

Ubiquitous Sensor Network Management: The Least Interference Beaconing Model

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Abstract—Network management is revisited in the emerging ubiquitous sensor networks (USNs) that form the Internet-of-the-Things (IoT) with the objective of evaluating the impact of traffic engineering on energy efficiency and assessing if routing simplicity translates into scalability. USN management is formulated as a local optimization problem minimizing the number of traffic flows transiting by a node: the nodes traffic flow interference with other nodes. The least interference beaconing algorithm (LIBA) is proposed 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. Simulation 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 (TOB), and up to 40% compared to collection tree protocol (CTP) 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 to provide various services to different users. As currently deployed in 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-range communication. In future USN applications, sensor devices are predicted to be deployed in thousands of computing elements into multi-technology and multi-protocol platforms, where access to the information will be available not only “anytime” 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 in the IoT. However, while the 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 power, 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 used 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 redesigns are built upon models that discount the simplicity and efficiency principles that should guide USN designs.

A. Related work

Collection protocols such as CTP [4] and 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. CTP uses the trickle algorithm [6] to enable data traffic to quickly discover and fix routing inconsistencies. It relies on the *Collection tree* and *adaptive beaconing* features to reduce route repair latency and beacon messages. The TOB protocol has 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 against some of the inefficiencies of the beaconing protocol, such as 1) the lack of resilience to node failures and 2) the tree-like m-to-1 sensor readings dissemination model leading to uneven power consumption across network nodes. The lack of resilience can lead to an

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Acknowledgement: This paper was supported by the project “Secured quality of service aware wireless sensor networks: toward effective network and energy management”, funded by a joint-project grant from the South African NRF and Algerian DGRSDT.

entire sub-tree being cut off from the base-station when a parent node fails. The uneven power consumption results in nodes surrounding the base-station consume a lot of power, whereas the leaf nodes in the tree structure, 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 named TinyAODV [8] and standardization of the AODV protocol 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 deployments.

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 LIBA as an algorithmic solution to the problem of routing the sensor readings from sensor nodes to the sink of a USN and 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. Simulation 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. The remainder of this paper is organized as follows: Section II presents the proposed LIB model. The results obtained through comparative simulation study are presented in Section III, and finally Section IV draws the conclusions.

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 many sensor network routing configurations, depending on how the parent nodes are selected. These include a path multiplexing configuration illustrated by Figure Fig 1 (b) where each node, except the sink, is transit for the traffic flows of at most three of its neighbours, and a path separated configuration shown in Figure Fig 1 (c) where each node, except the sink, carries the traffic flows of at most one of its neighbours. Compared to the path

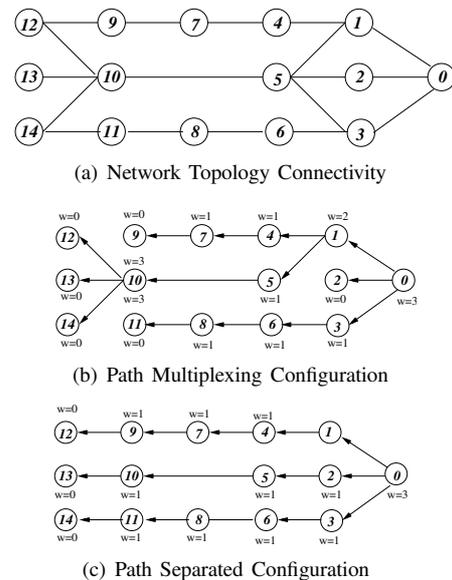


Fig. 1. Path Discovery

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 problem of finding for each node i , the subset $\mathbf{N}_0 \subseteq \mathbf{N}[i]$ of its neighbours that solves the following local optimization problem

$$\min \sum_{j \in \mathbf{N}[i]} x_j \quad (1)$$

subject to

$$\begin{cases} w(i) &= \sum_{j \in \mathbf{N}[i]} x_j & (2) \\ \text{parent}(j) &= i \mid w(i) = \min_{x \in \mathbf{N}(j)} \{w(x)\} & (3) \\ \forall j \in \mathbf{N}[i] &; D(i, j) \leq C(i, j) & (4) \end{cases}$$

where $x_j \in [0, 1]$ and $\text{parent}(j)$ is a function that returns the preferred parent for a given node j . $w(i)$ is the weight associated with the node i to express its interference in the number of children that it is carrying. $D(i, j)$ and $C(i, j)$ are respectively the distance and communication range between nodes i and j . Note that as expressed above, the routing model 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 *local optimization problem* expressed by the routing objective (1), ii) a *routing metric/cost* expressed by equation (2), iii) a *parent selection* expressed by equation (3) and iv) wireless communication constraints expressed by equation (4). The local optimization problem may be solved using a heuristic

solution presented in subsection II-B and implemented as a protocol summarily described in section II-C.

