Cluster-Based Fast Broadcast in Duty-Cycled Wireless Sensor Networks

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***Abstract*—This paper proposes a cluster-based broadcast protocol to disseminate delay-sensitive information throughout a wireless sensor network (WSN). The protocol considers the use of duty-cycling at the MAC layer, which is essential to reduce energy dissipation. LEACH's energy-efficiency approach is used for cluster construction. 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 reduce broadcast latency. The clustering mechanism allows for simultaneous local broadcasts at several clusters in the WSN, and it also ensures scalability with the increase of the network size. The protocol has been simulated, numerically analyzed, and compared with LEACH. The results show clear improvement over LEACH with regard to the latency.**

***Keywords*-wireless sensor networks, global broadcast, duty-cycle MAC, QoS protocols.**

I. Introduction

The broadcast considered herein consists in disseminating a message throughout the network. In multi-hop networks, optimally translating this into a set of local (one-hop) broadcasts is challenging. 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 minimizing the number of transmissions. This is insufficient when introducing duty-cycling, as sleep-time of the receivers at each hop inevitably increases the latency, and several retransmissions may be needed to achieve a local broadcast. Some recent broadcast protocols focus on this problem and takes sleep-time delay into account. Opportunistic Flooding [1], ADB [2], Hybridcast [3], and the solution of [4] are examples of such protocols. All these solutions are either flat or tree-based, where several serial transmissions are needed to achieve a global broadcast due to the shared nature of the medium. The proposed protocol uses a different approach that enables parallel transmissions. It is based upon LEACH [5], which splits up sensor nodes into clusters with one cluster-head (CH) for each cluster. The CH main function is to aggregate data it receives from its members and 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 between CH nodes, which reduces the latency. The key idea behind the proposed solution is to plan for all sensor nodes –in addition to their respective transmission slots– common active (receiving) periods, so that every CH can send any potential received broadcast message during this period with a single transmission. To achieve such a goal, the following assumptions are made, i) the WSN is static,i.e. node mobility is not considered; ii) sensor nodes are homogenous; and iii) the synchronization between sensor nodes is assured by applying some synchronization protocols, such as [6].

Before a detailed description of the proposed protocol, a brief description of LEACH is first needed. LEACH runs in rounds, each of which consists of two phases, set-up phase and steady phase [5]. In the set-up phase, clusters are created, and TDMA schedules are accordingly established, which are used for communications between a member node and its cluster-head. FDMA 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 communication between cluster-heads and the BS, direct-sequence spread spectrum (DSSS)-which is a CDMA technique - is used, whereby each cluster-head is assigned a unique spreading code. Once the set-up phase achieves, the steady-phase then begins, where the sensed data is sent by the member nodes to their respective CH during their allocated timeslot within the schedule. This allows each node to turn off the radio until 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.

II. Solution Description

This section describes the proposed cluster-based protocol, termed in what follows BOD-LEACH. Following LEACH concept, it runs in two phases, i) the set-up phase, and ii) the steady-phase. 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. The DAP creation depends upon the messages-arrival times. These periods (DAPs and BAPs) are dedicated to broadcast messages. As aftereffect of the assumptions announced in Section I, 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 after that.

The first phase of the protocol is timed from the beginning of the steady phase until the end of the time slot(s) attributed to the last cluster-member within the TDMA schedule. This is for each cluster in the WSN. Right after phase 1, BAP1 is activated and succeeded by BAP2. BOD-LEACH figures out the broadcast over duty-cycled MAC protocol problem as follow. 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 for each node- including BS and CH nodes- after the time slot of the last member in the cluster that have 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 set-up phase. BAP2 always starts before the end of the round, for the purpose not to let the message stalling till the next round. Beside activating the two static periods, messages that arrive between them are handled separately. Delaying the broadcast of such messages to BAP2 yields to a dramatic latency, specially when the round length time is long, which is typical in WSN for the sake of ensuring power-efficiency. The main idea to tackle this 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 periods (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 on the incoming broadcast messages during the pervious round. Detailed description will be provided in Section II-B. Note that the scheduled time of both BAP and DAP for every node in the WSN is assured by the BS, after running the set-up phase at each node level.

A. Phase I

This phase depends upon the number of member nodes in each cluster, as well as on the time-slot length. 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 time-slot, then it goes to sleep. 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 coincides with the time of the first time-slot in the TDMA schedule.

B. Phase II

The second phase of the proposed solution handles broadcast messages that arrive through the period between BAP1 and BAP2, which should be proportional to the duty-cycle ratio. It is generally set for as long as possible to save power consumption. The idea is to study the dynamical messages arrival process to decide on DAP activations (creation). This is to minimize the end-to-end delay of such messages. Discrete Markov chain and Poisson process distribution probability [7] are used by the proposed solution for this purpose.

