Infrastructure Communication Reliability for WSN on Sink-manycast and Sink-anycast Model *

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Abstract - We consider the problem of the infrastructure communication reliability (ICR) of wireless sensor networks (WSN) on sink-manycast and sink-anycast model. We formulate ICR metrics for WSN with hierarchical clustered topology base on an reduced ordered binary decision diagrams (ROBDD) approach. Furthermore, we give the case study of the metrics application of WSN with hierarchical clustered topology. Based on the reliability metrics, we will optimize the structure of WSN to achieve the optimal network reliability.

Index Terms - Wireless sensor network, Infrastructure communication reliability, Sink-manycast, Sink-anycast.

I. Introduction

A WSN consists of a large number of sensor nodes and a base station. The sensor nodes are designed to collect data from the environment. The base station is an aggregation node for collecting data and it can also performs as an interface between the WSN and other networks or human operators. The communication within WSN can be conceptually classified into two categories: application communication and infrastructure communication [1], [2]. Application communication relates to the transfer of sensed data collected from the physical environment. Infrastructure communication relates to the delivery of configuration and maintenance messages (e.g. network set-up, query, path discovery, processing tool, operating system, and policies). The reliable data delivery in both paradigms must be guaranteed. Refer [3] for studies on the reliability analysis of WSN under the application communication paradigm. This work only addresses the infrastructure communication reliability (ICR) of WSN.

Presently, star, tree, mesh, and hierarchical clustered topologies have emerged as the topology choices for WSN. Each topology has its own pros and cons in terms of communication efficiency, complexity in routing protocol design, and overhead to setup and maintain the topology with the presence of node failure and possible mobility [4]. hierarchical clustered topologies is very porpular in WSN application ,so in the section 3,we formulates ICR metrics for WSN with hierarchical clustered topology. We also give the case study in the section 4.

II. Problem Statement

For the infrastructure communication for WSN with hierarchical clustered architecture, three different data delivery models have been considered for the WSN reliability analysis in [5]. They are: 1) sink unicast where the base station sends control messages to a single sensor, 2) sink multicast where the base station sends control messages to a group of sensors, 3) sink broadcast where the base station sends control messages to all sensors. In this work, we consider two new data delivery models for WSN, namely sink manycast and sink anycast. In the sink manycast model, the base station sends control messages to a subset of sensors out of a large group of qualified sensors. For example, when there are n qualified sensors, the control message is expected to be received by any m out of n sensors. As a special case of sink manycast, sink anycast requires the base station to send control messages to any one out of a group of qualified sensors (i.e., m = 1) [6, 7]. To the best of our knowledge, no work has been done to address the infrastructure communication reliability (ICR) of WSN under the sink manycast and anycast models. This section proposes new reliability metrics for the manycast and anycast ICR analysis in WSN with hierarchical clustered architecture.

In the hierarchical clustered topology, sensors are organized into clusters with cluster heads (CH), and low-level cluster heads form high-level clusters. Communications within a cluster and between cluster heads are based on multi-hop mesh routing [8]. Figure 1 illustrates a small example of WSN with hierarchical clustered topology. Note that level 0 is the lowest level in the hierarchy.

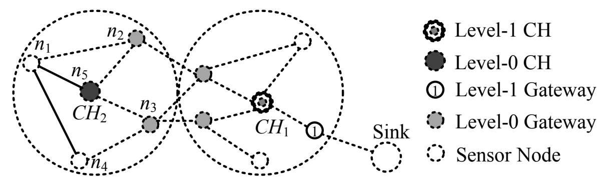

Figure 1 An example of WSN.

III. Reliability Model

The progressive reduction method proposed in [9] can greatly reduce the complexity of reliability analysis in WSN. A level-i graph can be reduced to a graph containing only the level-i CHs and level-i inter-cluster gateways. Here, inter-

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cluster gateways are the nodes that are connected to the nodes in the neighboring clusters within one hop. With this reduction, it is sufficient to analyze only the clusters/sub-networks for reliability, instead of the entire network.

