Ubiquitous Sensor Network Management: The Least Interference Beaconing Model

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***Abstract*—We revisit the issue of network management in the emerging ubiquitous sensor networks (USNs) that form the Internet-of-the-Things (IoT) to evaluate the impact of traffic engineering on energy efficiency and assess if routing simplicity translates into scalability. We formulate the USN management problem as a zero-one linear optimization problem minimizing the number of traffic flows transiting by a node: the node's traffic flow interference with other nodes. We propose the least interference beaconing algorithm (LIBA) as an algorithmic solution to the problem and the least interference beaconing protocol (LIBP) as its protocol implementation. LIBP extends the beaconing process widely used by collection protocols with load balancing to improve the USN energy efficiency. Our experimental results reveal the relative efficiency of the resulting traffic engineering scheme compared to state of the art protocols. These results show up to 30% reduction in power consumption compared to TinyOS beaconing, and up to 40% compared to collection tree protocol while sustaining better performance in terms of scalability.**

I. Introduction

Ubiquitous sensor networking [1] is emerging as a new form of modern communication where sensors are combined with RFID devices and many other different processing devices to interact pervasively with the physical world using a variety of applications to provide various services to different users. As currently deployed in ubiquitous sensor networks (USNs), the sensor nodes are operated with low-power batteries to achieve acoustic, chemical, biological, physiological and other types of sensing activities. USNs use a multi-hop model enabling nodes to route their readings via their neighbour nodes, thus circumventing the high power requirements for long-distance communication.

Future USN applications are predicting the deployment of sensor devices in thousands of computing elements into multi-technology and multi-protocol platforms, where access to the information will be available not only *any time* and *anywhere*, but also using *anything* in a first-mile of the Internet referred to as the *"Internet-of-the-Things" (IoT)* [2]. The management of such a large-scale and heterogeneous network could benefit from some of the traditional IP-based network management techniques, which can be re-designed to achieve efficient routing of the sensor network traffic. However, while USNs that form the IoT are based on a network management model where sensing, processing and routing can be performed into the core of the network, traditional IP-based networks use an intelligent edge to process the information which is routed into a dumb core capable of only forwarding this information. Furthermore, USNs are built around lightweight devices with low processing capabilities, small memory footprints and limited communication capabilities constraining these networks to be operated using simple routing mechanisms and lightweight routing protocols. This differs from the more complex management systems and protocols deployed by traditional IP-based networks. While many routing algorithms have been proposed for wireless sensor networks management, collection and MANET protocols have recently raised the interest of the IETF [3] as suitable candidates to be redesigned for USN management. However, many recent proposals for such redesign are built upon models that discount the simplicity and efficiency principles that should guide USN designs.

A. Related work

Collection protocols such as collection tree protocol (CTP) [4] and TinyOS beaconing (TOB) [5] are designed around a collection tree structure where minimum-cost trees for nodes that advertise themselves as tree roots are built and maintained to forward the sensor readings from nodes to the base-station. Building upon periodic broadcasting/advertisement of control beacons at fixed interval and an "address-free" networking paradigm, collection protocols forward the sensor readings to the minimum cost base station when the sensor network has multiple base stations, discounting its address. *Collection tree* and *adaptive beaconing* are two features implemented in both the CTP and the RPL protocol using the trickle algorithm [6] to enable data traffic to quickly discover and fix routing inconsistencies. As implemented in the trickle algorithm, these two features are used to reduce route repair latency and beacon messages. It has been credited to the *TinyOS Beaconing (TOB)* protocol the attractive feature of node simplicity and the advantage of not having to maintain large routing tables or other complicated data structures. In TOB, each node needs to keep track of only its parent node, which is the next hop for the traffic carried by that node in the path to the base station. When combined with a TDMA-like MAC layer scheduling scheme, the TOB beaconing process can keep the node's radio off most of the time to achieve power savings. However, this attractive feature has to be weighted

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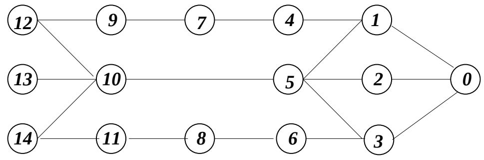
against some of the inefficiencies of the beaconing protocol, such as 1) the lack of resilience to node failures, leading to an entire sub-tree being cut off from the base-station during the current epoch when a parent node fails, 2) the tree-like m-to-1 sensor readings dissemination model leading to uneven power consumption across network nodes as the nodes surrounding the base-station tasked to forward packets from all the nodes in their sub-tree consume a lot of power, whereas the leaf nodes in the spanning tree, which do not perform any forwarding, consume least power.

