Modeling and Evaluating the Reliability of Wireless Sensor Networks

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SUMMARY & CONCLUSIONS

The reliability of wireless sensor networks (WSN) depends on both network connectivity and sensing coverage. Common-cause failures (CCF) can contribute significantly to the WSN unreliability. This paper considers the problem of modeling and evaluating the coverage-oriented reliability of WSN subject to CCF. Our approach is computationally efficient due to the use of a progressive reduction scheme, reduced ordered binary decision diagrams, as well as a decomposition and aggregation scheme for considering CCF. A hierarchical clustered WSN is used as an example to illustrate the basics and advantages of our approach.

1 INTRODUCTION

Wireless sensor networks (WSN) have been identified as one of the most important technologies for the 21st century. In WSN, hundreds of smart and low-cost multimodal micro-sensor devices, networked through wireless links and the Internet, provide unprecedented opportunities for environment monitoring, healthcare, national security, military surveillance, manufacturing and industry automation, and any other conceivable application. While the Internet has transformed the way we exchange information, WSN is taking this stride further to build an environmentally aware ubiquitous network that will empower us to assimilate an even deeper and broader understanding of the environment. But before the WSN revolution can truly take place, it is critical that the communication among these smart sensors be reliable and dependable. Any network outage, loss of transmitted data, or failure to capture important data decreases the users' trust on the system. Reliability evaluation is, therefore, a critical task for the successful operation of WSN.

Reliability evaluation has been researched extensively for traditional computer networks and non-network critical systems like space phased-mission systems. However, only little work [1] has been done in the reliability evaluation of WSN. The following unique features of WSN contribute to the limitations of the existing techniques in WSN reliability modeling and evaluation:

- WSN usually have a very large number of resource-constrained sensor nodes due to the dense deployment of redundant nodes for fault tolerance. The complexity of network reliability analysis algorithms increases sharply with the number of nodes [2]. And traditional analytical network reliability analysis approaches, suitable for networks of moderate size (10-100 nodes), cannot be, at least directly, applied to WSN (100-1000 nodes).
- The successful operation of WSN depends on both network connectivity and sensing coverage. The traditional connectivity-oriented network reliability may not be sufficient to accurately model the WSN failure behavior.
- WSN have dynamic network topology due to demand-based duty-cycle adjustments of the power-constrained sensor nodes for energy preservation while maintaining the required sensing coverage and connectivity [3].

There are two types of communication within WSN: *application communication* relates to the transfer of sensed data about the phenomenon; *infrastructure communication* relates to the delivery of configuration and maintenance data [4]. The reliability metrics in these two contexts are significantly different, and thus the evaluation approaches are different too. Detailed discussions on reliability metrics and evaluation methodologies suitable for the infrastructure and application communication reliability of WSN are presented in [5] and [6] respectively.

This paper extends the modeling and analysis of application communication reliability (simplified as reliability, hereafter) by incorporating the consideration of common-cause failures (CCF). CCF are multiple dependent component failures within a system that are a direct result of a common-cause [7]. For example, in WSN where sensor nodes are deployed either inside or in very close proximity to the phenomenon, a group of sensors can be affected by a common cause, such as earthquakes, landslides, and bombs simultaneously. It has been shown by many reliability studies that CCF tend to increase a system's joint failure probabilities and thus contribute significantly to the overall unreliability of systems subject to CCF [8]. Therefore, failure to consider CCF in the reliability analysis of such systems also leads to overestimated system reliability measures [9]. Accordingly, it is important to incorporate the consideration of CCF into the reliability evaluation of WSN.

2 BACKGROUND AND PRELIMINARY CONCEPTS

This paper considers a randomly deployed hierarchical clustered architecture (Figure 1 of [5]) for the reliability modeling and analysis of WSN subject to CCF. All the sensor nodes in the network are joined at the lowest level. The

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cluster head in the lowest level (*level-0*) are arranged into clusters in a higher level (*level-1*) and a cluster head is assigned for each cluster at this level. The process is repeated for each level until the highest level in the architecture is reached. The clustered hierarchical architecture is used as a vehicle for illustrating our analysis methodology because it is a generic network architecture that covers other architectures like star and mesh structures. Nevertheless, our analysis methodology is similarly applicable to other architectures too.