For the sake of simplifying the modeling and without loss of generality, we study the case when at most two DAP can be created. 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 is supposed to be a random process following a Poisson distribution, which is studied using a discrete Markov chain [7]. In this case, four possible states are considered:
(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, and (e_3) : the two DAP are created. These DAP are triggered depending on the number of the broadcast messages. This number is a random variable (rv) following Poisson process [7]. 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,

$$P(X=k)=\frac{e^{-\lambda}*\lambda^{k}}{k!}, \tag{1}$$

where k stands for the number of random events, X the rv representing the number of events. Using the Poisson probability distribution associated to the Markov chain that models the solution, the transition probability, say $P_{e_ie_j}$, between every pair of states, i, j, can be calculated;

$$(P_{e_0e_1})=1-(\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_1}*\lambda_1^k}{k!})*\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_2}*\lambda_2^k}{k!}, \tag{2}$$

$$(P_{e_0e_2})=\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_1}*\lambda_1^k}{k!}*(1-\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_2}*\lambda_2^k}{k!}), \tag{3}$$

$$(P_{e_0e_3})=(1-\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_1}*\lambda_1^k}{k!})*(1-\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_2}*\lambda_2^k}{k!}), \tag{4}$$

$$(P_{e_1e_0})=\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_1}*\lambda_1^k}{k!}*\sum_{k=0}^{K=\alpha-1}\frac{e^{-\lambda_2}*\lambda_2^k}{k!}. \tag{5}$$

Where α represents the minimum threshold on the number of messages that must arrive during the phase for the creation of the appropriate DAP. Mathematical concepts related to Markov Chain and transition probability calculation can be found in [7].

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 in given state, e_i, has to fulfilled the following.

$$(P_{e_ie_i}) = 1 - \sum_{j \neq i} P_{e_ie_j} \forall i \in \{0, 1, 2, 3\} \tag{6}$$

The desired stationary distribution is obtained by resolving,

$$\Pi = \Pi * P \tag{7}$$

Where Π is the stationary distribution vector, which is a (row) vector whose entries are non-negative and sum to 1, and P represents the transition probability matrix. The resolution of the system of equations Eq. (7) yields the following unique stationary distribution of the steady state,

$$\Pi_j = P_{e_0e_j}, \forall j \in \{0, 3\}, \tag{8}$$

In practice, if 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 be selected to determine DAP activation/deactivation. As the number of broadcast messages is a Poison proses, their respective time arrivals follow exponential distribution [7]. Therefore, these successive events (called inter-arrival times) are independent exponentially distributed rv, with parameter λ (mean 1/λ). Let us consider a Poisson process with rate λ, and T_k the time of the k_{th} arrival, for $k \in \{1, 2, 3, ...\}$. Time arrivals (T_k) can be generated using,

$$T = \frac{-ln(X)}{\lambda} \tag{9}$$

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 Eq. (9) is used to generate a series of an exponential rv.

III. Simulation and Analysis

In this section, the performance of the proposed solution is investigated. For the first diffusion phase, we implemented the solution on the $TinyOS_{2.x}$ operating system using nesC language and PowerTOSSIM simulator. For the second diffusion phase, Mathlab environment has been used to analyze the mathematical modeling. Plots presented hereafter are the average of several measurements, with a 95% of confidence interval.

As shown in Fig. 1, the gap between the two protocols in terms of 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 that 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 ensures partial reception, such as Hybridcast.

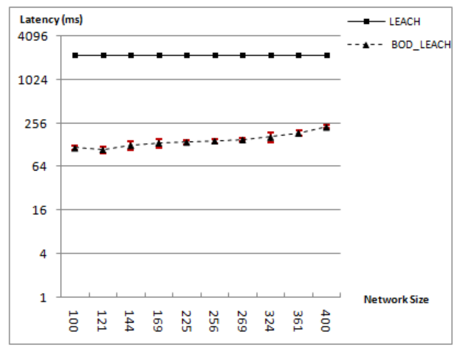
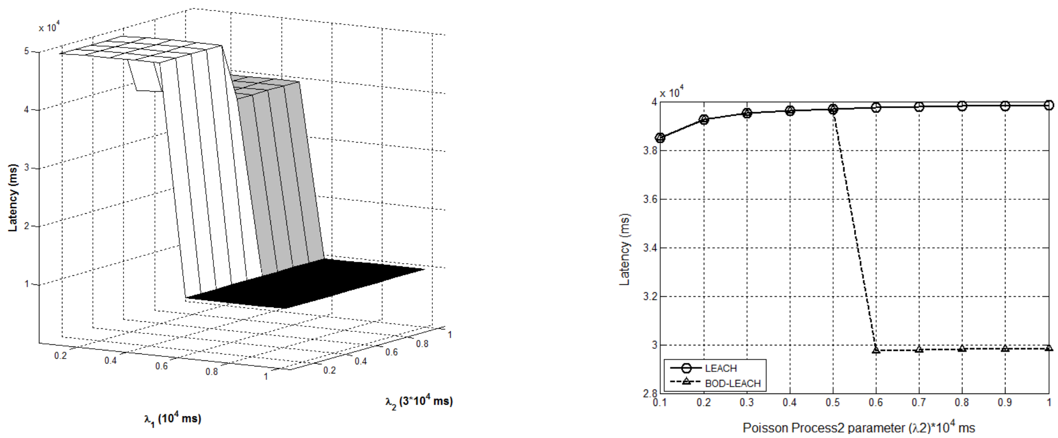


