

Let $G = (S, E) \cup Sink$ be an arbitrary graph which represents the desired network. $E = e_{ij}$ is the set of links each connecting a pair of nodes. Nodes i and j are neighbors to each other if $e_{ij} = 1$. We assume that the links between neighboring node are reliable. Nodes perform surveillance operations for a given time T. For the sleep scheduling, T is divided into smaller time slots. Node s_i store the sensed data chunk d_{it} at time slot t, $0 \leq t < T$. The data $d_{i\tau}$ observed by a node S_i at a given time τ has a value of information $V_{d_{i\tau}}(t)$, at time $t \geq \tau$ with highest at τ. The function $V_{d_{i\tau}}(t)$ is non-increasing in t. The VoI of a data chunk is the highest, when its value is $V_{d_{i\tau}}(\tau)$; this base value varies depending on the importance of the information captured in the data chunk.

Throughout the time of network operations, a data collection point (a sink) periodically collects the sensed information. Finding the path that yields the maximum VoI is done by first defining the VoI of the data chunks collected from a node S_i when the data travels a given path P, and then choosing the path P that maximizes the VoI of data chunks when it reaches the sink.

The value of information of the data sensed by node S_i and delivered to the sink traveling path P during time T is given by summing the values of information collected by s_i when each packet is delivered to the sink. More precisely:

$$V(s_i, P) = \sum_{t=1}^{T} V_{d_{it}}(h_{it}) \tag{1}$$

where h_{it} is the time that the packet sensed by node s_i at time t, is delivered to the sink by passing path P.

Path and sleep scheduling problem regarding value of information as the only concern is stated as follow:

Problem 1: *Given $|S|$ nodes and their locations, and given the value of information of the sensed data, determine the paths and sleep schedule of each node so that the overall value of information at sink is maximized*:

$$\underset{p_i, h_{it}}{\arg\max}\, PTT = \sum_{i=1}^{N} V(s_i, P_i) \tag{2}$$

We assume any collected but undelivered packets would be worth nothing. Efficient energy consumption is another major concern in the network. Indeed, between those paths which result in the highest value of information, the ones which cause less energy consumption in network are preferred.

We assume the energy consumed by node s_i, represented as e_i, during T is proportional to the number of time slots which is not sleeping, which we refer to active slots. In an active time slot, a node is in either sensing, receiving or sending state. Without lose of generality, e_i is given by summing the number of active slots of node s_i and the overall energy in the network is given by summing the energy consumed by all nodes alive in network.

Path and sleep scheduling problem regarding energy consumption as the only concern, we state as follow:

Problem 2: *Given $|S|$ nodes and their locations, and given the sensed data, determine the paths and sleep schedule of each node so that the overall energy consumed by network nodes is minimized*:

$$\underset{p_i, t_i}{\arg\min}\, PTE = \sum_{i=1}^{N} e_i \tag{3}$$

III. A MATHEMATICAL MODEL FOR JOINTLY FINDING PATH AND SLEEP SCHEDULING

We model the problem by the following Integer Linear Programming formulation.

Definitions

We use the following definitions to describe our formulation.

- neighbors: node i and node j are neighbors if they can communicate directly; in other words, they are in the wireless range of each other
- One-step neighbor: two nodes are one-step neighbor if they can communicate with each other via at least one third node.

Variables

- $l_{i,j}^t(s)$: Binary variable taking the value 1 if a data chunk sensed by node S is traveling on the link between node i to j at time t; 0 otherwise.
- $b_i^t(s)$: Binary variable taking the value 1 if node i received a packet from node s and have it in its buffer to send it in time $\tau > t$; 0 otherwise.
- $e_{i,t}$: Binary variable taking the value 1 if node i is wakeful at time slot t; 0 otherwise.

Parameters

- T is the length of network operations, divided into time units numbered from 1 to T. When a node optically transmits a data chunk to another node or sink at time $t \leq T$ both receiver and sender are awake.
- S is the set of source nodes (and their locations).
- V is the set of nodes (and their locations). We use the letters i and j to indicate generic nodes (their location).
- $l_{i,p}$ is the latency that data $d_{i,p}$ experience once it reaches the sink.
- N_i is the set of all node i's neighbors.
- $\Gamma = \{(i,j,k,p) | j \in N_i \wedge k \in N_j \wedge p \in N_k \wedge (i \neq j \neq k \neq p)\}$ is the set of all legal quad (i,j,k,p) where each node is the neighbor of the previous one and they are different nodes.
- NumberOfNeighbors(i) is a function that given a node returns the number of nodes in its neighborhood.
- A is the set of neighbor nodes. $(i,j) \in A$ if node i and node j are neighbors
- NumberOfPackets(i) is a function that given a node returns the number of packets it should send during T.