The hierarchical clustered architecture maintains a hierarchical structure for network addressing and organization, while still maintaining the multi-hop routing of mesh architecture for actual data communication. The scheme forms a tree structure for routing with the sink node as the root of the tree. Whenever a sensor node needs to send a message to the sink or another sensor node, it sends the message to its cluster head along a multi-hop route. The message is routed progressively to the immediately higher-level cluster head, each of which forms a more detailed segment of the multi-hop route, until it reaches the cluster head that is the common ancestor of both the source and destination nodes and therefore has the routing information about the destination node. The message is then routed progressively to lower-level cluster heads until it reaches the destination node.

In WSN, reliable monitoring of the phenomenon depends on both sensing coverage and communication of collected data provided by the target cluster of sensors in the proximity of the phenomenon to the observer. Consequently, the reliability of WSN depends on both network connectivity and the sensing coverage. Although the coverage concept and the connectivity-based reliability are both widely researched topics, only few have studied the two concepts in a unified framework [10] and none, to the best of our knowledge, have provided any quantitative measures incorporating the two notions for the reliability analysis of WSN. Therefore, we proposed a novel reliability measure that integrates the conventional connectivity reliability with the sensing coverage measure of WSN [6]. This new coverage-oriented reliability provides a more accurate representation of WSN failure behavior than existing measures, and will be used for the study of reliability analysis of WSN subject to CCF in this paper.

3 PROBLEM STATEMENT

This paper considers the problem of modeling and evaluating the coverage-oriented reliability of WSN subject to CCF. The following assumptions are considered for analysis:

- The connectivity of WSN is modeled by an undirected probabilistic graph $G (V, E)$, where V is the set of vertices (sensor nodes and base station) and E is the set of edges (links between sensor nodes) [2].
- Let $d (i, j)$ be the distance between sensors i and j, and R_c be the range of each transceiver. Sensors i and j can communicate directly and a corresponding undirected edge e_{ij} exists, i.e. $(i, j) \in E$ *iff* $d (i, j) \leq R_c$.
- A link $e \in E$ fails *s*-independently with a known probability. A node $v \in$ V also fails *s*-independently with a known probability.
- The failure probability for each link or node is given as a fixed probability for a given mission time or in terms of a lifetime distribution.
- Each sensor node is stationary and belongs to a single cluster at any given time. The network topology can change due to duty cycle adjustments. Topology changes due to cluster head reassignments are not considered.
- A general and practical CCF model [9] is used, in which WSN can be subject to CCF from different common-causes (CC) and different CC can occur mutually exclusively, or *s*-independently, or *s*-dependently. A single component may be affected by multiple CC.
- The occurrence probabilities of CC and their statistical relationship can usually be available from sufficient weather data or equipment data [11].

4 AN ILLUSTRATIVE EXAMPLE

The example WSN (Figure 1) consists of a single base station and eight clusters that are numbered accordingly. The cluster head for each cluster i is identified as the node labeled CH_i. These cluster heads represent *level-0* cluster heads in our hierarchy. The nodes that are connected to nodes in neighboring clusters are called gateway nodes.