Figure 1. Latency

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 having the higest number of member nodes among all the clusters. This latency is in fact the time difference between the time-slot of the first node in the TDMA schedule and the BAP.

The end to end latency of messages arriving during phase II depends on how many DAP shall be created, which in turn depends on the broadcast message arrival process. The intensity of the two Poisson processes has been varied, and the stationary distribution vector has been calculated. The state having the highest probability has been selected. In order to simulate and evaluate the end-t-end broadcast latency vs. the DAP creation, a sample of broadcast message arrival times has been generated using Eq. (9). The latency is measured as the time gap between the arrival of the broadcast message and the next created DAP. The diffusion phaseII 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 to 30.000ms. Fig 2 (a) plots the latency of BOD-LEACH for messages that arrive during the first Poisson process. It can be remarked that for an intensity of the first process (λ_1) in the interval $[0.5, 1]$, BOD-LEACH latency is minimized, which is due to the DAP1 creation. For $\lambda_1 \in [0, 0.5[$, the latency inevitability increases, because of the non-creation of DAP1. However, λ_2 values in $[0.5, 1]$ helps reducing the latency through the creation of DAP2 compared to the case where both λ_1 and λ_2 are in $[0, 0.5[$ (no



(a) (b)

Figure 2. Latency for messages arriving during: (a) process 1, (b) phase 2

DAP creation). Note that Opposed to BOD-LEACH, the end-to-end latency under LEACH has been constant and equaled the maximum value of BOD-LEACH, regardless the values of λ_1 and λ_2.

Unlike the 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. Fig. 2 (b) demonstrates a reduction over LEACH when $\lambda_2 > 0.5$. This is justified by the creation of DAP2.

IV. Conclusion and Perspectives

In this paper, the problem of broadcast message latency in wireless sensor network (WSN) with active/dormant cycles (duty-cycled MAC) has been considered. The BOD-LEACH protocol has been proposed; a duty-cycle enabled protocol 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 that are 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. The improvement has been demonstrated by a comparative simulation and numerical studies. A case study for the creation of two dynamic periods in maximum (two upper-bound) has been described and investigated in this paper. However, 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. 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 DAP (dynamic access period) activation. Securing the proposed protocol is a must for many applications. Nonetheless, adding security services must be done with careful consideration of the resulting additional cost. Finally, generalization of the model to n upper-bound for DAP creation is also in our agenda.

References

[1] Y. G. huo Guo, B. Jiang, and T. He, "Opportunistic flooding in low-duty-cycle ireless sensor networks with unreliable links," in *ACM MobiCom'09*, september 2009, pp. 167–172.

[2] Y. Sun, O. Gurewitz, S. Du, L. Tang, and D. B. Johnson, "Adb:an efficient multihop broadcast protocol based on asynchronous duty-cycling in wireless sensor networks," in *SenSys'09*, November 2009.

[3] S. Lai1 and B. Ravindran, "On multihop broadcast over adaptively duty-cycled wireless sensor networks," in *IEEE International Conference on Distributed Computing in Sensor Systems (IEEE DCOSS)*, 2010.

[4] F. Wang and J. Liu, "Duty-cycle-aware broadcast in wireless sensor networks," in *IEEE INFOCOM'09*, April 2009, pp. 468–476.

[5] M. Handy, M. Haase, and D. Timmermann, "Low energy adaptive clustering hierarchy with deterministic cluster-head selection," in *IEEE MWCN*, 2002, pp. 368–372.

[6] D. Djenouri, "R^4syn : Relative referenceless receiver/receiver time synchronization in wireless sensor networks," *IEEE Signal Process. Lett.*, vol. 19, no. 4, pp. 175–178, 2012.

[7] C. Cocozza-thivent, *Discrete Stochastic Processes*. Kluwer Academic Publishers Boston, 1998.