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BOD-LEACH: broadcasting over duty-cycled radio using LEACH clustering for delay/power efficient dissimilation in wireless sensor networks

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SUMMARY

Broadcasting delay-sensitive information over a duty-cycled wireless sensor network is considered, and a cluster-based protocol is proposed. The proposed protocol, namely Broadcast over Duty-Cycle and LEACH (BOD-LEACH), takes advantage of the LEACH's energy-efficient clustering. This approach shifts the total burden of energy consumption of a single cluster head by rotating the cluster-head role among all nodes in the network. It also permits the ordinary (member) nodes in a cluster to turn off their radios whenever they enter inactive TDMA slots. However, LEACH does not consider broadcast messages, and the member nodes scheduling is established as a sequence of Time Division Multiple Access (TDMA) without any common active period. A broadcast message should then be postponed to the next TDMA schedule and transmitted in a sequence of unicast messages, which is inefficient in terms of latency, bandwidth occupation, and power consumption. The proposed protocol adds new common static and dynamic broadcast periods to support and accelerate broadcasting. The dynamic periods are scheduled following the past arrivals of messages and using a Markov chain model. To our knowledge, this work is the first that proposes the use of clustering to perform simultaneous local broadcasts at several clusters. This reduces broadcast latency and ensures scalability. The protocol has been simulated, numerically analyzed, and compared with LEACH. The results show clear improvement over LEACH with regard to broadcast latency, at a low energy cost.

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KEY WORDS: wireless sensor networks; global broadcast; duty-cycled MAC; QoS protocols

1. INTRODUCTION

A wireless sensor network (WSN) consists in interconnecting sensor motes for a specific application. These motes are tiny computer devices embedding sensor boards capable to sense the physical environment. The motes are also enabled with wireless communication capability through radio frequency channels. However, they are limited with respect to computation, memory, and particularly energy supply. The key solution to minimize power consumption of the radio is to use duty-cycling at the medium access control (MAC) layer, which considerably helps to reduce the energy that nodes tend to consume when in idle mode. This consists of periodically turning off/on the radio, instead of keeping it switched on all the time. Many duty-cycled MAC protocols have been proposed [1], which are by far more energy efficient than full duty-cycled protocols (e.g., 802.11). However, most of the high layer QoS solutions assume the radio at any potential receiver to be always on and ignore duty-cycling of the radio at underneath layers. Duty-cycling has the side effect of introducing additional delay needed to coordinate the active periods of senders and receivers on each hop. That is,

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instead of immediately transmitting a frame at the MAC layer, a transmitter may have to wait for the next active period of the receiver (the next wake-up of the receiver) before starting the transmission. This adds an additional unexpected delay at each hop—known as sleep time delay—that inevitably and considerably influences the performance of the high layer solutions. Broadcast packets have even more important effects, where a broadcast packet may need to be transmitted several times to meet active periods of all neighboring nodes, which increases the probability of collision with hidden terminals and energy consumption at the transmitters.

To overcome the latency arising from duty-cycling the radio, this paper proposes a LEACH-based protocol, which is baptized BOD-LEACH. Contrary to the state-of-the-art broadcast protocols that consider duty-cycling, such as opportunistic flooding [2], Hybridcast [3], the protocol proposed by Wang and Lui [4], and ADB [5], where the structure of the WSN is flat, BOD-LEACH lies on a cluster topology. The LEACH's clustering approach allows for simultaneous local broadcasts at several clusters in the WSN. This parallelism minimizes the message count, i.e., the number of transmissions (local broadcasts) required to achieve the global message broadcast, as well as the end-to-end broadcast latency. It also ensures scalability with the increase of the network size, contrary to the flat topology solutions where the end-to-end broadcast latency and the message count are proportional to the network size. Moreover, clustering has been demonstrated to have potentials for energy saving in WSN [6]. The proposed protocol inherits the LEACH's advantages with respect to energy saving [7]. The latter implements two strategies: The first one is to shift the total burden of energy consumption of a single cluster head (CH) by rotating the CH role among all nodes in the network. The second strategy is to activate ordinary nodes only during their allocated TDMA slot and allow them to turn to sleep mode elsewhere. These features have been kept with BOD-LEACH, but new static and dynamic broadcast periods have been added to support and accelerate broadcasting. In addition to its TDMA slot, every node is activated in common static and activated dynamic broadcast periods. The activation/deactivation of dynamic periods is determined based on a Markov chain model. BOD-LEACH has been simulated using a network simulator, numerically analyzed, and compared with LEACH. The results show clear improvement over LEACH with regard to latency, at a low energy cost.

The remainder of this paper is organized as follows. Section 2 lists the related work. Section 3 is dedicated to the solution background and assumptions. The proposed protocol is described in detail in Section 4. Section 5 evaluates BOD-LEACH through simulations and numerical analysis and compares the protocol's performances to those of LEACH. Finally, Section 6 draws the conclusion and summarizes the future work.