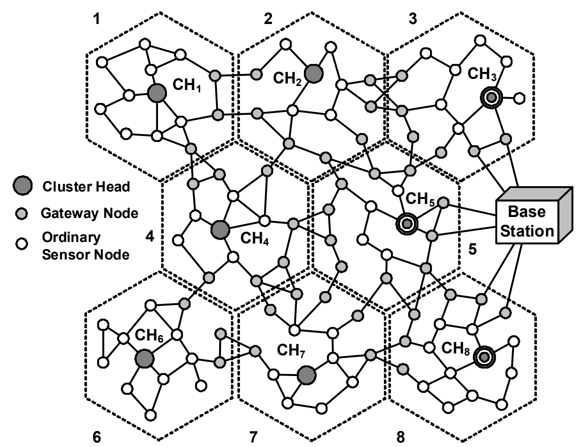

Figure 1 - Example WSN configuration in level-0

In the *level-1* of the hierarchy, clusters 1, 2 and 3 are organized into a single higher-level cluster with cluster head CH_3 assigned as the *level-1* cluster head. Similarly clusters 4 and 5 are organized into a higher-level cluster, and clusters 6, 7 and 8 are organized into a cluster with the nodes CH_5 and CH_8 assigned as cluster head for those two *level-1* clusters respectively. The base station represents the sink node and our reliability measures require computing the probability of reliable communication with this base station.

5 RELIABILITY MEASUREMENT AND EVALUATION

Sensing coverage of a region of interest is defined as the ability to monitor every point in the region by at least one sensor node [3], [10]. A more general concept of coverage, called K-coverage, requires every point to be covered by at least K sensors [3]. We define K-coverage-set as a set of sensor nodes in a cluster such that all the points in the cluster are covered by at least K nodes. The degree of sensing coverage required by a WSN depends on the specific application requirements and serves as a measure of the quality of service (QoS) of the WSN.

5.1 Coverage-oriented reliability measures

We define the reliability of WSN as the probability of observing every point in the sensed field by at least K nodes and there exists an operational path from each of these K nodes to the sink node. Specifically, it is the probability that each cluster of interest is K-covered, and there exists a path from these nodes that provide K-coverage to the *level-0* cluster heads, from these *level-0* cluster heads to the respective parent *level-1* cluster heads and so on up to the top level cluster heads, and from these top level cluster head to the sink node.

Let $\Pr_2(\ )$ denote the terminal-pair reliability, i.e., the probability that a specified pair of source and destination nodes is able to communicate via at least one operational path [2]. Let the highest hierarchical level in the architecture be t. Let R be the subset of clusters of interest and H_0 be the set of cluster heads for clusters in R. And let H_k be the set of cluster heads that is hierarchically above R at parent level k, $1 \le k \le t$, then the coverage-oriented reliability can be expressed as:

$$
\begin{aligned}
R = &\left(\prod_{i \in H_t} \Pr_2[\text{sink to top hlch } i]\right) \\
&* \left(\prod_{\substack{i \in H_t,\\ j \in H_{t-1}}} \Pr_2[\text{top hlch } i \text{ to next hlch } j]\right) * \ldots * \\
&\left(\prod_{\substack{m \in H_1,\\ n \in H_0}} \Pr_2[\text{hlch level 1 to hlch level 0}]\right) * \\
&\left(\prod_{w \in R} \Pr[\text{hlch level 0 w's K-coverage}]\right)
\end{aligned} \tag{1}
$$

(hlch=hierarchical level cluster head).

Consider the special case when we are interested in the reliable monitoring of the entire sensor field, the coverage-oriented reliability can be calculated as:

$$
\begin{aligned}
R = &\left(\prod_{i} \Pr_2[\text{sink to top hlch } i]\right) \\
&* \left(\prod_{i,j} \Pr_2[\text{top hlch } i \text{ to next hlch } j]\right) * \ldots * \\
&\left(\prod_{m,n} \Pr_2[\text{hlch level 1 to hlch level 0}]\right) * \\
&\left(\prod_{w} \Pr[\text{hlch level 0 w's K-coverage}]\right)
\end{aligned} \tag{2}
$$

The last term in equations (1), (2) is the cluster K-coverage probability. Based on our assumption that a sensor node belongs to a single cluster, each cluster can be analyzed individually to evaluate the K-coverage probability.

