A Border-Oriented-Forward Routing Protocol for Large-Scale WSANs with Support to Actuator-Sensor-Actuator Communication

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***Abstract*—Wireless Sensor and Actuator Networks (WSANs) refer to a class of unattended wireless networks whose goal is to provide communication between distributed applications that perform the monitoring and control of certain characteristics of an environment. Among the vast number of WSANs applications, we focus on those designed to the natural disaster monitoring, such as forest fire control. It is therefore essential that the routing algorithms for these applications provide adequate scalability, reliability and energy efficiency. In addition, considering large-scale scenarios and the absence of direct communication between actuators, the message delivery reliability, fundamental for the mutual coordination of actuators, is a requirement not fully supported by the existing protocols. In order to cope with this shortcoming, in this paper we propose a novel Border-Oriented-Forward routing protocol (BOFP) for WSANs with support to actuator-sensor-actuator communication. We carried out simulations to attest the BOFP performance according to three metrics: the goodput, the overall end-to-end delivery delay and the energy consumption. The results of the simulations were statistically analyzed and suggested that BOFP satisfied the requirements of large-scale WSANs.**

***Keywords*–WSAN; Routing; Energy Efficiency; Reliability.**

I. Introduction

Wireless Sensor and Actuator Networks (WSANs) have appeared as an extension of Wireless Sensor Networks (WSNs) in which the actuation tasks can be performed directly in a monitored environment. Such networks usually operate unattended and are composed by a set of heterogeneous devices mainly equipped with microprocessors, wireless communication adapters, sensors and actuation mechanisms. These devices may play particular roles in the field, such as data gathering that is performed by low-cost devices, named sensor nodes. In this case, the desired condition of the environment is maintained by more complex and expensive devices known as actuators nodes. A substantial number of WSANs applications can be enumerated, as, e.g., precision agriculture, natural disaster monitoring, tracking and location in hospital environments, home, industrial automation and so on [1].

In particular, applications intended to monitoring large geographical areas demand a large number of sensor nodes. In such cases, the actuators density might be much lower than the sensor nodes density, primarily due to the cost of actuator nodes. In large-scale unattended WSAN applications, e.g., the forest fire control or the landslide monitoring, the coordination between the actuator nodes can be considered essential [2]. Moreover, in these specific applications, a common assumption is to consider that actuators can communicate directly to each other. However, in such a scenario, the communications are subject to fail due to either obstacles or long distances between the actuators. Therefore, the network scalability is limited by the maximum communication range of the wireless adapter of the actuators. For this reason, routing protocols designed for large-scale WSANs must be scalable and also to provide both appropriate efficiency of energy consumption and adequate reliability on message delivery.

One can find several WSAN routing protocols in the literature that may be in line with some of the aforementioned requirements [3]–[13]. However, among them, the on-demand gradient-based routing protocol (DGR) [11] was specially designed to provide communication between actuators, named Actuator-Sensor-Actuator Communication (ASAC), by defining routing paths linking the set of sensor nodes. However, due to its on-demand feature, the DGR may not achieve satisfactory overall data delivery reliability and energy conservation required for some WSAN applications.

In line with this shortcoming, in this paper, we present a new routing protocol, named Border-oriented routing protocol (BOFP), specially designed to large-scale WSANs with support to ASAC communication. The BOFP is a gradient-based protocol that organizes the sensor nodes in levels and defines some of them as the relays of the actuators messages. Therefore, the BOFP automatically delimits broadcast regions in the network by defining special sensor nodes, located in border of the regions, each of them here named Border Node (BN). The BNs have as main task to establish routing paths between two or more actuator nodes. However, the BNs can also prevent the propagation of broadcast of messages (broadcast storm) outside the delimited regions, consequently, reducing the overall intra-network collision rate.

For assessing the performance of the BOFP, we carried out simulations considering different scenarios. Moreover, we compared the results of the BOFP with those from DGR with regard to their energy consumption efficiency, delay and message delivery reliability considering the event detection and ASAC data traffics. Consequently, the results achieved by the BOFP outperformed those achieved by the DGR protocol.

The remaining sections of this paper are organized as follows. In the next section, we briefly present the protocols closely related to the proposed strategy. Section III presents the BOFP specification and the WSAN model employed in this study. The performance evaluation of the BOFP and the results are presented in Section IV. To sum up, we conclude the paper by presenting some final remarks in Section V.