2. RELATED WORK

Several duty-cycled MAC protocols have been proposed thus far, such as X-MAC [8], B-MAC [9]. The paper by Bachir *et al*. [1] is a good review on these protocols. Lately, delay-efficient MAC protocols are proposed, which try to deal with the latency problem introduced by the duty-cycled mechanism, e.g., A-MAC [10], Duo-MAC [11], and [12]. A review on these MAC protocols can be found in [13]. Several solutions for ensuring delay efficiency and reliability at higher layers have been prosed, such as QoS routing [14], [15], solutions using cross-layer design, for example, [16], [17], [18], [19], and solutions for global broadcast, which represents the subject treated in this work. The global broadcast consists in broadcasting a message thought the network. In multihop networks, optimally translating this into a set of local broadcasts is challenging [20]. In addition to low-power consumption, optimality should include low latency for delay-sensitive messages. Traditionally, this may be achieved by organizing the network into a broadcast tree in such a way to minimize the number of transmissions. This is insufficient when introducing duty-cycling, as the sleep time of the receivers at each hop inevitably increases the latency. Several retransmissions may be needed to achieve a local broadcast. Some recent broadcast protocols focus on this problem and take sleep-time delay into account. Opportunistic flooding [2] targets low duty-cycle networks with unreliable wireless links and predetermined working schedules. The key idea is to make probabilistic forwarding decisions at a sender, based on the delay distribution of next-hop nodes. Early packets are opportunistically forwarded using links outside the power-optimal tree. This is to reduce

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the flooding delay and redundancy in transmission. Opportunistic flooding suffers from the overhead needed to resolve simultaneous forwarding.

In the solution of Wang and Liu [4], the broadcast problem is translated into a graph equivalence by presenting a centralized optimal solution for low-scale networks. The solution is then extended to a distributed implementation, which relies on local information/operations with built-in loss compensation mechanisms. The shortcoming of the protocol is to perform multiple forwards by the same nodes and to maintain huge tables to keep track of the broadcast message. ADB [5] allows a node to switch into the sleep mode as soon as it realizes that no more neighbors need to be reached. It is designed to be integrated with a unicast-MAC that does not occupy the medium for long periods, in order to minimize latency when forwarding a broadcast message. Hybridcast [3] is an asynchronous and multihop broadcasting protocol, which can be applied to low duty-cycling schedule where nodes send out a beacon message at the beginning of wake-up slots. A node defers broadcasting by one or more timeslot(s) after receiving the beacon message from the first awake neighbor in order to wait for more nodes that may potentially wake up, so that more nodes are accommodated in one broadcast. In contrast, delivery deferring is not recommended to minimize the broadcast latency. A novel solution that tackles the shortcomings of the aforementioned listed protocols and ensures a network-wide broadcast service is presented in the following. It is a comprehensive extension of our previous conference short paper [21], with more detailed descriptions and analysis.

3. SOLUTION BACKGROUND AND ASSUMPTIONS

BOD-LEACH is based upon LEACH [7], which splits up sensor nodes into clusters with one CH for each cluster. The main function of a CH is to aggregate data it receives from its members and to send the final aggregated data to the base station (BS) or the sink. This clustering concept may be helpful to establish a broadcast downstream path using the hierarchy made by LEACH, in parallel to the upstream path used for the delivery of the aggregated data. The broadcast messages are first sent from the sink to the CH, then broadcasted locally to the member nodes at each cluster. The use of LEACH clustering concept allows for parallel transmissions by CH nodes, which reduces the latency. The key idea behind the proposed solution is to plan for all sensor nodes common active (receiving) periods, in addition to their respective transmission slots. This way, every CH can send any potential received broadcast message during the common period with a single transmission.

The protocol supposes the following assumptions:

- The WSN is static; that is, node mobility is not considered.
- Sensor nodes are homogenous in terms of computation and communication capability.
- The communication range is controlled to optimize energy, and they are identically set to the same value by all nodes for communications with the CH.
- The interference range is not considered for the protocol design, but the protocol works independently of this range as long as channels are contention-free (LEACH feature).
- The synchronization between sensor nodes is assured by applying some underlying synchronization protocols, such as [22],[23], and [24].