5.2 Finding the K-coverage probability

First, we find the K-coverage-sets (CS^K). This is an extension of the classic *art gallery problem* that deals with determining the set of observers necessary to cover an art galley room such that every point is seen by at least one observer (i.e., *1*-coverage set or CS^1). A point p is covered by a node v if their Euclidean distance $d(p, v)$ is less than the sensing range R_s of v, i.e., $d(p, v) < R_s$. Reference [3] proposes a solution to the decision problem of whether every point in the monitored area is covered by at least K sensors via checking the perimeter of every sensor's sensing range.

The algorithms proposed in [3], [12] can be adapted for finding the coverage sets $\{CS^K{}_i\}$. For example, the algorithm in [12] can be modified to solve the K-coverage problem by redefining sensor intensity matrix as the coverage matrix and redefining the minimum intensity value as K. In passing, if there are m K-coverage-sets $\{CS^K{}_1, CS^K{}_2, \ldots, CS^K{}_m\}$, then the lifetime of the network is increased by a fraction of m. Let $CS^K{}_i$ be composed of t_i nodes $\{n_{i,1}, n_{i,2}, \ldots, n_{i,t_i}\}$. Then the probability of obtaining this coverage-set is the probability that there exists a Steiner tree that connects all the nodes $\{n_{i,j}, 1 \le j \le t_i\}$ in the coverage set with the cluster head, which is a k-terminal reliability problem [2], [13] with $k = t_i + 1$.

The K-coverage probability, i.e., reliability of a cluster is the probability that at least one of the K-coverage sets is operational. Therefore,

$$
\Pr(K - \text{coverage}) = \Pr\left(\bigcup_{i=1}^{m} CS^K{}_i\right) \tag{3}
$$

The equation (3) can be calculated using the binary decision diagrams (BDD) based method [9], [13], [14]. Specifically, a BDD is generated for each K-coverage set and the final BDD is obtained by *OR*ing all the K-coverage set BDD. The evaluation of the final BDD gives the K-coverage probability.

In this subsection, a method to compute the final term in equations (1), (2) was outlined. In the following subsection, a progressive and hierarchical reduction approach for computing the remaining terms in equations (1), (2) is presented.

5.3 The progressive approach to reliability analysis

Ref. [5] proposed a progressive reduction approach to analyzing the reliability of WSN, which is concerned with network connectivity only. Since all the terms except the last term in equations (1), (2) are related to the network connectivity, and not relevant to the coverage concept, the progressive approach can be applied to evaluating these remaining terms.

Specifically, the *level-0* graph is analyzed to obtain the terminal-pair reliabilities between the cluster head and gateway nodes for each cluster (by considering only the nodes within the analyzed cluster). The *level-0* graph (Figure 1) is reduced to a *level-1* graph containing only the *level-0* cluster heads and inter-cluster gateways as shown in Figure 2. The *level-1* graph is analyzed to compute the next to last term in equations (1) and (2). This graph is reduced further to include only *level-1* cluster heads and associated gateways between *level-1* clusters in a *level-2* graph as shown in Figure 3.

In general, the *level-i* graph is progressively reduced to a graph containing only the *level-i* cluster heads and *level-i* inter-cluster gateways. And this progressive reduction scheme is iterated until the graph is reduced to the top level of the hierarchy (*level-2* for the example WSN), which will be used to evaluate the first term in equations (1) and (2).

For reducing each *level-i* graph to a *level-(i+1)* graph, it is necessary to compute the cluster head to gateway terminal-pair reliabilities. The reduced ordered BDD (ROBDD) based method from [14] is applied to perform such two-terminal network reliability analysis. Also, at each level of the reduced graph analyses, only the nodes within the cluster boundary are considered for the reliability calculations.