 ISBN: 978-1-61208-398-8

II. Related Work

Most of the existent protocols [3]–[6] [8]–[10] [12] [13], which have some relation to the objective of the present study, use a central controller to configure or coordinate the overall operation of the network. Consequently, these protocols have scalability limitations and may not be suitable for large-scale WSANs. Differently, the BOFP, proposed in this paper, makes use of a distributed algorithm in which the network operation is decentralized and the communication between sensors and the actuators occur locally, with sensors within their neighborhood. Besides, with exception of the study introduced in [8], the protocols earlier cited in this section do not consider ASAC. Additionally, in spite of using ASAC, the protocol proposed in [8] assumes the existence of a specific hardware for directional antennas and the knowledge of the geographic location of nodes both not regarded in this paper.

To the best of our knowledge and considering only the routing protocols designed for WSANs, the approach most related to this work is the DGR, proposed by Guo et al. [11].

The operation of the DGR starts with the dynamic gradient setup phase, where announcement messages (*ADV*) are propagated, hop-by-hop, from each actuator to all sensor nodes. In this phase, all sensor nodes in the network calculate a k value that will correspond to a cost gradient. Added to this k, an energy gradient s and a balance coefficient α define a backoff timer t_b that depending on its value, it reveals whether or not a sensor node will belong to a routing path. Accordingly, in the case that an actuator is supposed to perform an ASAC, and from it there does not exist a routing path, it initiates a routing path establishment phase. The actuator broadcasts a transmission-request message (*TR*) and waits for the response of the sensor nodes.

Each sensor node that received the TR calculates its t_b that is the required backoff timer for response. Since the t_b value is influenced by the residual energy of the sensor node, the node with the largest amount of residual energy and that is the nearest (has the smallest k) to the destination provides the lowest t_b and, consequently, answers first. The answer message is called transmission-agreement message (*TA*). The source of the *TA* message is then warned, by the actuator, that will become part of the routing path and does the same steps of the actuator, by broadcasting a *TR* to its neighbors, to find the next hop to the destination. This process is repeated until a *TR* reaches the destination. From this point on, data messages can be sent by the source actuator to the destination through the routing path found.

The DGR relies on the assumption of the existence of high traffic between the actuator nodes. Consequently, by just considering the actuator activities, the DGR protocol does not explicitly consider the influence of the data traffic generated by the sensor nodes for constructing the routing paths between the actuators. In the DGR, routing paths are built without taking into account the distance between the nodes involved in a point-to-point transmission. This can reduce the chances of transmission success leading to a decrease in the reliability of data delivery in large-scale networks.

Bearing all these limitations pointed up in the DGR in mind, we developed the BOFP.

III. Protocol Specification

In this paper, we introduce the BOFP that overcomes some limitations pointed up in the previous section. As well as the DGR, the BOFP builds routing paths for the communication between actuators through the set of sensor nodes. Unlike the DGR, in our proposal we assume that monitoring applications for event detection produce low traffic between actuators, and this traffic is active only when critical events are detected. Another difference between the BOFP and the DGR is with respect to the routing path establishment. In the DGR, routing paths are established on-demand while in the BOFP they are established only at the beginning of the protocol operation. Additionally, the BOFP uses a threshold of Received Signal Strength Indicator (RSSI) to determine the maximum distance that a node can have in relation to the transmitter, to make part of a routing path. Thereby, the BOFP allows the adjustment of the RSSI threshold in order to maintain the reliability of data delivery in adequate levels.

A. The WSAN model and Assumptions

In this paper, we consider a stationary and unattended WSAN composed by a set of actuator nodes and a set of sensor nodes unaware about their geographic location coordinates. The set of sensor nodes is homogeneous with regard to the hardware and software capabilities. Accordingly, the sensor nodes are equipped with the same radio device in which the transmission power is not dynamically adjustable. All actuator nodes are homogeneous in hardware and software capabilities and use the same transmission power of sensor nodes for short range communication. Although actuator nodes are assumed to be more powerful than sensor nodes, we consider that, due to the long distances implied in large-scale WSANs, any of them does not directly transmit messages to other actuator.