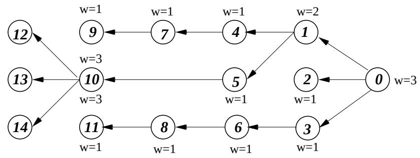
One of the recent concerns of the IETF 6LoWPAN Working Group (WG) has been to find how to apply MANET routing protocols such as Ad-hoc On-demand Distance Vector routing (AODV) [7] for low-power wireless personal area networks (LoWPANs) which comprise devices that conform to IEEE 802.15.4 standard. The efforts made to reach such an objective have led to an AODV adaptation for LoWPANs refereed to as TinyAODV [8] and AODV protocol standardization for LoWPANs as an IETF draft under the LOAD [9] denomination. In addition to adapting MANET protocols, node mobility has also been largely considered in the literature when dealing with data collection. Mobile sink techniques such as surveyed in [10] have been proposed in the literature for data collection in wireless sensor networks. They target the construction of a load-balanced tree structure in terms of number of children but they are still absent in most state-of-the art protocols. Furthermore, node mobility is not necessarily a natural fit for many IoT deployment scenarios.

B. Contributions and outline

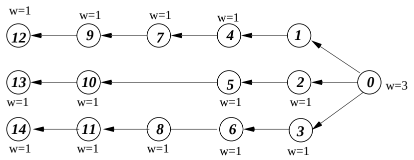
Both CTP and TOB are collection protocols which use a beaconing process that may lead to uneven power consumption. This paper tackles the issue of energy efficiency for USNs to assess the relevance of using routing simplicity to achieve scalability and evaluate the impact of traffic engineering on energy efficiency. The main contribution of this paper is to propose the least interference beaconing algorithm (LIBA) as an algorithmic solution to the problem of routing the sensor readings from sensor nodes to the sink of a USN and the least interference beaconing protocol (LIBP) as a protocol implementation of the LIBA algorithm. LIBP builds upon routing simplicity to enable USN scalability and extends the beaconing process with load balancing to improve the USN energy efficiency. Our experimental results obtained using TOSSIM [11] reveal the relative scalability and efficiency of the traffic engineering scheme resulting from LIBP compared to state of the art collection protocols TOB and CTP. They show up to 30% reduction in power consumption compared to TOB and up to 40% compared to CTP while maintaining better performance in terms of scalability for radio energy consumption. The remainder of this paper is organized as follows: Section II presents the proposed LIB model. The experimental results obtained through comparative simulation study are presented in Section III, and finally Section IV draws the conclusions.



(a) Network Topology Connectivity



(b) Path Multiplexing Configuration



(c) Path Separated Configuration

Fig. 1. *Path Discovery*

II. The Least Interference Beaconing Model

The application of any of the collection protocols to the USN illustrated by Fig 1 (a) may lead to two sensor network routing configurations, depending on how the parent nodes are selected at each epoch: A path multiplexing configuration illustrated by Figure Fig 1 (b) where each node, excepted the sink is transit for the traffic flows of at most three of its neighbours, and a path separated configuration revealed by Fig 1 (c) where each node excepted the sink carries the traffic flows of at most 1 of its neighbours. Compared to the path multiplexed configuration, the path separated configuration has the advantage of achieving energy efficiency as by balancing the traffic flows carrying the sensor readings from nodes to the root of the routing tree, each node will support less traffic and thus keep its radio transceiver idle more often, this resulting in energy savings. The *"least interference beaconing (LIB)"* paradigm combines the path separation principle illustrated by Figure 1 (c) and periodic beaconing to achieve efficient and scalable USN management.