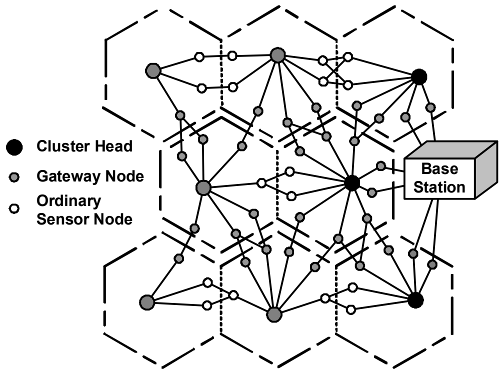

Figure 2 - The example WSN configuration in level-1

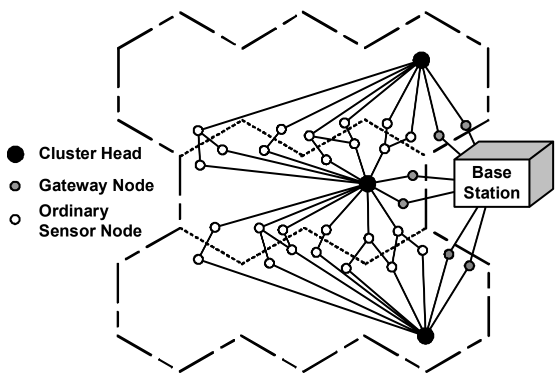

Figure 3 - The example WSN configuration in level-2

In summary, a set of reduced graphs is generated to solve the sub-problems in equations (1), (2). Specifically, the second to the last term is calculated from the *level-1* graph, the third last term is calculated from the *level-2* graph and so on. Finally the first term is computed from the top-level graph.

5.4 Incorporating CCF

The challenge with considering CCF is to cope with multiple dependent component failures at the same time. This challenge is addressed by applying a decomposition and aggregation approach [9] to and only to the lowest *level-0* graph analysis. Specifically, we use the approach to incorporate CCF in the computation of *2*-terminal reliabilities between the cluster heads and the gateway nodes as well as the computation of the *K*-coverage probabilities (equation (3)) based on the *level-0* graph of the WSN.

The methodology is to decompose a reliability problem with CCF into a number of reduced reliability problems, in which the effects of CCF are factored out through reduction. These reduced problems can be solved using any approach that ignores CCF; for e.g., an efficient one is ROBDD based method [14]. The final system reliability considering CCF is obtained by aggregating results of those reduced problems.

Specifically, let *m* be the number of elementary common-causes (CC) in a network. The *m* CC partition the event space into the following 2^m disjoint subsets, each called a common-cause event (CCE): $CCE_1 = \overline{CC_1} \cap \overline{CC_2} \cap \ldots \cap \overline{CC_m}$, $CCE_2 = CC_1 \cap \overline{CC_2} \cap \ldots \cap \overline{CC_m}$, ……, $CCE_{2^m} = CC_1 \cap CC_2 \cap \ldots \cap CC_m$. A space called "CCE space" (denoted by Ω_{CCE}) can be built over this set of collectively exhaustive and mutually exclusive CCE that can occur in the network, i.e., $\Omega_{CCE} = \{CCE_1, CCE_2, \ldots, CCE_{2^m}\}$. If $\Pr(CCE_j)$ denotes the probability of CCE_j occurring, then we have $\sum_{j=1}^{2^m} \Pr(CCE_j) = 1$ and $CCE_i \cap CCE_j = \phi$ for any $i \neq j$.

Based on the CCE space, the total probability theorem is applied to calculate the unreliability (two-terminal, k-terminal, or all-terminal) of the network as

$$\begin{aligned} U_{\text{network}} &= \sum_{i=1}^{2^m} [\Pr(\text{network fails} \mid CCE_i) \bullet \Pr(CCE_i)] \\ &= \sum_{i=1}^{2^m} [U_{N_i} \bullet \Pr(CCE_i)] \end{aligned} \tag{4}$$

As defined in equation (4), U_{N_i} is a conditional probability that the network fails conditioned on the occurrence of CCE_i. The evaluation of U_{N_i} is actually a reduced network reliability problem in which the components affected by CCE_i do not appear. Most importantly, the evaluation of U_{N_i} can proceed without further consideration of CCF. The ROBDD based methods [14] is used to solve the reduced problems U_{N_i}. The evaluation of $\Pr(CCE_j)$ is based on the relationship between elementary CC and occurrence probabilities of CC which are given as input parameters (Section 3). See Section 6 for an example of evaluating $\Pr(CCE_j)$ where elementary CC are *s*-independent. Also, see [9] for an example where elementary CC are *s*-dependent.