Nevertheless, for the source and the destination identification, we assume that every node (sensor or actuator) is assigned to an unique identity, as MAC address. Additionally, each sensor node keeps a routing table where each entry indicates the next hop and the distance (in hops) to a specific actuator node. Thus, we consider that each sensor node will always send data messages to the closest actuator node, related to the entry in the routing table with the smallest distance to it. Finally, we also consider that all nodes do not need to be clock synchronized. Taking this WSAN model into account, we specify the introduced protocol in the next section.

B. The BOFP General Operation

The proposed protocol has a two-phase approach consisting of a startup phase (S-Phase) and a communication phase (C-Phase). The S-Phase comprises the execution of two asynchronous distributed procedures with the purpose of discovering routing paths from sensor nodes to actuators and from actuators to actuators.

The first procedure, here called Node-to-Actuator Discovery Path Procedure (N2A-DP), is executed at the beginning of the S-Phase. In this procedure, each actuator node broadcasts a Route Discovery Message (RDM) to all sensor nodes in its communication range. The *RDM* carries a tuple of three integer values: the level counter (*lc*) initially set to zero, the unique source sensor node identity (*snid*) and the actuator unique identity (*aid*). All RDM sent by actuator nodes have the *snid* set to zero. At this point, in the S-Phase, all sensor nodes execute the Algorithm 1.

It is important to notice that, according to the proposed algorithm, a given sensor node accepts a received message if and only if the Signal Strength Indicator (RSSI) of the received message, $m.rssi$, is above a specific threshold value γ . The value for γ is considered variable and defined according to the application requirements. After receiving and accepting a RDM, say *m*, a sensor node verifies whether or not the received *aid*, $m.aid$, matches some *aid* in the routing table entry set (*RT*). In the first case, if the received *lc* value is smaller than the *lc* value stored in the *RT*, it updates its *RT* entry related to the *aid* with the received values of *lc* and *snid*. In the second case, the sensor node includes the received values in the *RT*.

Afterwards, each sensor node, receiver of *m*, generates and broadcasts a replica of *m*, say *m'*, which carries the following information: a *lc'* with the value of *lc* increased by one; and both the *aid* and the *snid* are set as the sensor node own identity. This process is repeated by every sensor node receiver of *m* or its replicas. Therefore, the *lc* stored in any entry of *RT* indicates how far (in hops) the sensor node is from a given actuator node.

Notwithstanding, regarding to distinct lc values of *aid* entries stored in the *RT*, $RT.aid.lc$, a sensor node may find similar values of the received lc, $m.lc$.Here we define similar as those $RT.aid.lc$ that differ at most by one to the value of the received lc. Whenever a sensor node finds similar values of a received lc in the *RT*, it becomes a border node (BN) of the actuator of the received lc and of every distinct actuator whose lc is similar in the RT. As a matter of fact, the following steps with regard to the BN happens for every actuator whose lc is similar to the received lc. However, the operations are pairwise, being one of the pairs always the source of the received lc. By considering one of these pairs of actuators (represented by the received *aid* and the *aid* stored in *RT*), from the point it is defined as BN on, the sensor node stops the RDM propagation and starts a complementary Actuator-to-Actuator path Discovery Procedure (A2A-DP).

In the A2A-DP, each BN sends two Actuator-to-actuator Route Discovery Messages (ARDMs) via unicast to the pairs of actuators ($m.aid$, $RT.aid$). On the one hand, the ARDM for the actuator $m.aid$ contains the information of the distance in hops between the BN and the actuator $RT.aid$. On the other hand, the ARDM for the actuator $RT.aid$ contains the information regarding the distance in hops between the BN and the actuator $m.aid$. The ARDM has a very similar structure to the RDM. The sensor nodes in the path from the BN to the actuator $m.aid$ (or $RT.aid$) will handle the ARDM as they did with the RDM by including in their RT the distance and the next hop to the actuator $RT.aid$ (or $m.aid$) and by increasing the values of lc in the ARDM for every retransmission. Immediately after receiving the ARDM, both actuators store the next hop and the distance to each other in their *RT*. It is worth mentioning that, for a given path between two actuators, there will be always only one BN. Considering a path between two actuators whose number of sensor nodes is even, two sensor nodes are candidate to be BN. But, is this case, the first candidate sensor node to become BN will stop the propagation of the RDM. Consequently, the second candidate sensor node will not receive the corresponding RDM.