Before the detailed description of the proposed protocol, a brief description of LEACH is given in the following. LEACH runs in rounds, and each of which consists of two phases: setup and steady. At the beginning of the setup phase, every node stochastically decides to become a CH using the following equation [7]:

$$T(N) = \begin{cases} \dfrac{p}{1 - p * (rmod(1/p))} \text{if} & N \in G; \\ 0 & \text{otherwise}, \end{cases} \tag{1}$$

where r is the current round number, P is the ratio of nodes willing to serve as CH, and G denotes the set of nodes that have not been CH during the last $1/p$ rounds. Two steps are involved in the setup phase: advertisement and cluster-setup. In the advertisement step, the CH nodes advertise the

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creation of their cluster amongst the neighboring nodes using an advertisement packet, which contains the generated $T(N)$ value. Each non-CH (member) node then decides to join the CH from which it receives the advertisement packet with the strongest signal strength; then, it informs the chosen CH by submitting a *join packet*. Based on all messages received within the cluster, the CH creates a timing schedule that it broadcasts to its members. The schedule can be used by the nodes to determine the timeslots during which they must be active. This allows member nodes to turn off their radio until their respective allocated timeslots. LEACH assumes that nodes within a cluster start the cluster-setup phase at the same time and remain synchronized thereafter. To reduce intercluster interference, LEACH uses a transmitter-based code assignment scheme. Communications between a node and its CH are achieved using a TDMA scheduling, and Frequency Division Multiple Access (FDMA) [25] is applied to avoid interferences between neighboring clusters. This permits parallel transmissions at different clusters of unicast packets, which is beneficial to the proposed protocol when introducing broadcast periods. For the communications between the CHs and the BS, direct-sequence spread spectrum—which is a Code Division Multiple Access (CDMA) [25] technique—is used, whereby each CH is assigned a unique spreading code. Once the setup phase is achieved, the steady phase then begins, where in every cluster, the sensed data are sent by the member nodes to the CH, during their allocated time (slot) within the schedule. This allows every node to turn off the radio out of its allocated time, which minimizes energy dissipation. When all the data packets have been received, the CH aggregates and sends the final result to the BS.

4. NEW SOLUTION

4.1. Overview

Following the LEACH concept, BOD-LEACH runs in two phases: (i) setup and (ii) steady. The phases are similar to those of LEACH with the exception of adding two static broadcast access periods ($BAP1$ and $BAP2$), as well as dynamic access periods (DAP) during the time between the beginning of a steady phase and the end of the appropriate round. DAP creation depends upon the messages-arrival times, as shown in Figure 1. Both BAP and DAP are dedicated to broadcast messages. An aftereffect of the assumptions announced in Section 3 is that BAP and DAP of all nodes in a cluster are synchronized. All the members within the cluster turn on their radio at the beginning of each BAP or DAP and go to sleep thereafter. The steady phase consists of two phases. The first phase (phase I) is timed from the beginning of the steady phase until the end of the timeslot(s) attributed to the last cluster member within the TDMA schedule. This is for each cluster in the WSN. Right after phase I, $BAP1$ is activated and succeeded by the seconde phase (phase II). The BS is awake all the time, and for each round, it decides when the $BAP1$ appointment period shall start according to the number of member nodes within each cluster. $BAP1$ shall start after the timeslot of the last member in the cluster that has the maximum number of members in the WSN. The information related to the number of nodes in each cluster is available at the BS level upon the completion of the setup phase.

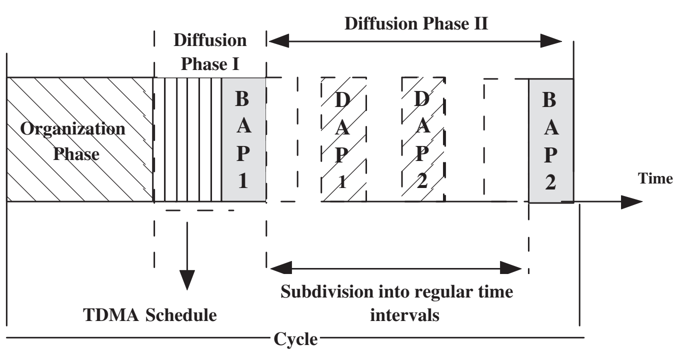

Figure 1. Description of the proposed solution.

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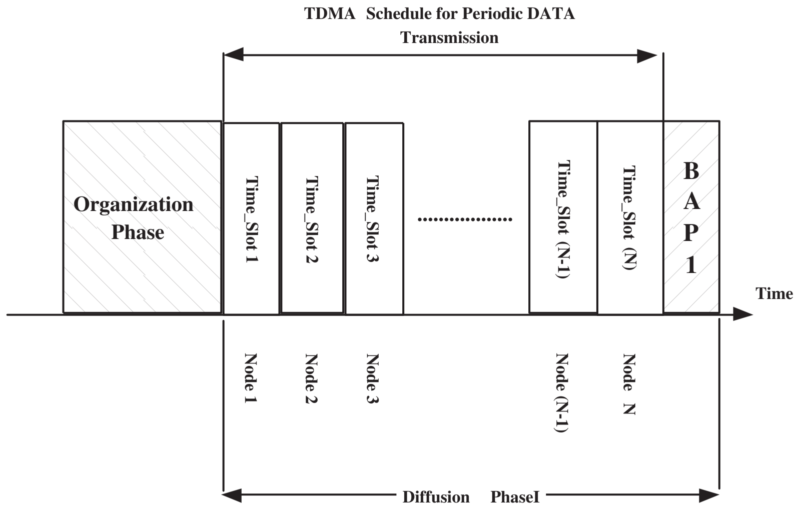

Figure 2. Diffusion phase I.