Problem assumptions

- Each sensor node is equipped with omni-directional half-duplex antennas
- Transmission power and data rate are constant.
- Source nodes periodically collect data from the environment and send them to the sink via other nodes using multi-hop paths
- Each source node has a fixed frequency period which can vary from periods of other source nodes
- Neighboring nodes are synchronized
- Frame length is determined according to the characteristics of the sensor network.

ILP formulation. The actual value of each data chunk can varies by application. However, as we mentioned before, value of the data as perceived by the user typically decays in time. Therefore, we can focus the time each data chunk it reaches the destination. The more late each data chunk reach sink the more decay will occur and the less VoI. We also assume that all nodes has the periodicity of data generation for each node is equal to T and therefore each node's data chunk does not have overlap in terms of VoI. Accordingly, we consider the objective function as follows instead of equation 2:

$$\arg\min_{p_i, h_{i,t}} PTT = \sum_{t=1}^{T} \sum_{i=1}^{N} h_{i,t} \tag{4}$$

The ideal model we are looking for should select the path with less energy consumption in network once there are multiple paths which result in highest value of information. So we define model as follow:

Problem 3: *Given $|S|$ nodes and their locations, determine the paths and sleep schedule of each node so that the overall latency as well as energy consumed by network nodes is minimized [8].*

Assuming E is the total energy consumed by nodes during T and L is the total latency experienced node's data during T which is given by summing the latency experienced by all node's data, the model jointly minimizing E and L is preferred. Accordingly, we combine the two previous objective functions as can be seen below:

$$\text{minimize } \epsilon = \frac{E - E^\star}{E^\star} + \frac{L - L^\star}{L^\star} \tag{5}$$

where $E^\star$ and $L^\star$ are the optimal energy consumption and latency when we use problem description 1 and 2 respectively.

The objective function maximizes the value of information by minimizing the latency that data sensed by network nodes experience when they reach sink. It also jointly minimizes the energy consumed by nodes for sensing data from environment and routing it or data received from their neighbors to sink by time T. This model can be used as it considers summation of both objectives and also scale each to avoid dominant of one objective.

The model is dependent on models 4 and 3 to obtain $E^\star$ and $L^\star$. Once we gained them, they will be considered as two constants. The model can be written as follows:

$$\text{minimize} \quad \epsilon = \frac{\sum_{(s_i,t)\in W} e_{i,t} - E^\star}{E^\star} + \frac{\sum_{d_{i,p}\in D} l_{i,p} - L^\star}{L^\star}$$

subject to the following constraints.

$$b_i^0(s) + \sum_{j \in N_i} l_{i,j}^t(s) = \text{NumberOfPackets()}^1 \forall s \in S \tag{6}$$

$$b_i^t(s) + \sum_{j \in N_i} l_{i,j}^{t+1}(s) = b_i^{t-1}(s) + \sum_{j \in N_i} l_{j,i}^t(s), \forall s \in S \wedge \forall t \geq 0 \tag{7}$$

$$\sum_{s \in S} \Big(\sum_{j \in N_i} l_{i,j}^t(s) + \sum_{j \in N_i} l_{j,i}^t(s) \Big) \leq 1, \forall i \in V \wedge \forall t \geq 0 \tag{8}$$

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[1] We assume that a data chunk can be transferred through optical and wireless communication well within one unit of time. In this case, NumberOfPackets() will return the fraction of time unit needed to transfer the data chunk they are applied to

$$\text{NumberOfNeighbors(j)} * \sum_{s\in S} l^t_{i,j}(s) + \sum_{(i,j,p,k)\in\Gamma(i)} \sum_{s\in S} l^t_{k,p}(s) \leq \text{NumberOfNeighbors(j)} \quad \forall i \in s, t \geq 0 \qquad (9)$$

$$\text{NumberOfNeighbors(k)} * \sum_{j\in N_i} \sum_{s\in S} l^t_{i,j}(s) + \sum_{(i,j,k)\in\Lambda(i)} \sum_{s\in S} l^t_{k,j}(s) \leq \text{NumberOfNeighbors(k)} \quad \forall i \in s, t \geq 0 \qquad (10)$$