Algorithm 1: Algorithm for S-Phase executed in sensor nodes

```
input: A received message m;
       The routing table entry set, RT;
       The sensor node state, BN, initially set to FALSE;
       The ID of the sensor node, myid.
if m.rssi ≥ γ then
    if m is RDM then
        if m.aid ∈ RT then
            if m.lc < RT.(m.aid).lc then
                Updates the m.lc, m.snid values of
                RT.aid entry;
            end
        else
            Includes a new entry in RT with m.aid, m.lc
            and m.snid values;
        end
        for each RT.aid ≠ of m.aid do
            if m.lc = RT.aid.lc or [ m.lc − RT.aid.lc] =1
            then
                set BN to TRUE;
                set m′ to ARDM with (aid=m.aid,
                lc=m.lc+1, nexthop=RT.aid.snid);
                set m″ to ARDM with (aid=RT.aid,
                lc=RT.aid.lc, nexthop=m.snid);
                sendbyUnicast (m′, m″);
            end
        end
        if not BN then
            set m′ to RDM with (aid=m.aid,
            lc=m.lc+1);
            Broadcast(m′);
        end
    else
        if m is ARDM then
            if m.snid = myid then
                if m.aid ∉ RT then
                    Include m.aid in RT with m.lc,
                    m.snid values;
                    for each aid ∈ RT ≠ of m.aid do
                        set m′ to ARDM with
                        (aid=m.aid, lc=m.lc+1,
                        nexthop=RT.aid.snid);
                        sendbyUnicast(m′);
                    end
                end
            end
        end
    end
end
```

Finally, in the C-Phase, sensor nodes and actuators are able to send data messages. In the C-phase we consider two types of unicast data messages: the Sensor-to-actuator Data Message (SDM) and the Actuator-to-actuator Data Message (ADM). As stated before, the SDMs are transmitted, from sensor nodes, through the shortest path to their nearest actuator. Differently, the ADMs include the *aids* of both source and destination actuators.

IV. Performance Evaluation

For evaluating the performance of the BOFP, we propose three metrics: end-to-end delay, energy consumption and good-put. The main reason behind the use of these specific metrics is the overall assessment of the proposed protocol mainly by means of energy conservation efficiency and reliability on message delivery. Each of these assessment measures, simulation parameters, scenarios and performance evaluation results are gone into detail in the next sections.

A. Simulation Models, Scenarios and Parameters

We compared the performances of the BOFP, its variations, and the DGR into three extents of square sensing areas, representing small, moderate and large-scaled scenarios, as we can observe in the summary of the simulation parameters indicated in Tables I and II. Additionally, for each sensing area we set different numbers of nodes. We also consider that the application periodically senses the environment, at every five seconds, and depending on the simulation purpose, it may generate one data message whenever it detects an event.

Table I summarizes the parameters for the first simulation model designed to assess the performance of both protocols with respect to the event detection. We configured two static events to be activated in two non simultaneous periods of 50 seconds during the execution of the simulation. The sensor nodes were uniformly placed in the field while the actuator nodes were arbitrarily placed out of the communication range of each other. We set the sensors nodes in the DGR to send messages to their closest actuator. To better assess the impact of the main differential of BOFP, the BN nodes, in addition to the DGR Protocol, we also modeled simplified version of the BOFP, here named Simple Gradient Protocol (SGP). This simplified version of the BOFP has the same procedures developed in the BOFP, however, without the BNs. Therefore, the SGP uses the same implementation of the gradient based level count as well as all the discovery procedures used in the BOFP without the limitation of broadcast messages done by the BN nodes. We also include the RSSI threshold in the SGP implementation in order to compare s performance with the BOFP. The RSSI values were defined by analyzing, for each scenario, whose values maximized the delivery ratio in point-to-point communication.

Table II summarizes the parameters of the second simulation model designed to compare the performance of the BOFP with the DGR with respect to the ASAC. In this second model, we do not consider the traffic generated by sensor nodes as result of event detection, as defined in [11]. Differently of the former model, we deployed only two actuator nodes in the opposite extremity sides of the sensing field. We also consider that the traffic load is generated by one of the actuators, that sends one message at every five seconds.