$BAP2$ always starts before the end of the round for the purpose not to let the message stall until the next round. Besides activating the two static periods, $BAP1$ and $BAP2$, messages that arrive between $BAP1$ and $BAP2$ are handled separately. Delaying the broadcast of such messages to $BAP2$ yields a dramatic latency, specially when the round length is long, which is typical in a WSN for the sake of ensuring power efficiency. The key idea used in BOD-LEACH is to study dynamically the behavior of the arrival times of messages, then subdividing the gap between the two periods, $BAP1$ and $BAP2$, into regular intervals periods, i.e., several DAP. For each DAP, a decision shall be made by the BS on its activation/deactivation. A Markov chain is used to model the message arrival process and to decide on the activation/deactivation of the DAP. For each period, this decision depends upon the incoming broadcast messages during the pervious round. Note that the scheduled time of both BAP and DAP for every node in the WSN is assured by the BS, after running the setup phase at each node level. Phase I depends on the number of member nodes in each cluster and on the time-slot size. After organizing the WSN nodes into clusters, each CH establishes a timing schedule for each node within the cluster then communicates it to all members. Every node stays awake during its timeslot then goes to sleep, as shown in Figure 2. Messages arriving throughout diffusion phase I will be stored at the BS until the beginning of $BAP1$. Therefore, the broadcast latency peaks out for this phase when the broadcast message arrival times coincide with the time of the first timeslot in the TDMA schedule.

4.2. *Dynamic access periods*

In this section, the second phase of the proposed solution is described in detail. We recall that this phase handles broadcast messages that arrive through the period between $BAP1$ and $BAP2$, which should be proportional to the duty-cycle ratio. It thus should be set for as long as possible to save power consumption. The idea is to study the dynamic messages arrival process for DAP activations (creation), at the aim of minimizing the end-to-end delay of such messages. Discrete Markov chain and Poisson process distribution probability [26] are used. For the sake of simplifying the modeling and without loss of generality, the case enabling at most two DAP creation is presented, as shown in Figure 3. The model can be extended to any upper bound on the number of DAP but with an increasing complexity. The interval of time between the two static periods, $BAP1$ and $BAP2$, is divided into two intervals, respectively, of length $t1$ and $t2$. Possible incoming broadcast messages within each of the two intervals are supposed to be a random process that follows a Poisson distribution, which is studied using a discrete Markov chain [26, 27]. Four possible states are considered:

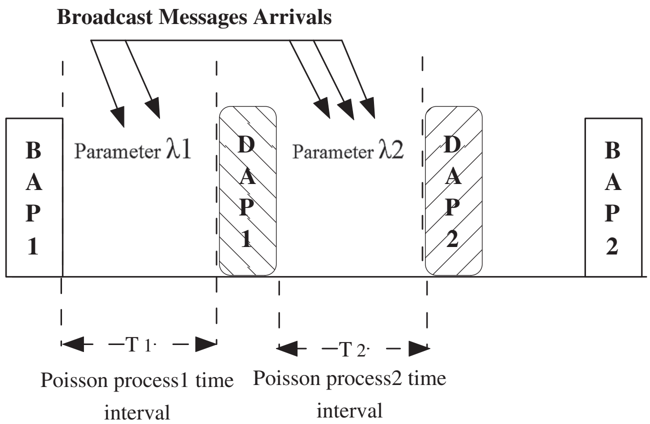

Figure 3. Diffusion phase II.

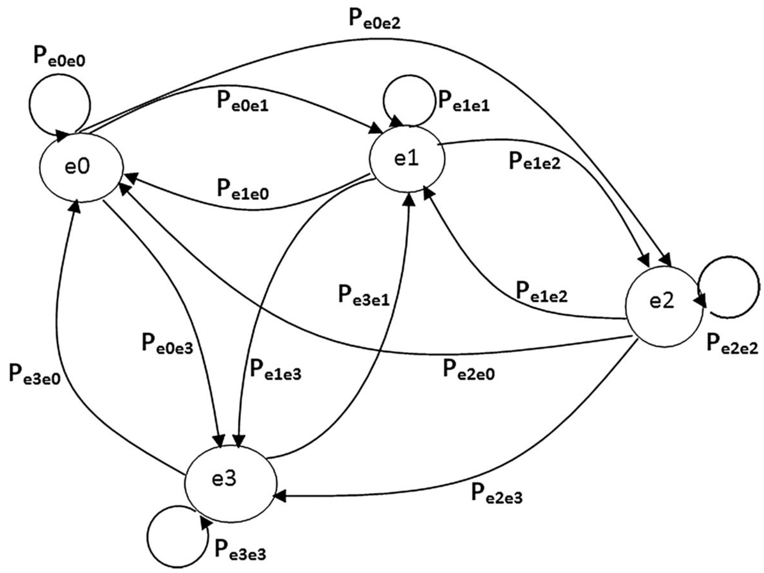

Figure 4. State transitions graph.

