Alleviating the Domino Effect in Wireless Sensor Networks

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Abstract—In hierarchical-based routing in sensor networks, the concept of Cluster-Heads (CHs) is used to reduce routing complexity and improve performance. This happens as non-CH members send their sensed data to the CH, which then sends the aggregated signal to the BS either directly or by collaborating with other CHs. However, in this type of routing, the death of one CH during a round leads to virtual death of all the nodes in its cluster. This cascades into other clusters and induces a series of identical effects, causing intensive virtual death of nodes which eventually leads to inefficient utilization of energy. We refer to this problem as the “Domino-Effect”, and propose a centralized energy-aware routing protocol, called Domino-effect-Evasive Energy-efficient Hierarchical Routing Protocol (DEEHRP) to explicitly reduce this effect. DEEHRP is an extension to the Energy-efficient Hierarchical Routing Protocol (EHRRP). Extensive simulation results confirm that DEEHRP outperforms the well-known Base-station Controlled Dynamic Clustering Protocol (BCDCP). In particular, it reduces energy consumption by up to 36% as compared to BCDCP. Furthermore, results show that DEEHRP succeeds in alleviating the domino-effect problem and curtailing its effect by up to 25.5% and 10.3%, over BCDCP and EHRP, respectively.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of a sheer number of densely deployed, small-sized, low-cost, limited power devices, which are fully equipped for the purpose of gathering certain information and monitoring physical environments. WSNs have been capturing interest in a wide range of applications in a variety of fields including environmental monitoring, industrial sensing, infrastructure protection, battlefield awareness, and others[1][2].

Routing protocols in WSNs include many efficient hierarchical-based protocols. Some of these protocols embrace the strategy where, after organizing themselves into dynamically changing clusters, CHs communicate directly with the BS. Examples of these protocols are LEACH [1], LEACH-C [1], HEED [2], HCR [2], DEEAC [2], and SPEAR [2]. Whereas the strategy followed by other protocols is to divide communication into intra-cluster and inter-cluster communication where the BS is reached by engaging into a multi-hop routing path. BCDCP [3], PCR [4], EPCR [4], PEDAP [5], PEDAP-PA [5], and EHRP [6] are all examples of these protocols. The death of one CH during a round leads to virtual death of all the nodes in its cluster. In protocols involving both intra-cluster and inter-cluster communication, this effect cascades into other clusters inducing a set of similar effects and causing intensive virtual death of nodes. We refer to this problem as the domino-effect problem.

The pillar contributions of this paper are: 1) providing first-hand discussion of the domino-effect problem, and 2) introducing explicit solution to alleviate this problem. In order to assess the domino-effect problem, we have used the average wasted energy dissipation as a quantitative metric. This paper presents a dynamic centralized hierarchical-based routing protocol that aims at augmenting energy savings and explicitly reducing the average wasted energy dissipation. The proposed protocol is an extension to EHRP [6]. The proposed protocol (DEEHRP) explicitly mitigates the domino-effect problem by handing over the role of a dying CH to another carefully selected node, called delegate, directly before it runs out of energy. The operation of the protocol is divided into rounds. Each round is composed of a set-up phase and a data communication phase. We assume the utilization of the first order radio model as it is the energy model typically used in literature [1][3], BCDCP [3] has been used as a benchmark for evaluating the performance of the proposed protocol.

The rest of the paper is organized as follows. Section II introduces the domino-effect problem. Section III presents a detailed discussion of the proposed protocol (DEEHRP). Section IV shows, via simulations, the effectiveness of DEEHRP in alleviating the domino effect problem. Section V concludes the paper.