We designed and executed the simulation models in OMNeT++/Castalia environment [14]. For each simulation scenario, the results we report correspond to the average of 40 independent executions with different seeds. Moreover, since the samples did not follow a normal distribution we proceeded with the statistical analysis, considering each scenario independently, by applying the Kruskal-Wallis test [15].

B. Metrics

1) End-to-end delay: Here, the end-to-end delay is the elapsed time between the message generation by any sensor node until the delivery of such message to an actuator.

TABLE I. PARAMETERS OF THE MODEL SETUP FOR TESTING SCENARIOS OF SENSOR-ACTUATOR COMMUNICATION.

	Small Scale	Moderate Scale	Large Scale
Event1:(x,y) coord.	50,50	50,50	50,50
Event2:(x,y) coord.	170,170	900,900	1900,1900
Event Detec. radius(m)	36	36	36
Area (mxm)	350x350	1000x1000	2000x2000
Sensor nodes (unit)	100	400	1600
Actuator nodes (unit)	4	5	8
Power Radio (dBm)	10	10	10
Model Radio	CC1000	CC1000	CC1000
Sampling interval (s)	5	5	5
Events (unit)	2	2	2
Simulation time (s)	200	200	200
Executions (unit)	40	40	40
Message size (bytes)	512	512	512
Transmission rate (kbps)	19,2	19,2	19,2
γ values (dBm)	-86	-92	-92

TABLE II. PARAMETERS OF THE MODEL SETUP FOR TESTING SCENARIOS OF ACTUATOR-ACTUATOR COMMUNICATION.

	Small Scale	Moderate Scale	Large Scale
Area (mxm)	350x350	1000x1000	2000x2000
Sensor nodes (unit)	100	400	1600
Actuator nodes (unit)	2	2	2
Power Radio (dBm)	10	10	10
Model Radio	CC1000	CC1000	CC1000
Sampling interval (s)	5	5	5
Simulation time (s)	270	270	270
Executions (unit)	40	40	40
Message size (bytes)	512	512	512
Transmission rate (kbps)	19,2	19,2	19,2
γ values (dBm)	-86	-92	-92

2) Energy Consumption: The energy consumption is a very important metric to assess the protocol efficiency. We estimate the individual energy consumption for a single transmission (E_{Tx}) and for a reception (E_{Rx}) considering the energy model proposed by Heinzelman et al in [16]:

$$E_{Tx}(k,d) = E_{elec} * k + e_{amp} * k * d^2 \quad (1)$$

$$E_{Rx}(k) = E_{elec} * k \quad (2)$$

where k is the number of bits to be transmitted with distance d, considering the energy spent $E_{elec} = 50nJ/bit$ for both transmission/reception and antenna amplification $e_{amp} = 100pJ/bit/m^2$. The total energy consumption of the network is given by the sum of the energy spent in each transmission/reception as given by the Equations 1 and 2 [16].

3) Goodput: This measure, highly related to the message delivery reliability, consists in the ratio of the total number of original application data messages to the total number of messages delivered to the actuators nodes.

 ISBN: 978-1-61208-398-8

C. Simulation Results and Discussion

1) Attesting the benefits of BN: The charts depicted in Figure 1 present the results corresponding to the scenarios of the first simulation model designed to evaluate the performance of the protocols considering the event data traffic generated by sensor nodes. In the chart, the black dots represent the mean values whereas the letters *a*, *b* and *c* indicate the statistical equivalence of the samples. For example, given the results of a specific metric for each distinct scenario, if two boxes are with the same letter, this means that they are not, according to the Kruskal-Wallis test, statistically different regarding this metric. Otherwise, they have a significant difference. One may noticed that, for the trhee metrics, BOFP behaves slightly better than the others as the extent of the scenarios increases. The statistical analysis has showed that the results obtained by BOFP and SGP are similar considering the goodput. However, the reduced energy consumption of BOFP compensates, since it can deliver almost the same average number of messages as SGP while requiring less energy. Additionally, BOFP presents an overall end-to-end delay smaller than other protocols.