5.5 Incorporating duty-cycle adjustment

The two approaches to considering the dynamic duty-cycle adjustment of sensor nodes into the reliability analysis of WSN are: 1) Calculate reliability values using connectivity information of only active nodes in the cluster. This measure gives the reliability measure of WSN at the current duty-cycle period, or more specifically the current snapshot of the WSN in the global context, as the duty cycles of different clusters are not synchronized. 2) Consider all the active and sleeping nodes in WSN and modify the node operational probability as the probability that the node is operational and it is active. For this, the operational probability of the node is multiplied by its non-sleeping probability.

For the remaining discussions, the duty-cycle adjustments is assumed to be already incorporated either by considering only the active nodes or by incorporating the duty-cycle factor in the node operational probability calculation.

6 RESULTS

The example WSN (Figure 1) is analyzed for illustrating the coverage-oriented reliability analysis of WSN subject to CCF. The base station is assumed to be perfectly reliable, and both links and nodes fail exponentially. Specifically, each link fails s-independently with a constant failure rate of λ_l=2e-5/hr, each node fails s-independently with a constant failure rate of λ_n=1e-5/hr. Note that this analysis methodology is equally applicable to any other failure distribution besides exponential distribution. A mission time of 1000 hours is considered.

To illustrate the effects of CCF on the reliability analysis of WSN, consider the following hypothetical scenario about CCF for the example WSN (Figure 1). The WSN is subject to CCF from two independent CC: hurricanes (denoted by CC_1) and earthquakes (denoted by CC_2). The occurrence probabilities of these two CC are Pr(hurricane)=P_{CC1}=0.03 and Pr(earthquake)=P_{CC2}=0.02. All sensor nodes in cluster 2 are affected by hurricanes while all sensor nodes in cluster 4 are affected by both earthquakes and hurricanes. Note that our example CCF assignment to all the nodes in a cluster is only for simplicity of illustration and analysis; we can likewise assign CCF to any subset of nodes in a cluster in our approach.

To incorporate the CCF into the lowest *level-0* graph analysis, the decomposition and aggregation approach described in Section 5.4 is applied. Specifically, the CCE space is composed of four CCE, that is, $\Omega_{CCE}=\{CCE_1, CCE_2, CCE_3, CCE_4\}$, because there are two CC. Each CCE_i is a distinct and disjoint combination of elementary CC as follows: $CCE_1=\overline{CC_1}\cap\overline{CC_2}$, $CCE_2=CC_1\cap\overline{CC_2}$, $CCE_3=\overline{CC_1}\cap CC_2$, and $CCE_4=CC_1\cap CC_2$. Because the two CC are independent, the occurrence probability of each CCE are calculated as follows: Pr(CCE_1) = (1-P_{CC1})(1-P_{CC2}), Pr(CCE_2) = P_{CC1}(1-P_{CC2}), Pr(CCE_3) = (1-P_{CC1})P_{CC2}, and Pr(CCE_4) = $P_{CC1}P_{CC2}$. Using equation (4), each network problem with CCF can be decomposed into four reduced problems without the consideration of CCF. Next, reliability results of example WSN with and without considering CCF are presented.

The cluster-i K-coverage probability is denoted by R_K(cluster-i), and 2-coverage is considered as the QoS requirement in this example. The 2-coverage-sets can be found using the approach described in Section 5.2, and probabilities for 2-coverage of all clusters can be computed using equation (3). These values are considered as given input parameters for this analysis and they are: R_2(cluster-1) = 0.91, R_2(cluster-2) = 0.93, R_2(cluster-3) = 0.96, R_2(cluster-4) = 0.97, R_2(cluster-5) = 0.98, R_2(cluster-6) = 0.94, R_2(cluster-7) = 0.96 and R_2(cluster-8) = 0.98.