The first constraint makes sure that the data buffered or ready to be sent in next time slot for each node is equal to the number of packets that node should send during T. Since the network life can be divided into multiple T period, without loss of generality, we solve path finding and time scheduling problem for one period, therefore it can be assumed that all packets which should be sent by each node to the sink by T is ready to be sent or to be buffered at the beginning of each period. Since, at the beginning of the period T, nodes have not received any data from other nodes yet, its constraint is different with the other time slots and is written in the form of equation 6.

Constraint 7 guarantees that the nodes which have received the packets send them out and the connectivity is kept until the sink receive packets. We should mention that, after the first time slot in which some of the nodes have sent their sensed data, relay nodes may have received one or more packets from other nodes. Accordingly they might have some packets in addition to those sensed by themselves. They can either buffer the available data to send them later or forward them immediately. Indeed, constraint 7 burden exchanging packets of every source node s, through intermediate nodes and in nonzero intervals. It is applied to all nodes except the sink at which every flow ends.

Constraints 8-10 take care of the interference. The performance of a WSN is highly affected by the interference which can result in packet drops and re-transmission in turn increasing node energy consumption implicitly. Therefore, once a node communicate with one of its neighbors, all other nodes in its radio coverage area should keep silent. Additionally, the half duplex antennas used in wireless sensor nodes cannot send and receive data simultaneously.

Given equation 8, if either one of the incoming or outgoing links of a node i is activated, its other links should be inactive. There are other types of interference that may affect a wireless transmission. Fig.1 depicts a possible interference scenario in underwater wireless sensor networks in which nodes are spatially distributed to sense the water-related properties such as pressure, temperature and quality. While node 4 is sending a packet to node 5, node 6 should keep silent. Otherwise, its transmitted packet will destroy those of node 4 at node 5.

More generally, when node i sends data to a node j, node k which is a one-hop neighbor of node j should be inactive. In other words, no packet should be forwarded neither along the link between k and j nor on the links between k and other nodes p which are one-hop neighbors of node k (Figure 1,). Inequality 9-10 satisfy this constraints.

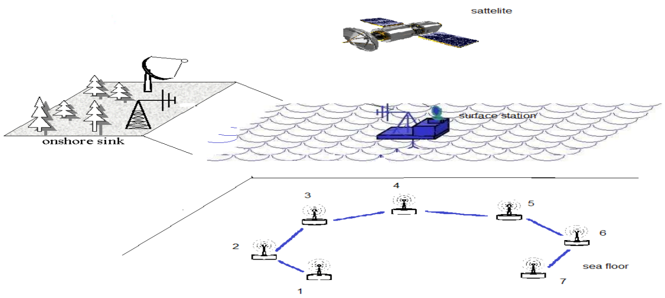

Fig. 1. Under Water Acoustic Communication

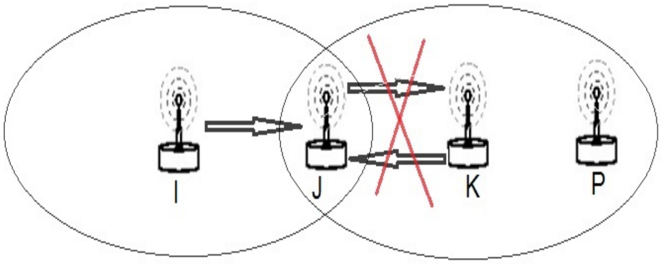

Fig. 2. Simple WSN to show possible interference

Inspecting again the setup in Figure 1, yet another interference scenario is plausible: while node 4 sends data to node 5, node 3, overhearing packets of node 4, cannot receive packets from its other neighbors, (e.g., node 2.) However, node 2 can still send its data to node 1. Therefore, we need a constraint that, while inhibiting the transmission of packets to node 3, allows node 2 to send data to node 1.

IV. PERFORMANCE EVALUATION

We analyze the proposed model in this paper through simulation and present the results of the performance evaluation. In this section, first we introduce the simulation scenarios and their parameters. We compare the proposed model with MLSR [9]. Our results show the total VoI which can be implicitly concluded by total latency as well as energy efficiency.