2) Performance in ASAC: The main goal of this evaluation is to compare the performance of the BOFP with the DGR considering the ASAC. As indicated in Figure 2, it is noteworthy that the BOFP outperforms the DGR with respect to the goodput and the end-to-end delay. Consequently, reliability with regard to data delivery of BOFP is better than from DGR. Moreover, the DGR has a better performance than the BOFP when considering the energy consumption. The reason is the number of transmissions executed by the BOFP: as the BOFP transmits much more messages than DGR, the energy consumption of the BOFP is higher. Finally, we also observed that the performance of the BOFP is significantly higher than of DGR because the latter is sensible to communication faults primarily during the routing path establishment phase execution.

3) Scalability properties of BOFP: In order to attest the scalability of the proposed protocol, we compared the goodput samples considering the three distinct extent scenarios. Figure 3 presents the results of this analysis. As stated before, distinct letters represent the statistical difference between the samples. According to this analysis, we did not find significant differences in the results. Thus, BOFP may cope with scalability requirement for large scale WSANs.

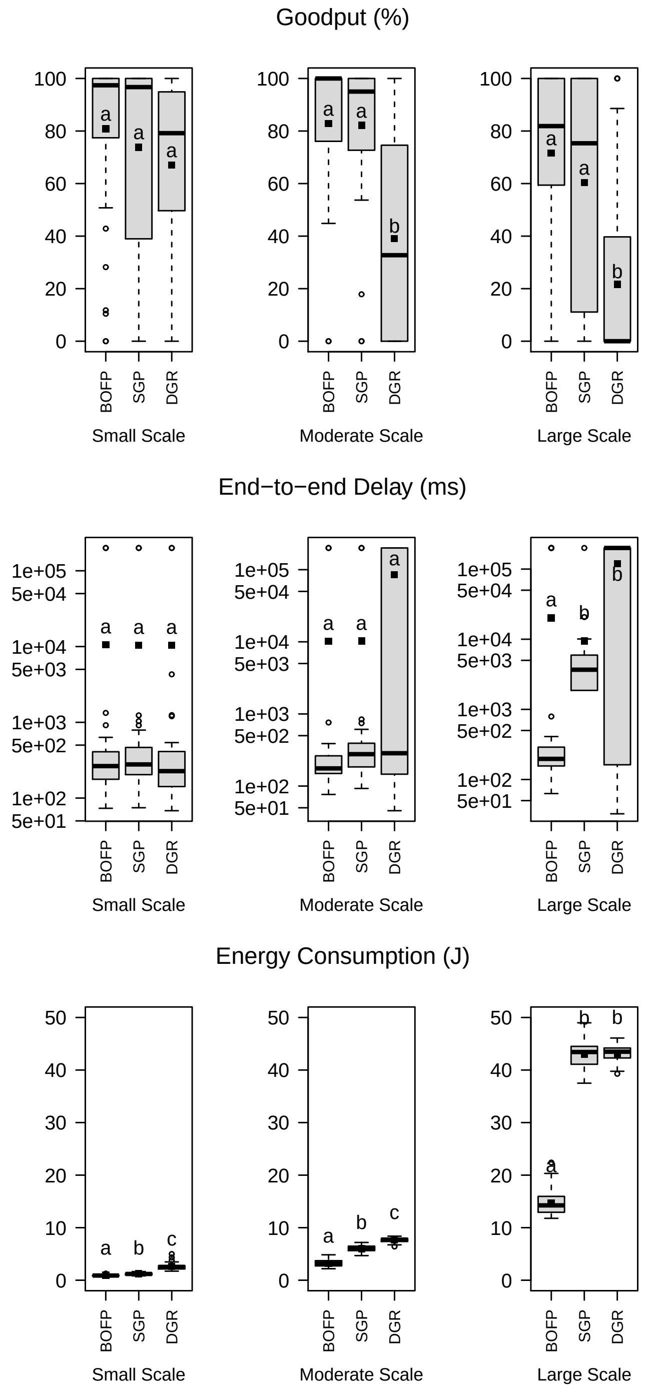

Figure 1. Results of Goodput, End-to-end Delay and Energy Consumption considering the event data traffic generated by sensor nodes.