The level-i graph is modeled by an undirected probabilistic graph G(i) (V, E), where V is the set of vertices (sensor nodes) and E is the set of edges (links). Let CH(k) denote the level-k cluster heads, and g(k) denote the gateway nodes connecting two neighboring level-k clusters. The progressive reduction scheme starts from G(0) (V, E), G(i) (V, E) is reduced to G(i+1) (V, E) which contains only CH(i) and g(j) where j ≥ i and the two-terminal reliabilities between CH(i) and g(i) are computed from G(i) (V, E) and assigned as reliability of the corresponding CH to gateway link at G(i+1) (V, E). This reduction scheme is iterated until the top level of the hierarchy is reached.

Reliability is generally defined as "the probability that the system will perform its intended function under stated conditions for a specified period of time" [10]. In particular, the infrastructure communication reliability (ICR) of WSN is the probability that there exists an operational path from the sink node to the required nodes.

A . Sink Anycast

The ICR in this scenario is the probability that there exists an operational path from the sink node to at least one sensor node out of a group of qualified nodes. For hierarchical clustered topology, the ICR is the probability that there exists an operational path from the sink node to top hierarchical level CH, then to the next hierarchical level CH and so on to the destination group's CH and finally to any sensor node in that group. Note that the qualified sensor nodes in the group may not belong to a single cluster. Let Q denote the set of qualified nodes, a denote any sensor node in Q, and hk denote the CH that is hierarchically above a at parent level k, 0 ≤ k ≤ t. Then the ICR of WSN with hierarchical clustered topology for sink anycast can be formulated as equation 1.

$$ICR_{anycast} = \Pr\left\{ \bigcup_{\forall a \in Q} \left[\begin{array}{l} E_2\left(\text{sink to}\, CH^{(t)}{}_{h_t}\right) \cap \\ E_2\left(CH^{(t)}{}_{h_t}\ \text{to}\ CH^{(t-1)}{}_{h_{t-1}}\right) \cap \cdots \cap \\ E_2\left(CH^{(1)}{}_{h_1}\ \text{to}\ CH^{(0)}{}_{h_0}\right) \cap E_2\left(CH^{(0)}{}_{h_0}\ \text{to}\ a\right) \end{array} \right] \right\} \quad (1)$$

where E2 represents the event that there exists an operational communication path between a given pair of nodes. Thus, Pr(E2) can be evaluated as two-terminal reliability.

Consider the special case in which all the qualified sensor nodes belong to a single cluster r. The ICR of WSN for this special case can be formulated as equation 2.

$$ICR_{anycast-r} = \Pr\left\{ \begin{array}{l} E_2\left(\text{sink to}\, CH^{(t)}{}_{h_t}\right) \cap E_2\left(CH^{(t)}{}_{h_t}\ \text{to}\ CH^{(t-1)}{}_{h_{t-1}}\right) \cap \cdots \cap \\ E_2\left(CH^{(1)}{}_{h_1}\ \text{to}\ CH^{(0)}{}_{h_0}\right) \cap \left[\cup_{\forall a \in Q} E_2\left(CH^{(0)}{}_{h_0}\ \text{to}\ a\right) \right] \end{array} \right\} \quad (2)$$

B . Sink Manycast

The manycast-based ICR is the probability that there exists an operational path from the sink node to at least one subset of sensor nodes out of a larger group of qualified sensor nodes. For hierarchical clustered topology, the manycast-based ICR is the probability that there exists an operational path from the sink node to top hierarchical level CH, then to the next hierarchical level CH and so on to the destination group's CH and finally to all sensor nodes in any one subset. Note that the qualified sensor nodes in the group may not belong to a single cluster. Let Rx denote a subset of qualified nodes, a denote any sensor node in Rx, n denote the number of sensor nodes in the qualified group, m denote the required number of sensor nodes in each subset, H0,x denote the set of CH(0) for nodes in Rx, and Hl,x denote the set of CH that is hierarchically above Rx at parent level l, 0 ≤ l ≤ t. Then the ICR of WSN with hierarchical clustered topology for sink manycast can be formulated as equation 3.