(e_0) : None of the two DAP is created.
(e_1) : Only the first DAP is created.
(e_2) : Only the second DAP is created.
(e_3) : The two DAP are created.

These DAP are triggered depending on the number of broadcast messages that arrives. This number is a random variable (rv) following the Poisson process [26], [27]. This process is characterized by a rate parameter, say λ, also known as intensity. The number of events in a short time interval $[t, t+\tau]$ is given by

$$P(X = k) = \frac{e^{-\lambda} * \lambda^k}{k!}, \qquad (2)$$

where k stands for the number of random events, and X is the rv representing the number of events. Using the Poisson probability distribution associated to the Markov chain that models the solution (illustrated in Figure 4), the transition probability, say $P_{e_i e_j}$, between every pair of states, i, j, can be calculated:

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$$(P_{e_0e_1}) = 1 - \left(\sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_1} * \lambda_1^k}{k!}\right) * \sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_2} * \lambda_2^k}{k!}, \tag{3}$$

$$(P_{e_0e_2}) = \sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_1} * \lambda_1^k}{k!} * \left(1 - \sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_2} * \lambda_2^k}{k!}\right), \tag{4}$$

$$(P_{e_0e_3}) = \left(1 - \sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_1} * \lambda_1^k}{k!}\right) * \left(1 - \sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_2} * \lambda_2^k}{k!}\right), \tag{5}$$

$$(P_{e_1e_0}) = \sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_1} * \lambda_1^k}{k!} * \sum_{k=0}^{K=\alpha-1} \frac{e^{-\lambda_2} * \lambda_2^k}{k!}, \tag{6}$$

where α represents the minimum number of messages required to arrive during the phase, for the creation of the appropriate DAP.

In the proposed solution, the transition probabilities to a given state are equal, regardless of the original state. That is, $P_{e_1e_2} = P_{e_0e_2}$, $P_{e_1e_3} = P_{e_0e_3}$, $P_{e_2e_0} = P_{e_1e_0}$, $P_{e_2e_1} = P_{e_0e_1}$, $P_{e_2e_3} = P_{e_0e_3}$, $P_{e_3e_0} = P_{e_1e_0}$, $P_{e_3e_2} = P_{e_0e_2}$, $P_{e_3e_1} = P_{e_0e_1}$. The probability to stay at a given state, say e_i, has to fulfill the following:

$$(P_{e_ie_i}) = 1 - \sum_{j \neq i} P_{e_ie_j} \, \forall i \in \{0, 1, 2, 3\}. \tag{7}$$

The desired stationary distribution is obtained by resolving

$$\Pi = \Pi * P, \tag{8}$$

where Π is the stationary distribution vector, which is a (row) vector whose entries are nonnegative and sum to 1, and P represents the transition probability matrix. In our case, the following system of equations is obtained:

$$\begin{cases} \pi_0 = \pi_0 P_{e_0e_0} + \pi_1 P_{e_1e_0} + \pi_2 P_{e_2e_0} + \pi_3 P_{e_3e_0} \\ \pi_1 = \pi_0 P_{e_0e_1} + \pi_1 P_{e_1e_1} + \pi_2 P_{e_2e_1} + \pi_3 P_{e_3e_1} \\ \pi_2 = \pi_0 P_{e_0e_2} + \pi_1 P_{e_1e_2} + \pi_2 P_{e_2e_2} + \pi_3 P_{e_3e_2} \\ \pi_3 = \pi_0 P_{e_0e_3} + \pi_1 P_{e_1e_3} + \pi_2 P_{e_2e_3} + \pi_3 P_{e_3e_3} \\ \pi_0 + \pi_1 + \pi_2 + \pi_3 = 1. \end{cases} \tag{9}$$

The resolution of the system represented by Equation (9) yields the following unique stationary distribution of the steady state:

$$\Pi_j = P_{e_0e_j}, \forall j \in \{0, 3\}. \tag{10}$$

In practice, if the message arrival parameters (λ_1, λ_2) are unknown, a high window of periods can be used for empirical estimation, which is essential to calculate the stationary state probabilities. After calculating these probabilities, the state with the highest probability will drive DAP activation/deactivation. As the number of broadcast messages follows a Poison proses, time arrivals of respective messages follow exponential distribution. Therefore, these successive events (called interarrival times) are independent exponentially distributed rv, with parameter λ (mean $1/\lambda$). Let us consider a Poisson process with rate λ, and T_k as the time of the k_{th} arrival, for $k \in \{1, 2, 3, \ldots\}$. Time arrivals (T_k) can be generated using

$$T = \frac{-ln(X)}{\lambda}, \tag{11}$$

where X denotes an rv that follows a uniform distribution in $]0, 1]$. That is, in a numerical analysis, a series of uniform rv are generated, and Equation (11) is used to generate a series of an exponential rv.