V. Conclusion and Future Works

In this paper, we addressed the problem of performing ASAC in large-scale WSANs. Additionally, for this type of WSAN, the protocols found in the literature revealed a shortcoming of not provide the adequate levels of energy efficiency and reliable data delivery. In line with this shortcoming, in this paper, we proposed a new routing protocol, the BOFP, specially designed for large-scale WSANs. Accordingly, for assessing the performance of the BOFP, we carried out simulations in different scenarios considering both data traffics of event detection and the ASAC. By comparing the BOFP with other protocols we observed results which revealed the benefits of the BN approach in determining the routing paths. The results also showed how the BOFP may achieve adequate reliable data delivery levels without compromise the energy efficiency. As future research, we intend to define a path reestablishment procedure in order to evaluate the BOFP considering the presence of multiple mobile actuators as well as to estimate the overall network lifetime. Additionally, we intend to proceed with the experimental analysis to evaluate BOFP performance in a real environment.

Acknowledgment

The authors thank to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for its financial support.

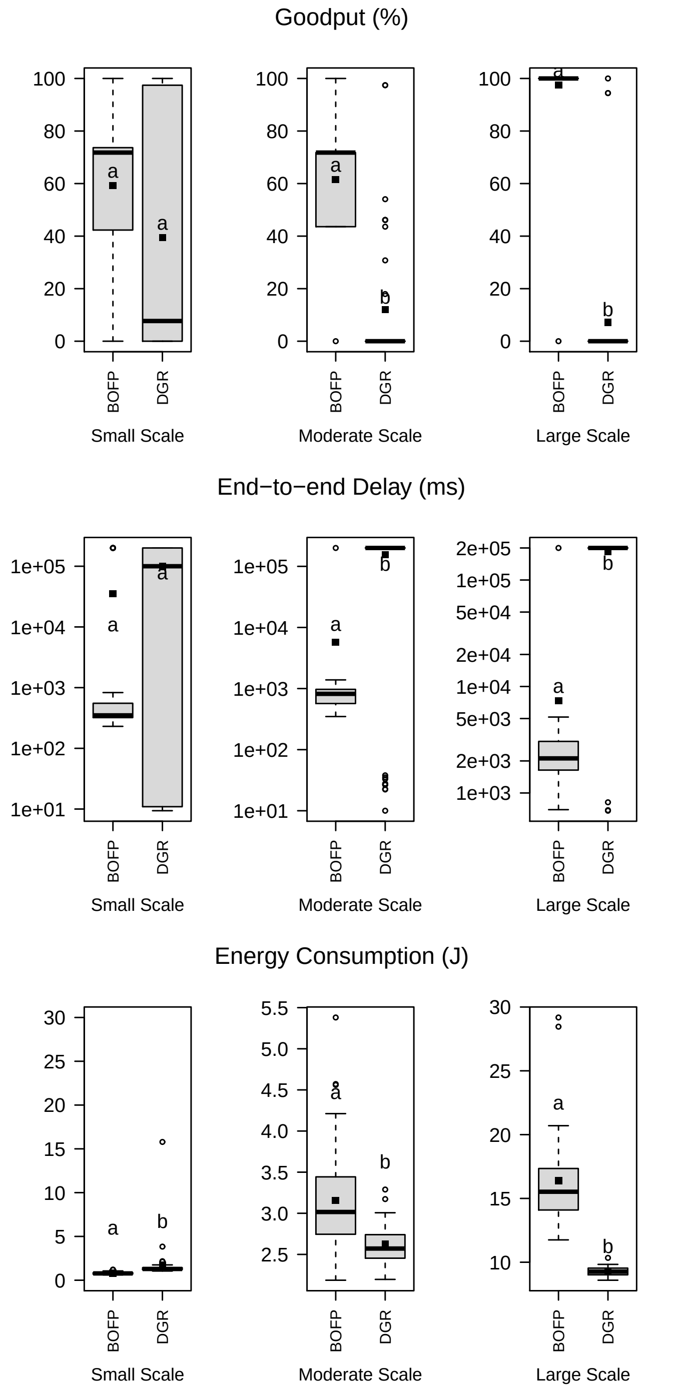

Figure 2. Results of Goodput, End-to-end Delay and Energy Consumption considering ASAC data traffic generated by one actuator.