$$ICR_{manycast} = \Pr\left\{ \bigcup_{x=1}^{C_n^m} \left[\begin{array}{l} \left[\cap_{\forall i \in H_{t,x}} E_2\left(\text{sink to}\, CH^{(t)}{}_i\right)\right] \cap \left[\cap_{\forall j \in H_{t-1,x}}^{\forall i \in H_{t,x}} E_2\left(CH^{(t)}{}_i\ \text{to}\ CH^{(t-1)}{}_j\right)\right] \\ \cap \cdots \cap \\ \left[\cap_{\forall j \in H_{0,x}}^{\forall i \in H_{1,x}} E_2\left(CH^{(1)}{}_i\ \text{to}\ CH^{(0)}{}_j\right)\right] \cap \left[\cap_{\forall a \in R_x}^{\forall i \in H_{0,x}} E_2\left(CH^{(0)}{}_i\ \text{to}\ a\right)\right] \end{array} \right] \right\} \quad (3)$$

Consider the special case in which all the qualified sensor nodes belong to a single cluster r. Let hl be the parent CH of cluster r at the level l. The ICR of WSN for this special case can be formulated as equation 4.

$$ICR_{manycast-r} = \Pr\left\{ \begin{array}{l} E_2\left(\text{sink to}\, CH^{(t)}{}_{h_t}\right) \cap E_2\left(CH^{(t)}{}_{h_t}\ \text{to}\ CH^{(t-1)}{}_{h_{t-1}}\right) \cap \cdots \cap \\ E_2\left(CH^{(1)}{}_{h_1}\ \text{to}\ CH^{(0)}{}_{h_0}\right) \cap \left\{ \cup_{x=1}^{C_n^m} \left[\cap_{\forall a \in R_x} E_2\left(CH^{(0)}{}_{h_0}\ \text{to}\ a\right) \right] \right\} \end{array} \right\} \quad (4)$$

Note that the ICR expressions (1), (2), (3), and (4) can be simplified to obtain tight approximations. For example, (4) can be tightly lower-bounded by (5). This is an efficient simplification because storing and manipulating symbolic expressions are very computationally intensive. This simplification is also realistic under the practical assumption that the clusters are non-overlapping, and nodes that participate in communication between CH(k) and CH(k+1) do not generally participate in communication between CH(k) and CH(k-1), and when they do participate, their contribution is insignificant. That is all the sub-events are disjoint provided that we account for each CH reliability only once along any operational path.

$$\begin{aligned} ICR_{manycast-r} &= \Pr_2\left(\text{sink to}\, CH^{(t)}{}_{h_t}\right) \times \Pr_2\left(CH^{(t)}{}_{h_t}\ \text{to}\ CH^{(t-1)}{}_{h_{t-1}}\right) \\ &\times \cdots \times \Pr_2\left(CH^{(1)}{}_{h_1}\ \text{to}\ CH^{(0)}{}_{h_0}\right) \times \Pr\left\{ \bigcup_{x=1}^{C_n^m} \left[\bigcap_{\forall a \in R_x} E_2\left(CH^{(0)}{}_{h_0}\ \text{to}\ a\right) \right] \right\} \end{aligned} \quad (5)$$

Similar simplified lower bound expressions can also be obtained for (1), (2) and (3) which are not shown here due to the space limitation.

IV . Case Study

The proposed metrics are illustrated via the analysis of the example WSN with two clusters in Figure 1, where CH1 and CH2 are CH(0) of cluster 1 and cluster 2 respectively, and CH1 is the CH(1) of the two clusters. In this example, links and nodes are assumed to fail s-independently. The fixed failure rates of 2e-6 hr-1, 5e-7 hr-1, and 1e-6 hr-1 are assigned to the links, base station (sink node), and sensor nodes (including both cluster heads and gateway nodes), respectively. Note that our analysis methodology has no limitation on the type of failure distributions. For simplification of illustration, we assume all qualified sensor nodes are in the same cluster 2. In other words, the set of all qualified sensor nodes Q belongs to {n1, n2, n3, n4, n5}. After applying progressive reduction scheme, G(0) (V, E) in Figure 1 is reduced to G(1) (V, E) containing only CH(0), g(0) and g(1) as shown in Figure 2(a). G(1) (V, E) is further reduced to obtain G(2) (V, E) composed of only CH(1) and g(1) between level 1 cluster and the sink as shown in Figure 2(b).