5. SIMULATION STUDY

In this section, the performance of the proposed solution is investigated through extensive simulations. The metrics used in the evaluation are as follows: (i) end-to-end delay or time cost, which is the total time required for a broadcast message to reach all the sensor nodes, and (ii) energy consumption, which can be viewed as the cost needed for reducing the latency. The proposed solution (BOD-LEACH) is compared with LEACH. We implemented the first diffusion phase (phase I) on the $TinyOS_{2.x}$ operating system [28] using the nesC language and PowerTOSSIM simulator [29]. For the second diffusion phase, MATLAB (MathWorks Inc., Apple Hill Drive, Natick, MA, 01760-2098, USA) environment is used to analyze the mathematical modeling. Plots presented hereafter are the average of several measurements, with a 95% confidence interval.

5.1. Phase I

In what follows, the solution dealing with messages arriving during phase I is investigated. Phase II (DAP creation) will be studied in the next section. Mica2 motes have been simulated with the CC1000 radio. The communication range has been fixed to 45 m, and a propagation model has been set to a lossy model that is the most realistic one supported by PowerTOSSIM [29]. Nodes are uniformity distributed in a 200 m^2 area, while the round, timeslot, and BAP duration have been fixed to 100, 10, and 20 ms, respectively. Table I summarizes the parameters used in the simulation, while the results are presented in Figure 5. Figure 5 illustrates the energy consumption with/without broadcasting for both the CH and member nodes. The number of nodes used here was 100 nodes. The figure shows that in the absence of broadcast messages, the energy consumed by the CH nodes in BOD-LEACH is slightly higher than that in LEACH. The small difference is due to the overhead needed for BAP scheduling. In contrast, the energy consumed by the BOD-LEACH member nodes

Table I. Simulation setup.

Parameter	Value
Sensor mote	Mica2
Radio model	CC1000
Covered area	200 × 200 m
Nodes deployment	Uniform
Energy model	PowerTOSSIM
Communication range (m)	45
Spreading model	Model lossy
Data packet size	32 byte
Round (ms)	100.0000
Timeslot (ms)	10
$BAP1$, $BAP2$ (ms)	20

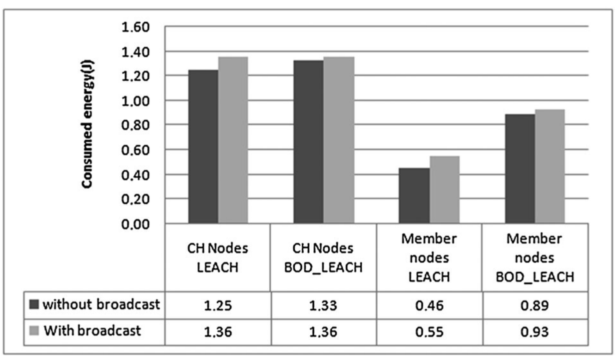

Figure 5. Average consumed energy.

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is almost twice than that consumed by the LEACH members. This can be justified as node members in BOD-LEACH turn on their radios during the whole BAP, contrary to the LEACH members. However, when using broadcast messages, the CH in the two protocols consumes almost the same amount of energy, and the difference between the member nodes reduces. It can be noted that introducing broadcast messages causes a rise in energy consumption for both protocols and both type of nodes. However, the rise for LEACH is more important than for BOD-LEACH. This can be argued by the fact that a CH performs several transmissions to make a broadcast in LEACH, as there is no common wake-up periods. BOD-LEACH eliminates this problem by introducing common BAP.

As shown in Figure 6, the gap between the two protocols in terms of the end-to-end broadcasting latency is very high (note the logarithmic scale). The improvements provided by BOD-LEACH here is due to the introduction of $BAP1$, which breaks the latency of messages that arrives between the organization phase and the end of the period (phase I). Also note that BOD-LEACH allows for a total broadcast (reception by all nodes), contrary to many protocols that only ensure partial reception (such as Hybridcast). The latency of BOD-LEACH increases gradually with the number of nodes. We remarked that the highest broadcast latency has been generated by the cluster with the highest number of member nodes among all the clusters. This latency is in fact the time difference between the timeslot of the first node in the TDMA schedule and the BAP. Table II illustrates the maximum number of member nodes in clusters as a function of the network size.