B. Least Interference Beaconing Algorithm

LIBA is an algorithmic solution to the routing problem formulated above. It 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. LIBA builds upon beacon messages which are (1) broadcast periodically at intervals called epochs, (2) propagated progressively to neighbours and (3) received by a few nodes located in range of the source of the beacon messages according to the constraint (4). A high-level description of the LIBA algorithm is presented in Table I, where T_e is the duration of an epoch while “*mod*” is the modulo operation used in our case to compute the beginning of a new epoch. LIBA is presented

TABLE I
ALGORITHM 1: 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 mod Te == 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 = 1;
12.     endif
13. endwhile

```

in Table I as a heuristic solution to the routing problem in subsection II-A. It uses a traffic engineering scheme which is similar to TOB, but with a modification to the beaconing process in order to meet the routing constraints (2) and (3) as follows:

- Before broadcasting a beacon to potential children, a parent node 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 broadcast 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).

Note that the LIBA algorithm might lead to the convergence of a network from a path multiplexing to a path separated configuration. In the illustration provided in Fig 1, the convergence from a path multiplexed to a path separated configuration happens upon weight allocation and broadcasting during an 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, thus leading node 5 to prefer node 2 as parent. Similarly, node 10 informs nodes 12, 13, and 14 that it has a *weight* = 3 while nodes 9 and 11 inform nodes 12 and 14 respectively that they have a *weight* = 1. Upon parent selection, node 5 selects node 2 and node 12 selects node 9,

while node 14 selects node 11 as their respective parents (next hops to the gateway), since they have lower weights.

TABLE II
ALGORITHM 2: SENSOR GATEWAY ALGORITHM

```

0.  faulty = check(gateway);
1.  while (faulty == 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.      faulty = check(gateway);
9.  endwhile

```

Table II presents a high level description of the algorithm implemented by the sensor gateway. It starts by checking the integrity of the gateway (*faulty* = *check(gateway)* in **step 0**) and involves a situation recognition process that triggers recovery mechanisms, by reinitializing the epoch counter, *epoch* = 0, upon failure: for example when a failed branch is found in the tree structure used to route the traffic from nodes to gateway. However, in this paper situation recognition has been limited to only collecting performance statistics and ensuring that as a protocol implementation of the local optimization problem, LIBP leads to a connected network. The study of the recovery processes under failure conditions is beyond the scope of this current work.

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 source marking progressive propagation 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 least interference paradigm is integrated into the process through selection of a parent node that has the smallest number of children, which is thus a point of least traffic flow 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. 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

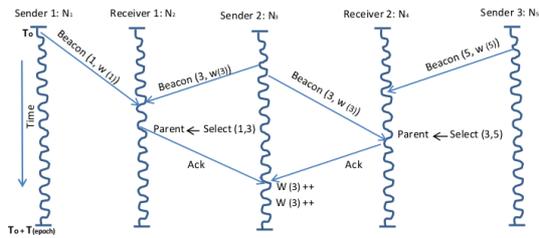


Fig. 2. The Least Interference Beaconing Protocol

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 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 decrease in energy consumption 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

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

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 the optimal path construction 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 resulting unbalanced tree. The problem would become drastic with dynamic topology networks, where tree reconstruction needs to be performed at each significant topology change. Note that as suggested in section II-B, in all our experiments situation recognition was implemented by the gateway as described in Table II to only gather performance statistics and discover if the USN constructed by LIBP was disconnected. The connectivity results (not presented here for space) revealed that each USN configuration led to a connected tree structure.

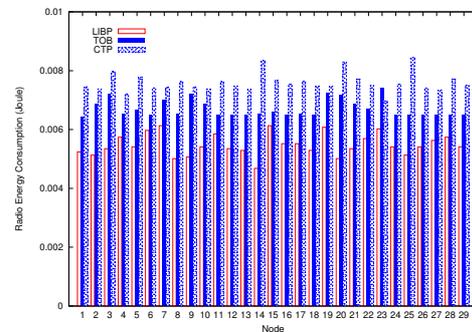


Fig. 3. Radio energy consumption

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 and scalability in the emerging USNs that form the IoT. Preliminary simulation 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

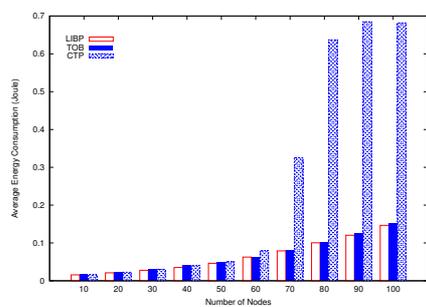


Fig. 4. Scalability for radio energy consumption

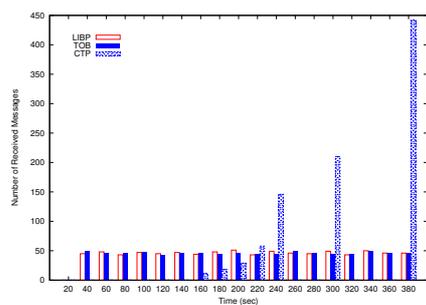


Fig. 5. Received Messages

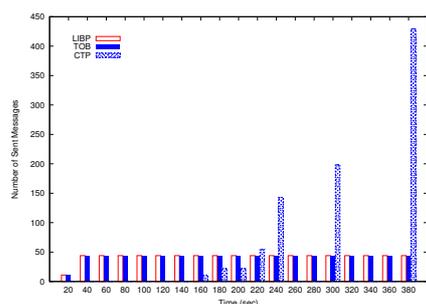


Fig. 6. Sent Messages

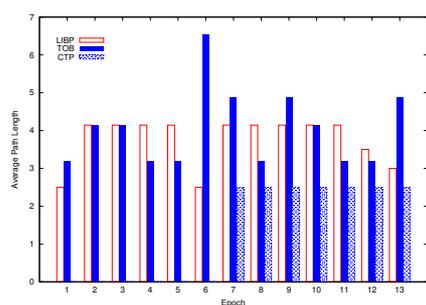


Fig. 7. Average Path Length

LIBP and the “least interference optimization” paradigm proposed in [12], [13] translate into network efficiency.

LIBP could be extended in terms of its fault tolerance capabilities, its dependability in terms of protection against

jamming attacks, and how its gateway algorithm could be extended to add situation recognition to the flexible and robust gateway system proposed in [14]. Extending LIBP to achieve QoS through multi-path routing as suggested by [15] or traffic differentiation following the model in [16] is another avenue for future work.

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