A. *Simulation environment*

The results for the proposed model in this paper have been obtained by solving the ILP model defined in Section II using AIMMS [10] running on Windows-based 64-bit core-i5 computer with 16GB of RAM. The various runs took from several hours to produce the optimal solutions. Simulations have been conducted for a sensing area of 2000m x 2000m and the number of nodes has been varied from 40 to 80 for different experiments. The sensor nodes are assumed to be positioned on a grid and the sink is located almost at the center of the area. In each scenario, 20% of the nodes are sources. Each node sends event packets to its neighbors over the acoustic data channel. Power consumption for data exchange is set to be the number of time-slots needed to receive and send the data. Delays of event packet notifications to the sink are computed and summed up for the final computation of the VoI of the collected data chunks. We consider a scenario where the nodes are used for monitoring (e.g., temperature or oil leakage monitoring) and sensed data can be forwardded to other nodes into one time slot. The actual VoI for each data chunk is dependent on the sensing node and its distance from the sink. The sooner it reaches the sink the more value it has unless the time that it reaches the sink does not exceed a deadline which depends on the application. After a given deadline T, the VoI of a data chunk goes to 0.

B. Optimal model vs. MLSR

We evaluate our model with respect to the end-to-end delay and the energy consumption of the nodes. Fig. 3 shows the total latency of data chunks delivered in networks with increasing number of nodes. The performance of both MLSR and our model are the same. They both found the minimum possible path for each packet having the number of sensed packets by each node.

Results concerning energy consumption are represented in Fig. 3 and Fig. 5. As expected, our model outperforms MLSR. This is because when there are several schedules with equal total energy consumption, our model chooses the one with minimum delay. We also compared it with our model with delay as the objective function, labeled as MLS-E and also with energy as the objective function, labeled as MLS-D.

We have repeated the experiments for a wireless sensor network with 80 nodes and vary the percentage of the source nodes. Indeed, this set of experiments concerns the case when some of the nodes have sensed the environment and the others would only relay the packets. As shown in Fig. 4 and Fig. 6, the delay experienced by our model is equal to MLSR in all cases. The equality happens as we assumed that the number of time slots in which each node is awake is proportional to the amount of energy which it consumes. The results can be more realistic if we consider the amount of energy each node needs once changes the state either for waking up or going to sleep mode. It shows the total latency of data chunks delivered in networks with increasing the percentages of source nodes. The results are essentially consistent with those obtained from our initial set of experiments.

V. RELATED WORK

Turgut and Bölöni [11],[12] define *pragmatic VoI* as value the data brings to the network operator which is dependent on not only the quantity and accuracy of information but also on when and how the customers will use the information given from the data as well providing heuristic approaches for transmission scheduling in sensor networks with multiple mobile sinks [13]. In a UWSN, Bölöni [14] use the VoI to schedule direct acoustic transmission of digests of large data chunks and optical transfer of the whole chunks to the sink and an AUV respectively [1]. This paper considers the decay of the VoI in time, mainly focuses on maximizing VoI through acoustic and optical transmissions scheduling.

Some of the existing work employed cross layer approach to consider latency in routing layer and energy efficiency using sleep scheduling in WSN MAC layer. To delineate sleep scheduling and routing using cross layer manner, three approaches can be followed. In the first approach, after routing is determined, sleep scheduling would be set accordingly. In the second approach, sleep scheduling of nodes is determined and routing would be scheduled accordingly. Finally, the third approach considers nodes sleep scheduling and routing simultaneously and delineates them jointly. Madan and Lall [15] and Bulut and Korpeoglu [16] use the first approach. Bulut and Korpeoglu [16] convert sleep scheduling problem to the graph coloring problem and determine it based on the network topology and flow routes. Therefore, sleep scheduling is affected by routing algorithm would have distance with its optimal solution. Goldsmith and Wicker [17] use linear programming and according to the third approach, determine node sleep scheduling and routing to maximize the lifetime of node with the lowest life expectancy. The solution proposed in recent works