A. Problem formulation

The routing in USNs can be formulated as a zero-one linear problem consisting of finding for each node $\imath$, the subset $\mathbf{N}_0 \subseteq \mathbf{N}[\imath]$ of its neighbours that solves the following zero-one linear problem

$$\min \quad \sum_{\jmath \in \mathbf{N}[\imath]} x_\jmath \qquad (1)$$
$$subject \text{ to}$$

$$\begin{cases} w(\imath) & = \sum_{\jmath \in \mathbf{N}[\imath]} x_\jmath & (2) \\ parent(\jmath) & = \imath \mid w(\imath) = \min_{x \in \mathcal{N}(\jmath)} \{w(x)\} & (3) \\ x_\jmath & = 0 \text{ or } 1 \ , \forall \jmath \in \mathbf{N}[\imath] & (4) \end{cases}$$

where $parent(x)$ is a function that returns the preferred parent for a given node x, and $w(x)$ is the weight associated with the node to express its interference in the number of children that it is carrying. Note that as expressed above, the problem formulation does not contain any explicit formulation of the energy efficiency or dependability constraints. It only expresses the least interference paradigm and how it is mapped into i) *a routing metric/cost* expressed by equation (2), ii) *a parent selection* expressed by equation (3) and iii) *the zero-one linearity model* expressed by equation (4). As formulated above, the routing problem is a local optimization problem that may be solved using a heuristic solution described in subsection II-B and implemented as a protocol in section II-C.

B. Least Interference Beaconing Algorithm

Least Interference Beaconing algorithm (LIBA) is an algorithmic solution to the routing problem formulated above that uses a time-bound by "epoch" breadth-first search model to find the routing paths for the traffic flows carrying the sensor readings from nodes to the sink. A high-level description of the LIBA is presented in Table I, where T_e is the duration of an epoch while "mod" is the modulo operation. It is used in our case to compute the beginning of a new epoch.

TABLE I
LIB: SENSOR NODE ALGORITHM

0.	$get(epoch)$; *get epoch id from neighbour*
1.	$T = Clock(syn)$; *get synchronized clock time*
2.	**while** $(epoch! = 0)$ **do**
3.	**if** $(T \bmod T_e == 0)$ **then**
4.	$epoch++$;
5.	$select(parent(x))$;
6.	$compute(w(x))$;
7.	$broadcast(w(x))$;
8.	**else**
9.	Collect and forward sensor readings to parent(x);
10.	**if** a faulty branch is announced by the gateway **then**;
11.	set $epoch = 0$;
12.	**endif**
13.	**endwhile**

TABLE II
LIB: SENSOR GATEWAY ALGORITHM

0.	$true = 1$;
1.	**while** $(true! = 0)$ **do**
2.	collect sensor readings from base station;
3.	record data at gateway and recognize situation;
4.	**if** a faulty branch is found in the network **then**
5.	set $epoch = 0$;
6.	broadcast(epoch);
7.	**endif**
8.	**endwhile**

As presented in Table I, LIBA provides a heuristic solution to the least interference routing problem expressed by (1) by using a similar scheme to TinyOS beaconing, but with a slight modification to the beaconing process in order to meet the routing constraints (2), (3) and (4) as follows:

- When broadcasting the beacon after the initial step, the parent computes its weight (interference) specifying the number of children it is supporting as expressed by the routing constraint (2). It then includes the calculated weight in the beacon that is being broadcasted in **step 7**.
- Upon reception of the beacons from potential parents, the children nodes select their preferences for the least interfering parent and update their forwarding tables in **step 5** based on the expression of the routing constraint (3).
- The zero-one linearity routing constraint (4) can also be expressed by

$$x_j = \begin{cases} 1 & \text{parent}(j) = i \\ 0 & \text{otherwise.} \end{cases}$$

  It suggests the creation of a breadth-first spanning tree rooted at the sink through recursive broadcasting of routing update beacon messages and recording of parents.

Table II presents a high level description of the algorithm implemented by the sensor gateway. It involves a situation recognition process that triggers recovery mechanisms, by reinitializing the epoch counter, $epoch = 0$, upon failure. However, in this paper situation recognition has been limited to ensuring that as a protocol implementation of the zero-one linear formulation, LIBP protocol leads to a connected network. The study of the recovery processes under failure conditions are beyond the scope of this current work.

It should be noted that the LIBA algorithm depicted in Table I might (i) lead to a path multiplexing configuration such as illustrated in Fig 1 (b) during an epoch where all weights are equal and (ii) converge to a path separated configuration as depicted in Fig 1 (c) after computation and broadcasting of weights. In the illustration provided in Fig 1, the convergence to a least interference configuration happens after weight allocation and broadcasting in a given epoch where node 1 informs nodes 4 and 5 that it has a $weight = 2$ while node 2 will inform node 5 that it has a lower $weight = 1$. Similarly, node 10 informs nodes $12, 13$, and 14 that it has a $weight = 3$. During the parent selection process that follows the weight allocation and broadcasting, node 5 selects node 2 and node 12 selects node 9, while node 14 selects node 11 as their parents (next hops to the gateway), since they have lower weights.