Let these values after incorporating CCF be: R_2(cluster-1) = 0.91, R_2(cluster-2) = 0.90, R_2(cluster-3) = 0.96, R_2(cluster-4) = 0.92, R_2(cluster-5) = 0.98, R_2(cluster-6) = 0.94, R_2(cluster-7) = 0.96 and R_2(cluster-8) = 0.98. It is noticeable that the 2-coverage probabilities of clusters 2 and 4 with consideration of CCF are lower than the probabilities without considering CCF because these two clusters are directly affected by CCF.

According to equation (2), the reliability of the entire WSN is calculated as:

$$R=\left(\prod_{i\in\{3,5,8\}}\Pr_2[\text{sink to level 1 ch } i]\right) * \left(\prod_{\substack{i\in\{3,5,8\}\\ j\in\{1,\dots,8\}}}\Pr_2[\text{level 1 ch } i \text{ to level 0 ch } j]\right) * \left(\prod_{n\in\{1,\dots,8\}}\Pr[\text{level 0 cluster n's 2-coverage}]\right) \quad (5)$$

(ch=cluster head)

Evaluating these terms, the reliability of the entire WSN is obtained as *0.524758.* The reliability value reduces from *0.608556* (without CCF, [6]) to *0.524758* after incorporating CCF. The 2-coverage reliability results for each cluster to the sink node computed using equation (1) is tabulated in Table 1. Figure 4 shows the graphical representation of these results.

Cluster	Reliability Without CCF	Reliability With CCF
1	*0.900450*	*0.893093*
2	*0.924340*	*0.891503*
3	*0.959054*	*0.959054*
4	*0.947051*	*0.853861*
5	*0.979109*	*0.979109*
6	*0.885750*	*0.885750*
7	*0.942562*	*0.942562*
8	*0.978055*	*0.978055*

Table 1 - WSN reliability analysis results

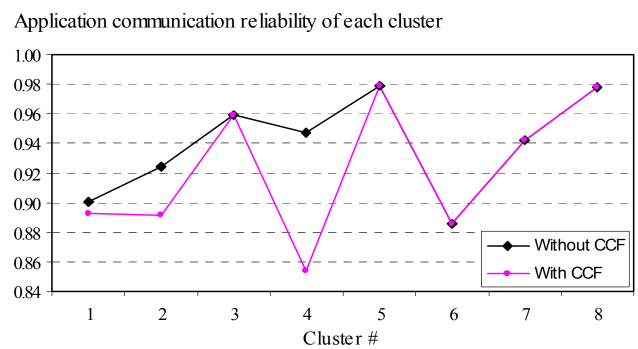

Figure 4 - Reliability results of each cluster

As seen from Figure 4, the reliability value without considering CCF for cluster 6 is the smallest. In a very naïve interpretation, cluster 6 is the weakest region in the WSN and thus is the best candidate for improving the WSN performance. With consideration of CCF, however, cluster 4 becomes the weakest region. Note that a more accurate approach for identifying the candidate region(s) for upgrade is to perform sensitivity analysis [9], [14], which is our future work.

7 CONCLUSIONS

This paper illustrated a novel approach of integrating sensing coverage with conventional network connectivity for the application communication reliability analysis of WSN subject to CCF. The coverage-oriented reliability of WSN provides a better measure of the WSN performance than the existing ones based solely on network connectivity. Our approach has low computational complexity because it is progressive and separable, and it is based on the computationally-efficient ROBDD approach. We demonstrated our approach though the analysis of an example hierarchical clustered WSN subject to two elementary common-causes.

Our future work includes the consideration of sensor nodes mobility and multi-state concept into reliability analysis, sensitivity analysis, and performance comparison between different WSN architectures.

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