II. PROBLEM STATEMENT

The death of one CH during a round leads to virtual death of the remaining nodes in its cluster. One of the problems of hierarchical routing protocols that incorporate both inter-cluster and intra-cluster communication into their structure, is that clusters are no longer isolated from each other. Consequently, the effect caused by the death of one CH during a round cascades into other clusters and triggers a series of identical effects, which causes other CHs and all the nodes in their clusters to be virtually dead. Since the influenced nodes are not aware of such effect, they continue transmitting and receiving their signals even though they can no longer reach the BS. This causes them to wastefully dissipate their energy. We refer to this problem as the domino-effect problem. For example, in Figure1(a), should cluster-head number 1 (CH1) run out...
of energy during a round of operation, all the nodes in its cluster (i.e. nodes 5 and 6) are bound to lose communication. Following this virtual death and until the end of the round, every data transmission conducted by these nodes will result in dissipating wasted energy. In addition, since CH1 is the CH through which CH2 and CH3 traverse their data to the BS, this effect will cascade into their clusters as well. This causes a series of similar effects that will extend to reach CH4 and its cluster. Note that the best case scenario is the death of a cluster-head that lies at the bottom of the tree (e.g. CH4 or CH2 in Figure 1(a)). This is because none of the CHs traverse their data to the BS through it. Thus the effect of its death will be merely confined to its own cluster. Whereas, the worst case scenario is the death of the leader CH (CH1 in Figure 1(a)) since the effect of its death will cascade into all the clusters in the network.

On the other hand, in hierarchical structures where CHs communicate directly with the BS, all clusters are completely isolated from the repercussions of any CH death. This guarantees only mild occurrence of the domino-effect problem as it would be merely confined to the cluster in question. For example, in Figure 1(b), the effect caused by the death of CH1 is merely restricted to the nodes in its cluster (i.e. nodes 4 and 5). CH2 and CH3 are not affected by such death, ergo, neither are the nodes in their clusters. In this paper, we are not interested in studying the domino-effect problem in this type of hierarchical structures as it does not occur severely.

III. PROPOSED PROTOCOL (DEEHRP)

DEEHRP uses the same hierarchical structure as EHRP [6]. EHRP mitigates the energy-intensive role allotted to CHs by confining their task to inter-cluster communication only while uniformly distributing intra-cluster communication among a set of powerful nodes in terms of energy reserve, called collecting-set. At any given time, only one member of the collecting-set is active, whereas the remaining members are in sleep mode. Hence, a sensor node in each cluster can either be a plain node, a collecting node, or a cluster-head. Plain nodes transmit the sensed data to their currently active collecting node, which in turn collects the sensed signals from the plain nodes and aggregates them before sending the aggregated data to the CH. Upon receiving the aggregated data, the CH forwards it to the BS via multi-hop CH-to-CH routing path. The data communication phase is divided into iterations. By the end of an iteration, all members of the collecting-set will become active once [6]. DEEHRP deals with the death of a CH and/or a collecting node by infusing certain precautions in the rounds following the manifestation of the first node death. During the set-up phase of the round following the first node death, the BS selects a checkpoint, denoted CP, occurring at some time after the beginning of the round. This checkpoint is sent to sensor nodes, along with other set-up information. The selected CP remains the same for the remaining rounds of operation. Starting from the checkpoint till the end of a round, for all the rounds following the manifestation of the first power drainage, a certain procedure is applied. This procedure is composed of three fundamental stages conducted by different elements. A detailed discussion of each of them is provided below.

A. Assigning Ranks to Collecting Nodes as Delegates

At the end of the set-up phase, the BS assigns a rank, denoted ran(j), to each collecting node in each cluster. This rank merits its capacity as a delegate for the CH should the latter fail to efficiently play its role. In each cluster, the rank assigned to each collecting node is based on the amount of energy it would dissipate relative to its residual energy if it assumed the role of the CH. Note that the amount of energy dissipated by CH_i, 1 ≤ i ≤ k per frame is given by the following equation:

$$E(CH_i) = (1 + h_i)E_R(L) + E_{T-parent(CH_i)}(L, d)$$ (1)

where $(1 + h_i)E_R(L)$ is the amount of energy dissipated by cluster-head i due to receiving from the active collecting node as well as from the h cluster-heads acting as its children in the spanning tree. $E_{T-parent(CH_i)}(L, d)$ is the amount of energy CH_i dissipates due to transmission to the CH acting as its parent. When assigning ranks, the receiving term in Equation 1 can be ignored. This is because it remains the same no matter which collecting node acts as the CH. Hence, for each cluster $i, 1 ≤ i ≤ k$, the BS applies the following:

1. Compute the following cost function for each member $j$ of the collecting-set, where $1 ≤ j ≤ m$, and $e_j$ is the residual energy of node $j$.

$$C_{j-parent(CH_i)} = \frac{E_{T-parent(CH_i)}(L, d)}{e_j}$$ (2)

2. Assign a rank $ran(j)$ to each member of the collecting-set based on the value of $C_{j-parent(CH_i)}$. The node yielding the lowest value is assigned the highest rank, and vice versa.