C. Least Interference Beaconing Protocol

The LIBP is an implementation of the LIBA algorithm. Its implementation model is based on the key features described below:

- Use of a simple ad hoc routing protocol, which creates a breadth-first spanning tree rooted at the sink through recursive broadcasting of routing update beacon messages and recording of parents.
- The beacon messages are (1) broadcast periodically at intervals called epochs, (2) propagated progressively to neighbours and (3) received by a few nodes located in the vicinity of the source of the beacon message.
- The transmission of the beacon is built around a source marking progressive propagation to neighbours and re-broadcasting progress, which sets up a breadth-first spanning tree rooted at the sink.
- The least interference paradigm is integrated into the process through selection of a parent node that has the

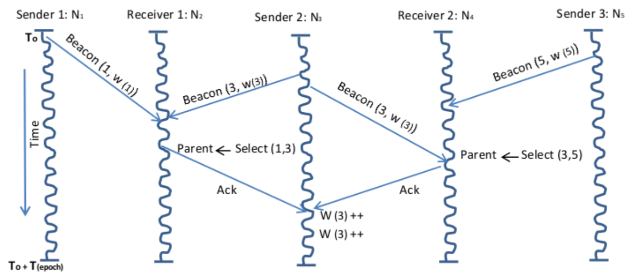


Fig. 2. *The Least Interference Beaconing Protocol*

smallest number of children (smallest forwarding table), which is thus a point of least traffic interference.

- While the LIBP protocol leads to the same number of messages exchanged as TOB, it implements a different parent selection model where instead of selecting the first parent node they heard from, the sensor nodes hear from a set of neighbours and select the least burdened (in number of children) as the parent node.

LIBP builds upon an ad hoc routing protocol similar to TOB in terms of simplicity, and to the emerging RPL protocol [12] in terms of structure. Its main messages (beacon and acknowledgement) and processes (weight updating and broadcasting, parent selection) are illustrated in Figure 2, where (i) beacon messages carrying the sender's identity and weight are broadcast to potential children by senders, (ii) parent selection is performed at reception of the beacon messages but acknowledged to only the selected parents and (iii) the selected parents increase their weights only after receiving the acknowledgement message. We note that by piggy-backing the parent identification into the beacon broadcasting process and adding parent identification to the packet header, our model may avoid the signalling overheads related to the addition of an acknowledgement into the routing process. However, as LIBP acknowledgements are sent to only the selected parents, they are bound by the maximum number of nodes in the network, thus reducing tremendously the signalling overheads during an epoch.

III. Performance Evaluation

A set of experiments were conducted using TOSSIM [11]; emulating real-time experimentation on the TinyOS operating system to evaluate the energy efficiency and the scalability of the proposed LIBP protocol compared current implementations of the TOB and CTP protocols. Comparison metrics included:

i) *Path length*, in number of hops from a node to the root of the collection tree. Shorter routes may translate into higher network dependability as they express a shorter tree resulting in lower damage under attack or node failure.

ii) *Energy consumption* expressing the energy consumed by the nodes, and finally

iii) *Throughput* in terms of packets successfully received at the gateway vs. time. It expresses the engineering efficiency

TABLE III
Simulation Setup

Traffic	every node sends a 28-byte packet every 5 s
Number of nodes	phase 1: 30, phase 2: 10-to-100
Topology	random
Simulation duration	1000 s
beacon interval	34 s
α (for LIBP)	1

of a model, since higher throughput is an indication of a better traffic-engineered network.