5.2. *Phase II*

The end-to-end latency of messages arriving during phase II depends on the number of DAP periods created, which in turn depends on the broadcast message arrival process. Numerical analysis with

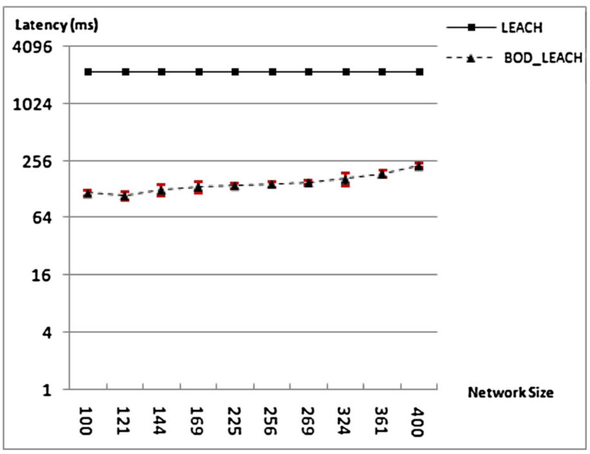

Figure 6. Latency.

Table II. Max number of member nodes vs Network size.

Network size	Maximum number of member nodes
100	10
121	20
144	23
169	30
225	38
256	43
269	48
324	57
361	61
400	36

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MATLAB has been carried out to analyze the Markov chain-based DAP creation. The intensity of the two Poisson processes has been varied, and the stationary distribution vector has been calculated. Consequently, the state with the highest probability has been selected. Figure 7 shows that the activation of the two DAP (e_3 state) takes place when the intensity of both Poisson processes is in the interval [0.7, 1]. Otherwise, if only $process1$ (respectively $process2$) has its intensity in that interval, the system is in state e_1 (respectively e_2). The system remains in state e_0 (no DAP is created) iff each of the two Poisson processes has an intensity below 0.6.

In order to simulate and evaluate the end-to-end broadcast latency versus the DAP creation, a sample of broadcast message arrival times has been generated using Equation (11). The latency is measured as the time gap separating the arrival of the broadcast message and the next created DAP. The diffusion phase II length is set to 50.000 ms, the time interval of the first Poisson process is set to 10.000 ms, and the one of the second Poisson process is set to 30.000 ms. Figure 8(a) and (b) plot the latency of BOD-LEACH and LEACH, respectively, for the first Poisson process, i.e., messages

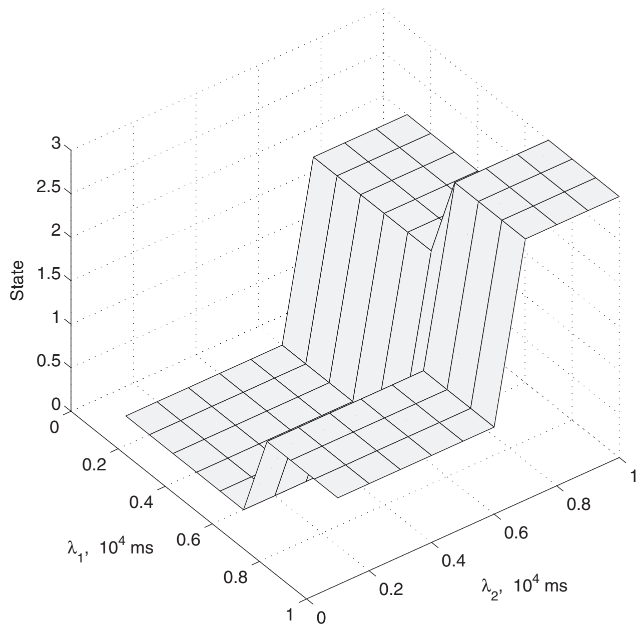
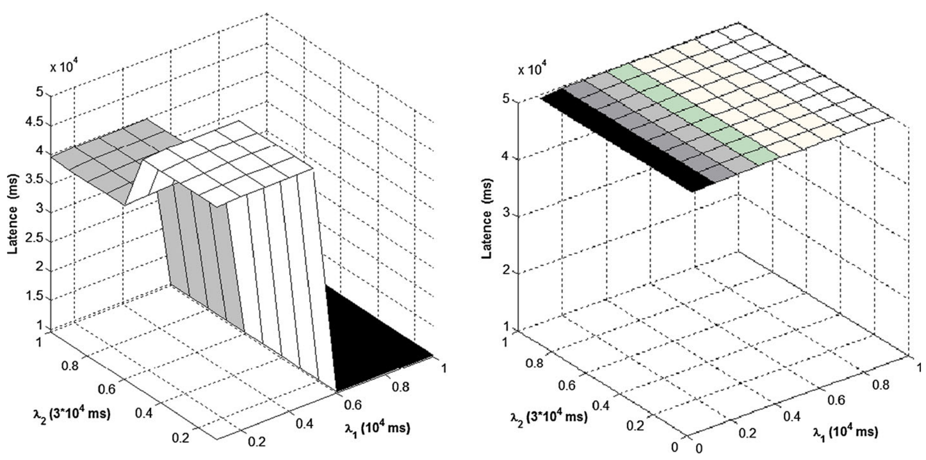


Figure 7. System states.