3. The BS sorts the collecting nodes of each cluster based on their ranks in a descending order, and keeps them in a table called the ranking table.

Upon conclusion of the setup phase, the data communication phase begins. This phase is divided into iterations. Starting from the round following the manifestation of the first node death till the end of operation, the following two precautionary stages are applied. They take place prior to each iteration, during the period starting from the checkpoint CP till the end of the round.

B. Checking the Current Energy Level

In this stage, each collecting node and CH checks its current energy level to determine if it has reached its risky level. The risky level of a collecting node $j$ in cluster $i$ is reached if its current energy level $e_j$ is less than the amount...
of energy required to perform its task. That is, the energy required to receive signals from the p plain nodes in the cluster, aggregate them, and transmit the aggregated signal to the CH. Therefore the risky level is reached if:

\[ e_j < p_i E_R(L) + E_{DA} + E_{T-CH}(L, d) \]  
(3)

During an iteration, a CH performs its task m times since m frames are transferred to the BS per iteration. Thus, the risky level of a CH is reached if:

\[ e_i < mE(CH_i) \]  
(4)

where \( E(CH_i) \) is illustrated in equation 1. If a CH realizes that its current energy level has indeed reached a risky level, it has to determine exactly how many frames, \( N_{frames} \), it can accommodate during this iteration before it becomes no longer fit for operation:

\[ N_{frames} = \left\lfloor \frac{e_i}{E(CH_i)} \right\rfloor \]  
(5)

Hence, \( CH_i \) will no longer be fit for operation, and consequently a delegate will be employed, at time \( t_{stop} \):

\[ t_{stop} = N_{frames} \times t_{frame-CH} \]  
(6)

where \( t_{frame-CH} \) is the time taken by \( CH_i \) to perform its task per frame. Upon determining its \( t_{stop} \), a dying CH sends a message called DEATH_ALARM; disclosing its own Id and \( t_{stop} \) to the BS. Also, if any collecting node realizes that its current energy level has indeed reached a risky level, it sends a message called DEATH_ALARM as well, dispatching its own Id to the BS.

C. Assigning Delegates and Performing Updates

Prior to each iteration in the data communication phase, the BS assigns among the clusters, and does the following: 1) If it has received a DEATH_ALARM message concerning one or more collecting nodes in the cluster, it looks them up in the ranking table and removes them. It then adjusts the ranks of the remaining collecting nodes accordingly. 2) If it has received a DEATH_ALARM message concerning the CH, it looks at the ranking table to determine the collecting node that should be chosen as its delegate. The node with the highest rank is to be selected. Once selected, the BS removes the node from the ranking table and adjusts the ranks of the remaining nodes accordingly. The delegate node is to be the new CH at time \( t_{stop} \). 3) Now the nodes remaining in the ranking table are the collecting nodes for the next iteration. Accordingly, the BS adjusts the time schedule pertinent to the uniform rotation of their transmission time. The BS then sends the updated set-up information to the sensor nodes. The delegate node will not play its role until the time \( t_{stop} \).

IV. PERFORMANCE EVALUATION

DEEHRP has been simulated using Visual C# 2008. Different simulation experiments have been conducted to evaluate its performance and weigh its leverage. BCDCP has been used as a benchmark in the evaluation process. Performance assessment is achieved using average energy dissipation, average wasted energy dissipation (i.e. due to the "domino-effect" problem), and the average delay as quantitative metrics. The main goal of this work is to alleviate the domino effect problem. Simulation results have been obtained by calculating the average of several independent experiments. The experiments have been conducted using various randomly-generated configurations of the simulation network whose parameters are summarized in Table I. The value of the check point (CP) is set to the last 50% of the round.

