Fault Tolerance of Connectivity Performance in CDMA-Based Wireless Sensor Networks

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Abstract. In this paper, we investigate the fault tolerance of connectivity probability for CDMA-based wireless sensor networks with variations of nodes deployment. The variations of deployment are modeled by 2D Gaussian distribution with zero-mean for the triangle, grid and hexagon topologies. Thus, the *k*-connectivity performance is studied through the outage probability of CDMA signal links. We evaluate the connectivity performance with $SIR_{0,3\text{-con}}$, the minimum requirement of SIR, SIR_0 for the 3-connectivity, when the nodes suffer a failure rate P_f. Simulation results show that the hexagonal and grid topologies suffer a degradation of -2.4 and -0.5 dB, respectively, when the failure rate P_f equals 0.1. However, the triangular topology shows robust fault tolerance with the failure rate P_f below 0.5 and moderate variations of deployment.

1 Introduction

The wireless sensor networks (WSN) consisted of many tiny nodes with sensing, storing and communicating capability have recently emerged as a hot research topic [1]. In the WSN, the data is collected by spreading the sensing nodes into a wide area, then the routing to the sink by multi-hop communications [2]. The code-division multiple-access (CDMA) technology is adopted to perform the 3G mobile communication systems with its high capacity potentials [3]. In CDMA systems, the spreading spectrum is performed to anti-interference. However, the multiple access interference (MAI) degrades the BER performance of multiuser environments [3].

In WSN, the deployment of sensor nodes is an important topic. The proper deployment can make good connectivity and high coverage in the area [4]. Thus, the connectivity performance of WSN obtains large attention [4-5]. In order to cover the entire area, three network topologies, hexagon, grid and triangle, have been proposed in [6] and then the performance with fixed deployment is investigated. However, in

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practical, the fixed node deployment is not easy. Contrarily, there exists some variations in node deployment. Therefore, the connectivity performance of different topologies with deployment variations was investigated in previous works [7]. However, the sensor nodes deployed in the adverse or inaccessible circumstances could be easily destroyed or out of order to be failure. Thus, how to remain the network connectivity even in fault-induced environments is an important issue [8-9]. Therefore, in fault-induced environments, the fault tolerance performance which to keep the WSN 3-connectivity with the deployment variations will be studied in this paper.

2 Network Models

In [6], three topologies are compared with fixed deployment. For easy analysis, the distance between the nodes is set to be constant in [6]. However, for cost fairness, we set the constant node density for three topologies. Thus the distance between the nodes are different with each other. It is easy to know that the nodes' distance of hexagon is the shortest, then grid. The nodes' distance of triangle is the longest. There are 3, 4 and 6 shortest links for hexagon, grid and triangle, respectively.

Due to the obstacles or the placement methods, the deployed node position is difficult to be fixed. Moreover, to be generalized and simplified, the position variation of deployment is modeled as zero-mean Gaussian distribution [10]. Thus, the distribution function of the position of the *n*-th node can be expressed by

$$Z_n(x_n, y_n) = \frac{1}{2\pi\sigma_x\sigma_y} \times \exp\left\{-\frac{1}{2}\left(\frac{(x_n - \eta_{x_n})^2}{\sigma_x^2} + \frac{(y_n - \eta_{y_n})^2}{\sigma_y^2}\right)\right\}, \tag{1}$$

where x_n and y_n are the disjoint x-axis and y-axis random variables for the *n*-th node respectively, η_{x_n} and η_{y_n} are the x-axis and y-axis of the *n*-th node of the fixed topology respectively. The parameters σ_x^2 and σ_y^2 are the variance of x-axis and y-axis of node deployment respectively. In different topologies, the distances between the nodes are not equal. Hence, to compare the performance of topologies, we define the normalized standard deviation of deployment variation in WSN as