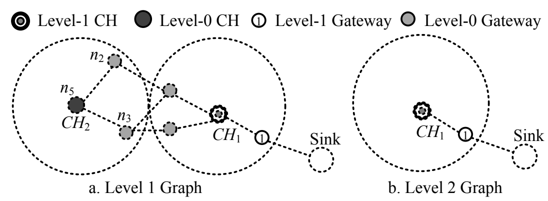

Figure 2 Graphs after reduction.

In this section, we study ICR of the example WSN for both anycast and manycast data delivery models.

A . Sink Anycast

Since all qualified nodes are in cluster 2, equation 2 is used to evaluate the anycast-based ICR of the example WSN. We consider four cases with different qualified sensor nodes groups: 1) Q1 = {n1} (unicast), 2) Q2 = {n1, n2}, 3) Q3 = {n1, n2, n3}, 4) Q4 = {n1, n2, n3, n4}.

As an example, for the case Q2 = {n1, n2}, equation 2 can be rewritten as equation 6.

$$ICR_{anycast-2} = \Pr\left\{ \begin{array}{l} E_2(\text{sink to } CH_1) \cap E_2(CH_1 \text{ to } CH_2) \\ \cap \left[E_2(CH_2 \text{ to } n_1) \cup E_2(CH_2 \text{ to } n_2) \right] \end{array} \right\} \quad (6)$$

The above reliability expression can be computed directly from the graphs in Figure 1 and Figure 2. In particular, the last two terms in equation 6 are obtained from Figure 1, Figure 2(a) is analyzed to obtain the second term E2(CH1 to CH2), Figure 2(b) is used to evaluate the first term E2(sink to CH1).

If a component's failure probability has been considered at a lower-level graph, it is considered zero in higher-level graphs. For example, since the failure probabilities of CH2 and the gateway node in cluster 2 g2(0) (n2) are already considered when evaluating the last term, failure probability of zero is assigned to CH2 and n2 in G(1) (V, E) to evaluate Pr2(CH1 to CH2). However, the inter cluster gateway-to-gateway link (g1(0), g2(0)) failure probability needs to be considered at G(1)(V, E).

Q1 is a special case of anycast where the data delivery model is actually sink unicast and the evaluation expression is equation 7.

$$ICR_{unicast} = \Pr\{E_2(\text{sink to} CH_1) \cap E_2(CH_1 \text{ to } CH_2) \cap E_2(CH_2 \text{ to } n_1)\} \quad (7)$$

The reliability expressions for the other two cases Q3 and Q4 can be similarly derived from equation 2. The reliability results for the four cases are given in Figure 3.

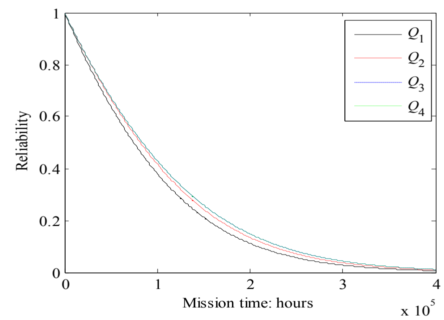

Figure 3 Reliability results for sink anycast-based WSN

Note that the results under cases Q3 and Q4 are exactly the same. The reason is that all the paths between CH2 and n4 have to pass through n1, n2, or n3. In other words, there is an operational path between CH2 and n4 only when there is an operational path between CH2 and n1, between CH2 and n2, or between CH2 and n3. In this case, adding n4 to the group of qualified sensor nodes has no effect on the ICR of WSN. However, as shown in Figure 3 the reliability of WSN increases as the number of sensor nodes in the qualified group increases for other cases. In general, WSN using sink anycast data delivery model is more reliable than WSN using sink unicast because sink anycast provides more flexibility than sink unicast. For this example system at the mission time of 200,000 hours, the reliability of anycast under the case Q3 is 10.53% better than that of anycase under the case Q2, which is 20.17% better than that of unicast under the case Q1.

B . Sink Manycast

Since all qualified nodes are in cluster 2, Equation 4 is used to evaluate the ICR of WSN for manycast data delivery model.

Assume the required number of sensor nodes in each subset is 2, i.e., m = 2. We consider two cases for the qualified sensor nodes: Q1 = {n1, n2} and Q2 = {n1, n2, n3}. For the case Q2, n = 3. Thus, there are combinations: 1) R1 = {n1, n2}, 2) R2 = {n1, n3}, 3) R3 = {n2, n3}.