Part of the energy dissipated by sensor nodes is wastefully consumed due to the domino-effect problem. Figure 2 quantifies the average wasted energy dissipation. As long as all sensor nodes are intact none of the routing protocols has to deal with the manifestation of wasted energy. In BCDCP, 26% of the energy dissipated during the rounds encountering nodes death is consumed in wasted vain. In EHRP, the manifestation of wasted energy constitutes 12%, 11.8%, 10.2% and 7.6% of the amount of energy dissipated when using 2, 3, 4, and 5 collecting nodes, respectively. This reduction can be attributed to two reasons. First, the task performed by CHs in BCDCP is more energy-intensive than the one assigned to CHs in EHRP. Second, in EHRP, a huge part of the task usually performed by CHs is uniformly distributed among collecting-set members. In DEEHRP, the manifestation of wasted energy constitutes 2%, 1.5%, 0.7% and 0.5% of the amount of energy dissipated when using 2, 3, 4, and 5 collecting nodes, respectively. In addition to the two reasons shared with EHRP, the reduction exhibited by DEEHRP can be attributed to the precautionary measures taken in delegating the task of a dying CH to any of the collecting nodes in its cluster to alleviate the domino effect even further.

Figure 3 depicts the average amount of energy dissipated over rounds of operation. It clearly exemplifies significant improvements yielded by DEEHRP over BCDCP. It shows that DEEHRP offers on average a reduction in energy dissipation of 13%, 20%, 25%, and 36% when using 2, 3, 4, and 5 collecting nodes, respectively. Such improvement in energy savings is attributed to the leverage gained due to alleviating the energy-intensive burden imposed upon CHs, and the fact that DEEHRP (like EHRP) uniformly distributes the load among all the collecting-set members. This explains why the yielded results insinuate a connection between the improvement gained and the number of collecting nodes. EHRP and DEEHRP graphs coincide until the manifestation of the first node death. However, in the rounds following that, a tightly limited increase in energy dissipation is generated when executing DEEHRP. This is since the expected increase in energy dissipation as a result of using collecting nodes as delegates when necessary is counteracted by the decrease

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Nodes</td>
<td>500</td>
</tr>
<tr>
<td>Field Area</td>
<td>100m × 100m</td>
</tr>
<tr>
<td>BS Position</td>
<td>75 m away from the nearest node</td>
</tr>
<tr>
<td>Number of Frames per Round</td>
<td>40</td>
</tr>
<tr>
<td>Frame Size</td>
<td>500 bytes (25 bytes header)</td>
</tr>
<tr>
<td>Initial Energy</td>
<td>25</td>
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<tr>
<td>Processing Delay</td>
<td>50µs</td>
</tr>
<tr>
<td>Data Transfer Rate</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Number of Collecting Nodes</td>
<td>2 to 5</td>
</tr>
</tbody>
</table>
in energy dissipation due to the reduction in wasted energy. Figure 4 demonstrates the average delay encountered by DEEHRP, EHRP, and BCDCP. EHRP shows an increase in the average delay by 10%, 26%, 36%, and 44% over BCDCP, when using 2, 3, 4, and 5 collecting nodes, respectively. This can be traced back to several reasons. One of them is that EHRP is inclined towards seeking energy-efficient compromise between the nodes residual energy and their spatial separation rather than merely considering the latter. This inclination can lead to relative delay in data propagation as nodes are not necessarily connected to those closest to them. Another reason is the increased amount of time required by the BS to configure the network, which evidently increases as the number of collecting nodes increases. In DEEHRP, the average delay starts to increase even further starting from the round witnessing the first node death till the end of operation. This is because data transmission is deferred prior to each iteration in order for the CHs and the collecting nodes of each cluster to check their energy level, inform the BS of their status when necessary, and wait for the BS to respond.

V. CONCLUSION

This paper introduces the domino-effect problem in the context of hierarchical routing protocols in WSNs. The proposed DEEHRP mitigates this problem by: 1) alleviating the energy-intensive load imposed upon CHs by restricting their role to inter-cluster communication only while uniformly distributing intra-cluster communication among a set of powerful nodes in terms of energy reserve, called collecting-set, and 2) handing over the role of a dying CH to one of the collecting nodes before running out of energy. Simulation results show that DEEHRP manages to curtail the domino-effect problem by up to 25.5% and increase energy savings by up to 36% over BCDCP. These improvements are proportional to the number of collecting nodes. However, increasing the number of collecting nodes results in a corresponding increase in delay.

REFERENCES