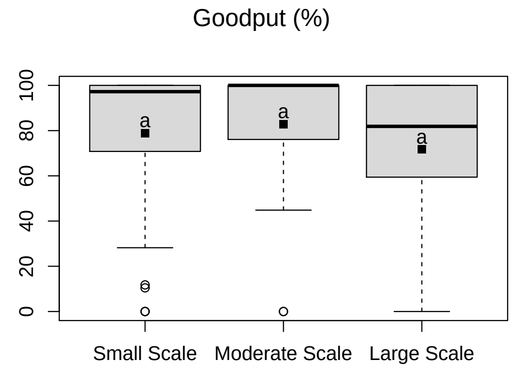

Figure 3. Comparison between the Goodput results, achieved by BOFP, considering the three scenarios extent.

REFERENCES

[1] I. F. Akyildiz and I. H. Kasimoglu, “Wireless sensor and actor networks: research challenges,” Ad Hoc Networks, vol. 2, no. 4, 2004, pp. 351 – 367.

[2] H. Salarian, K.-W. Chin, and F. Naghdy, “Coordination in wireless sensor-actuator networks: A survey,” Journal of Parallel Distributed Computing, vol. 72, 2012, pp. 856–867.

[3] W. Hu, N. Bulusu, and S. Jha, “A communication paradigm for hybrid sensor/actuator networks,” in 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2004), vol. 1, 5-8, September 2004, pp. 201–205.

[4] E. Cayirci, T. Coplu, and O. Emiroglu, “Power aware many to many routing in wireless sensor and actuator networks,” in Proceedings of the Second European Workshop on Wireless Sensor Networks, Jan-2 Feb 2005, pp. 236 – 245.

[5] H. Peng, W. Huafeng, M. Dilin, and G. Chuanshan, “Elrs: an energy-efficient layered routing scheme for wireless sensor and actor networks,” in 20th International Conference on Advanced Information Networking and Applications, AINA 2006., vol. 2, April 2006, pp. 452 – 460.

[6] A. Boukerche, R. B. Araujo, and L. Villas, “A wireless actor and sensor networks qos-aware routing protocol for the emergency preparedness class of applications,” in Proceedings of the 31st IEEE Conference on Local Computer Networks, November 2006, pp. 832–839.

[7] ——, “Optimal route selection for highly dynamic wireless sensor and actor networks environment,” in Proceedings of the 10th ACM Symposium on Modeling, analysis, and simulation of wireless and mobile systems, ser. MSWiM ’07, vol. 0. New York, NY, USA: ACM, 2007, pp. 21–27.

[8] K. Selvaradjou, N. Handigol, A. Franklin, and C. Murthy, “Energy-efficient directional routing between partitioned actors in wireless sensor and actor networks,” Communications, IET, vol. 4, no. 1, 5 2010, pp. 102 –115.

[9] M. Akbas and D. Turgut, “Lightweight routing with qos support in wireless sensor and actor networks,” in Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE, December 2010, pp. 1 –5.

[10] M. I. Akbas, M. R. Brust, and D. Turgut, “Sofrop: Self-organizing and fair routing protocol for wireless networks with mobile sensors and stationary actors,” Computer Communications, vol. 34, no. 18, 2011, pp. 2135 – 2146.

[11] Y. Guo, Z.-z. Xu, C.-l. Chen, and X.-p. Guan, “Dgr: dynamic gradient-based routing protocol for unbalanced and persistent data transmission in wireless sensor and actor networks,” Journal of Zhejiang University SCIENCE C, vol. 12, 2011, pp. 273–279.

[12] Z. Li and H. Shen, “A kautz-based real-time and energy-efficient wireless sensor and actuator network,” in IEEE 32nd International Conference on Distributed Computing Systems (ICDCS), june 2012, pp. 62 –71.

[13] E. Cañete, M. Díaz, L. Llopis, and B. Rubio, “Hero: A hierarchical, efficient and reliable routing protocol for wireless sensor and actor networks,” Computer Communications, vol. 35, no. 11, 2012, pp. 1392 – 1409.

[14] A. Boulis, “Castalia, a simulator for wireless sensor networks and body area networks. user’s manual.” NICTA, March 2011, last accessed 27-February-2015. [Online]. Available: http://castalia.npc.nicta.com.au

[15] W. H. Kruskal and W. A. Wallis, “Use of ranks in one-criterion variance analysis,” Journal of the American Statistical Association, vol. 47, no. 260, 1952, pp. 583–621.

[16] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-eficient communication protocol for wireless microsensor networks,” in Proceedings of the 33rd Hawaii International Conference on System Sciences (HICSS 00), January 2000.