Simplification technique in Section 2 is used to obtain the lower-bound for the case Q2. Equation 5 can be rewritten as equation 8.

$$ICR_{manycast-2}$$

$$= \Pr_2(\text{sink to} CH_1) \times \Pr_2(CH_1 \text{ to } CH_2) \times \Pr\left\{ \begin{array}{l} \left[E_2(CH_2 \text{ to } n_1) \cap E_2(CH_2 \text{ to } n_2) \right] \\ \cup \left[E_2(CH_2 \text{ to } n_1) \cap E_2(CH_2 \text{ to } n_3) \right] \\ \cup \left[E_2(CH_2 \text{ to } n_2) \cap E_2(CH_2 \text{ to } n_3) \right] \end{array} \right\} \quad (8)$$

Q1 is a special case of manycast where there are only two sensor nodes, n1 and n2. In this scenario, the data delivery model is actually sink multicast and the evaluation expression is equation 9.

$$ICR_{multicast-2} = \Pr_2(\text{sink to}CH_1)\times \Pr_2(CH_1 \text{ to } CH_2)\times \Pr[E_2(CH_2 \text{ to } n_1)\cap E_2(CH_2 \text{ to } n_2)] \quad (9)$$

Note that broadcast is a special case of multicast where the group includes all 11 nodes of the WSN in Figure 1. The comparison results for broadcast, multicast, and manycast are shown in Figure 4.

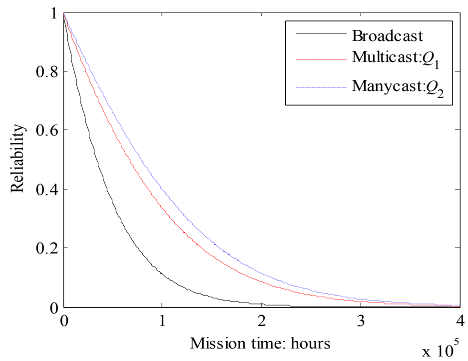

Figure 4 Comparison results for broadcast, multicast, and manycast.

From Figure 4, we can see that for a given number of sensor nodes of each subset, reliability increases as the size of the qualified group increases. In general, WSN based on sink manycast data delivery model is more reliable than WSN based on sink multicast because sink manycast provides more flexibility than sink multicast. For this example system at the mission time of 200,000 hours, the reliability of manycast under the case Q2 is 34.97% better than that of multicast under the case Q1, which is 862.02% better than that of the broadcast case.

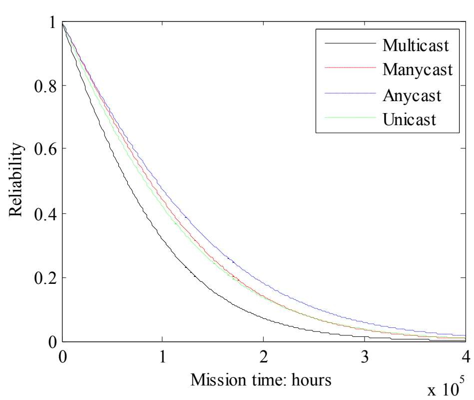

Figure 5 Comparison results for different data delivery models.

Given Q = {n1, n2, n3}, the reliability results for WSN with sink anycast, manycast (with m=2) and multicast are compared in Figure 5. For unicast, n1 is the destination sensor node. Because sink manycast requires more than one node connected with the sink node, WSN with manycast data delivery model is less reliable than WSN with anycast data delivery model for a given qualified group.

V. Conclusions and Future Work

Reliability models were proposed for the infrastructure communication reliability analysis of WSN with hierarchical clustered topology. Different data delivery models are compared through illustrative examples: WSN with anycast is the most reliable and WSN with broadcast is the least reliable. The proposed models have no limitation on the type of component failure distributions. The models can be adapted to other topologies.

In the future, we will study and compare the ICR for different biconnected graphs for the mesh topology with different node degrees and average path lengths. Based on the reliability metrics, we will optimize the structure of WSN to achieve the optimal network reliability.

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