In our simulation study, energy consumption is compared in different scenarios. The simulation setup is summarized in Table III. We conducted a first set of experiments with the number of nodes set to 30 in order to measure the energy consumed by every node for each of the three protocols as depicted by Figure 3). A second set of experiments was conducted to investigate the scalability of the different protocols by varying the number of nodes while measuring the average energy consumption as shown in Figure 4. Figure 3 reveals clearly that the proposed LIBP protocol outperforms the other ones, leading to energy consumption in the range $0.0046\,Joule$ to $0.0061\,Joule$. This translates into a reduction of between 15% and 30% compared to TOB, and between 18% and 40% compared to CTP. CTP demonstrates the worst performance because of its high overhead. Figure 4 shows that in contrast to CTP that leads to a drastic rise of energy consumption when the number of nodes reaches 70, both LIBP and TOB scale with the increase in the number of nodes. We also note that LIBP reveals the lowest energy consumption with the increase of number of USN nodes. Figures 5 and 6 plot the total number of data packets received by the sink and those sent by the nodes, respectively. From these plots, it can be seen that in general, CTP implementation results in higher latency owing to the spanning tree construction that takes a long time compared to the other protocols. This explains non-transmission (and accordingly no reception) of packets at the beginning, and peaks in a later stage of the experimentation. The favourable consequence of this slow tree construction is optimum path construction, as demonstrated by Figure 7 where CTP is perceived to find and use the shortest paths. However, this should be balanced with the shortcomings caused by the tree construction latency and the unbalanced resulting tree. The problem would become drastic with dynamic topology networks, where tree reconstruction needs to be performed at each significant topology change. Note that in all our experiments, situation recognition was implemented by the gateway as described in Table II to discover if the USN constructed by LIPB was disconnected. The results (not presented here for space) revealed that each USN configuration led to a connected tree structure.

IV. Conclusion and Future Work

This paper presents LIBP, a new routing protocol that builds upon routing simplicity and minimization of the interference among competing traffic flows to achieve energy efficiency

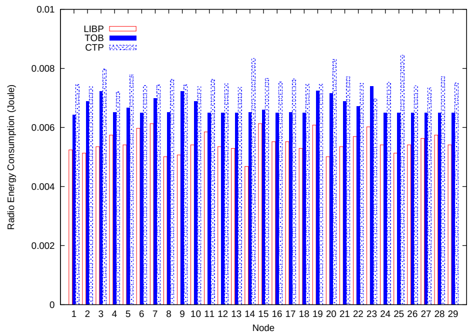


Fig. 3. Radio energy consumption

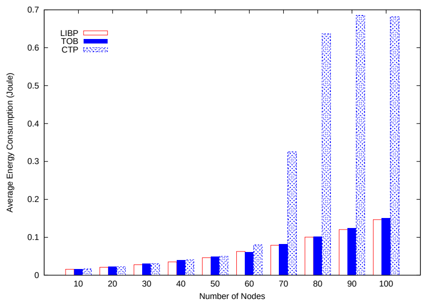


Fig. 4. Scalability for radio energy consumption

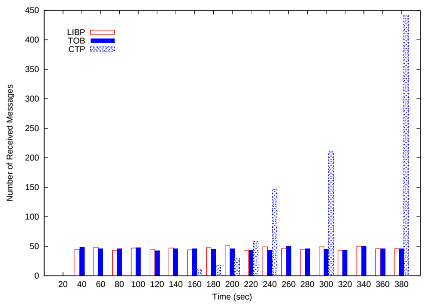


Fig. 5. Received Messages

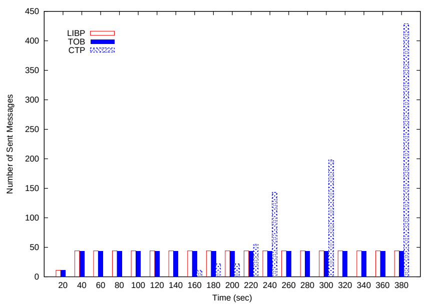


Fig. 6. Sent Messages

and scalability in the emerging USNs that form the IoT. Preliminary experimental results using TOSSIM reveal the relative efficiency of LIBP compared to the CTP and TOB protocols. These results reveal that the path separation principle behind the "least interference beaconing" paradigm embedded into LIBP and the "least interference optimization" paradigm proposed in [13], [14] translates into network efficiency.

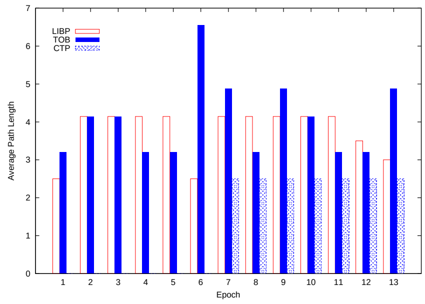


Fig. 7. Average Path Length

There is room for further investigation of the LIBP protocol in terms of its fault tolerance capabilities upon failure, its dependability in terms of protection against jamming attacks, its relative performance compared to recently standardized protocols such as RPL, and how the gateway can be used as a processing unit in a hybrid USN architecture combining centralized situation recognition and distributed sensor readings dissemination. This has been reserved for future work.

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