(a) (b)

Figure 8. Latency for messages arriving during process 1.

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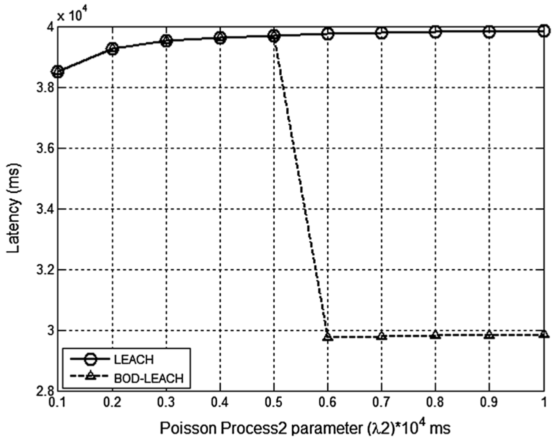

Figure 9. Latency for messages arriving during process 2.

Table III. Quantitive comparison.

	Protocol			
	Hybridcast	ADB	Opportunistic flooding	BOD-LEACH
Number of nodes	200	200	200	225
Power range (m)	10	10	10	10
Duty-cycle (%)	[0.1, 0.4]	[0.1, 0.4]	[0.1, 0.4]	0.01
Latency (ms)	[700, 1200]	[750, 1150]	[740, 110]	[110, 910]
Broadcast count	[90, 160]	[230, 300]	[210, 260]	43
Simulation environment	OMNET++	OMNET++	OMNET++	PowerTOSSIM
Propagation model	Lossy	Lossy	Lossy	Lossy
Timeslot (ms)	100	100	100	100

that arrive during the first Poisson process. It can be noted that for an intensity of the first process (λ_1) in the interval [0.5, 1], the BOD-LEACH latency is minimized, which is due to the $DAP1$ creation. For $\lambda_1 \in [0, 0.5[$, the latency inevitability increases due to the noncreation of $DAP1$. However, the λ_2 values in [0.5, 1] help reduce the latency through the creation of $DAP2$ compared with the case where both λ_1 and λ_2 are in $[0, 0.5[$ (no DAP creation). Contrary to BOD-LEACH, the end-to-end latency under LEACH is constant and equals the maximum latency of BOD-LEACH, and it is unrelated to the values of λ_1 and λ_2. Unlike messages arriving during the first Poisson process, the end-to-end latency for those arriving during the second Poisson process depends only on λ_2. Figure 9 demonstrates a reduction over LEACH when $\lambda_2 > 0.5$. This is justified by the creation of $DAP2$.

5.2.1. Rough comparison with other protocols. Unfortunately, no code of the delay-efficient broadcast protocols proposed for duty-cycled WSN is available. This prevents thorough comparison with these protocols, as performed in the previous section with LEACH. However, we tried to summarize each protocol simulation study from the literature and provide an overview of the obtained results, as shown in Table III. It can be noted from this table that the proposed protocol has the lowest latency interval, although it has been simulated in an environment with the lowest duty-cycle. This is basically due to the reduction of the count number whose average value is also reported in the table, that is, the number of messages required to perform a broadcast. This reduction reflects the efficiency of the use of LEACH's clustering that enables parallel transmissions.

6. CONCLUSION AND PERSPECTIVES

In this paper, the problem of broadcast message latency in WSN with active/dormant cycles (duty-cycled MAC) has been considered. The BOD-LEACH protocol has been presented; a duty-cycle

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enabled protocol that is based on the clustering concept of LEACH. To our best knowledge, the proposed protocol is the first cluster-based delay-efficient broadcast protocol for WSN. BOD-LEACH adds static and dynamic periods, dedicated for broadcast messages. The dynamic periods creation depends upon the message arrivals, and they are created thoroughly using a Markov chain model. This provides latency reduction over LEACH at a moderate additional energy, which is an inevitable cost. This improvement has been demonstrated by comparative simulation and numerical studies. A case study for the maximum creation of two dynamic periods (two upper bound) has been described and investigated in this paper. But the model can be extended to any upper bound.

This work is the fist attempt to use the clustering concept for reducing broadcast messages' latency. There is ample room for improvement; we enumerate the following issues that represent open perspectives.

- To tackle node mobility, a new module called reorganization module shall be added. It must take into account the balancing of node members between all the clusters in the WSN.
- The use of stochastic Petri nets for modeling phase II of the proposed solution can be investigated. Petri nets permit to memorize the past, unlike the ordinary Markov chain that is a memoryless model. This can be helpful for making more accurate decisions on the DAP activation.
- Securing the proposed protocol is a must for many applications. Nonetheless, adding security services must be performed with careful consideration of the resulting additional cost.
- Generalization of the model to n upper bound for DAP creation is also in our agenda.

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