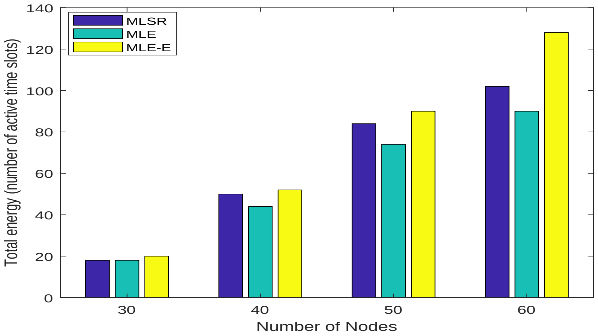

Fig. 3. Total energy consumption vs. number of nodes

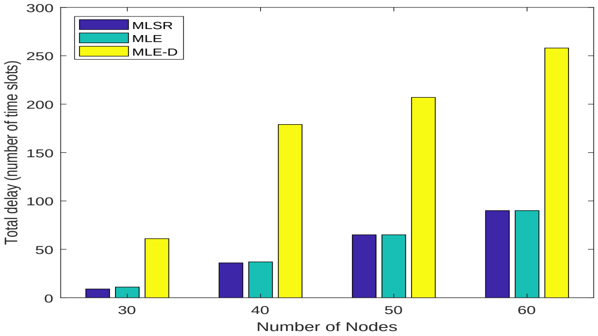

Fig. 4. Total delay vs. number of nodes

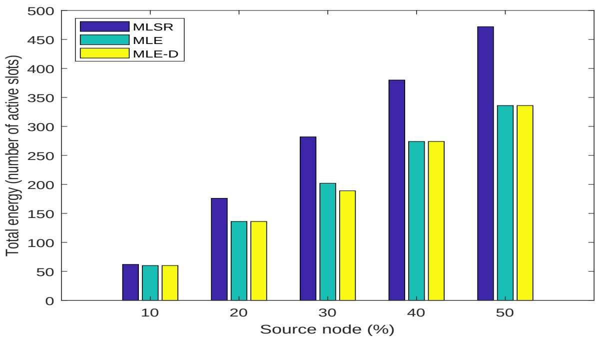

Fig. 5. Total energy consumption vs. source percentage

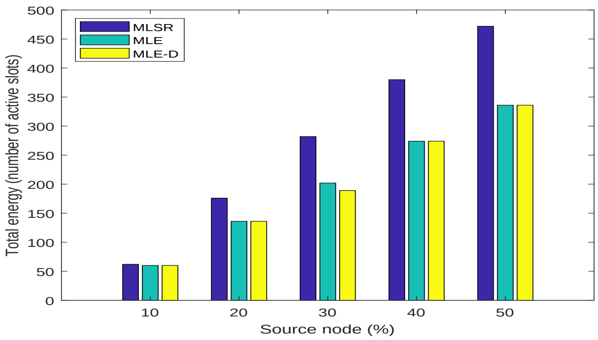

Fig. 6. Total delay vs. source percentage

is for competition based protocols. Lu and Krishnamachari [9] divide sensor nodes into different areas based on their distance from the sink. The sleeping schedule of each node is then determined according to the area in which it is located. Liu et al. [18] consider sleeping nodes for small-scale networks by packet flooding.

In this paper, we use the third approach by leveraging the linear programming. Our proposed model jointly determines the node sleep scheduling and VoI of data in a wireless sensor network. The proposed model minimizes the energy consumption of the nodes and the delay of flows to maximize data VoI simultaneously.

VI. CONCLUSION

We presented a mathematical ILP model in which jointly considers energy efficiency and value of information (VoI) in a WSN. The VoI is assumed to decay with time. The aim is to find traveling paths for the data generated by nodes that maximize the value of information of the data delivered to the sink while minimizing total energy consumption as much as possible. The model essentially minimizes latency to implicitly maximize the value of information while preventing any signal interference. Our model considers realistic and desirable network sizes, data communication rates, and distances. The experimental results show that our model outperforms MLSR in terms of energy while both achieve the same amount of delay in all scenarios. The proposed model can serve as a benchmark to evaluate any heuristics targeting the same problem.

For future work, we will consider more realistic energy consumption as well as transition energy which each node consumes to change its state either from wakeful state to sleeping state or vice versa. While our work can be used as a benchmark for evaluation of heuristics algorithms targeting the same problem, valuable contributions can be made in designing and developing of a good heuristic to approximate the model.

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