$$\sigma_N = \frac{\sigma_t}{d_t}, \tag{2}$$

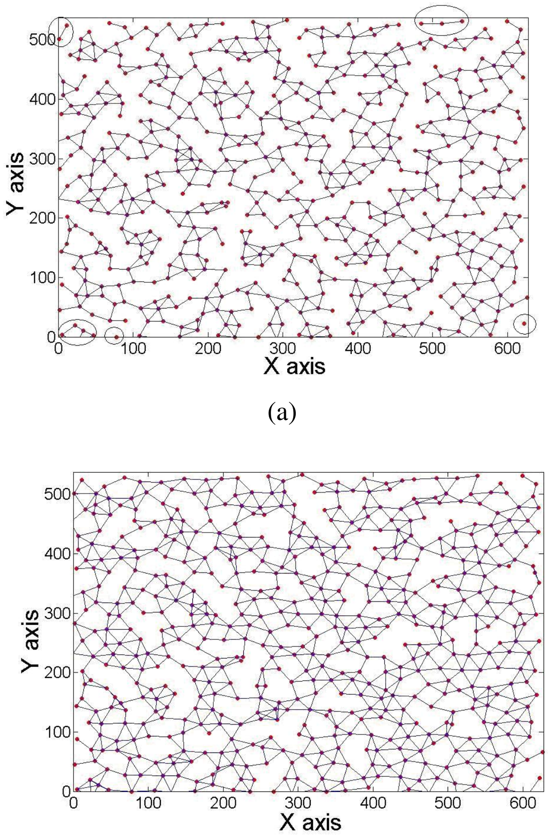
where σ_t is the standard deviation of deployment variation of the topology in WSN, and d_t is the distance between the nodes of the fixed deployment topology.

When we consider the network connectivity for the fixed deployment topology, it is easy to know that there are 6, 4 and 3 available links for the triangle, grid and hexagon topologies respectively with sufficient transmitting power in the links. However, when the distance is varied, the available links of each node could be less than 3. Then some nodes become isolated as shown in Fig. 1(a). If we increase the transmitting power, the links can increase to 3 or above. Then, the network can reach well connectivity performance as shown in Fig. 1(b).

In wireless communication channels, the transmitting signals suffer fading effects due to the multipath propagation. For simplicity, with assuming the stationary systems, the short-term fading and shadow fading are ignored. Thus the received signal strength is defined by the path loss of channels as

$$P_r = c\frac{P_t}{d^{\alpha}} \quad , \tag{3}$$

where d is the distance between the transmitter and receiver, P_t is the transmitting power of transmitter and c is the propagation coefficient. The attenuation exponent α is between 2 and 6 [7]. We assumed in free space, then $\alpha = 2$. That is, the consumed communication power is proportional to d^2. In this paper, the simulation area of WSNs is set to a rectangular area as in [7]. However, to be equally densely deployed for different topologies, the distances between nodes are set 26.4 m, 25 m and 21.486 m for triangle, grid and hexagon topologies respectively.



(a)

(b)

Fig. 1. The connectivity performance of networks: (a) poor (b) well

3 Connectivity Performance

In wireless CDMA systems, the MAIs limit the signal capacity of the links. That is, with the design on the length of spreading code, the link is qualified based on the signal-to-interference ratio (SIR) defined by

$$SIR = 10\log_{10}\frac{P_r}{P_i} \text{ (dB)}, \tag{4}$$

where P_r is the received signal strength at receiver, P_i is the interfering power at receiver. We can design the spreading codes to perform a minimum required SIR, SIR_0. When SIR of the link is lower than SIR_0, the link's signal strength is too weak to suppress the MAIs. Then the link suffers failure. We give the probability of outage by

$$P_{outage} = P[SIR < SIR_0] \ , \tag{5}$$

The connectivity probability of networks is defined by the probability of *k*-connectivity P_{k-con} [5] as

$$P_{k-con} = 1 - P_{k-outage} \quad , \tag{6}$$

where $P_{k\text{-}outage}$ is the outage probability of the *k*-th high SIR link. Then, P_{k-con} expresses the probability of that there are more links than *k* links in the networks. Moreover, we define that the network performs *k*-connectivity when

$$P_{k-con} \geq 0.99 \,. \tag{7}$$

To investigate the fault tolerant performance of network connectivity, we set the node failure rate P_f by 0.1, 0.3 and 0.5 which is uniformly distributed in the sensing area.

4 Simulation Results and Discussions

In the simulation, we performed the varied topologies with σN =0.05 and 0.07 respectively. The received signal strength and the MAIs are compared for the topologies. The simulation area are placed an area A. We deployed 576, 572 and 578 sensor nodes in the triangle, grid and hexagon fixed topologies, respectively. For generalization, we compute the results of inner nodes, 371, 320 and 350 nodes for triangle, grid and hexagon fixed topologies, respectively. Then, for simplicity, we assumed that Pt=20dBm, c=1 m2/mW and A=350000 m2. We neglected the MAIs from the areas where the distance is more far than 56 meters due to the negligible interference comparing to the near area.

Since the *k*-connectivity performance P_{k-con} of the networks should be on $k \geq 3$, we let $P_{3-\mathrm{con}} > 0.99$. In other words, the number of connectable links should be 3 or more [5]. Therefore, in this paper the three strongest links, L_1, L_2 and L_3 of the nodes is focused in our investigation. Moreover, the normalized variance σ_N is set 0.05 and 0.7, which are corresponding to the scales of 1 and 1.5m, respectively.

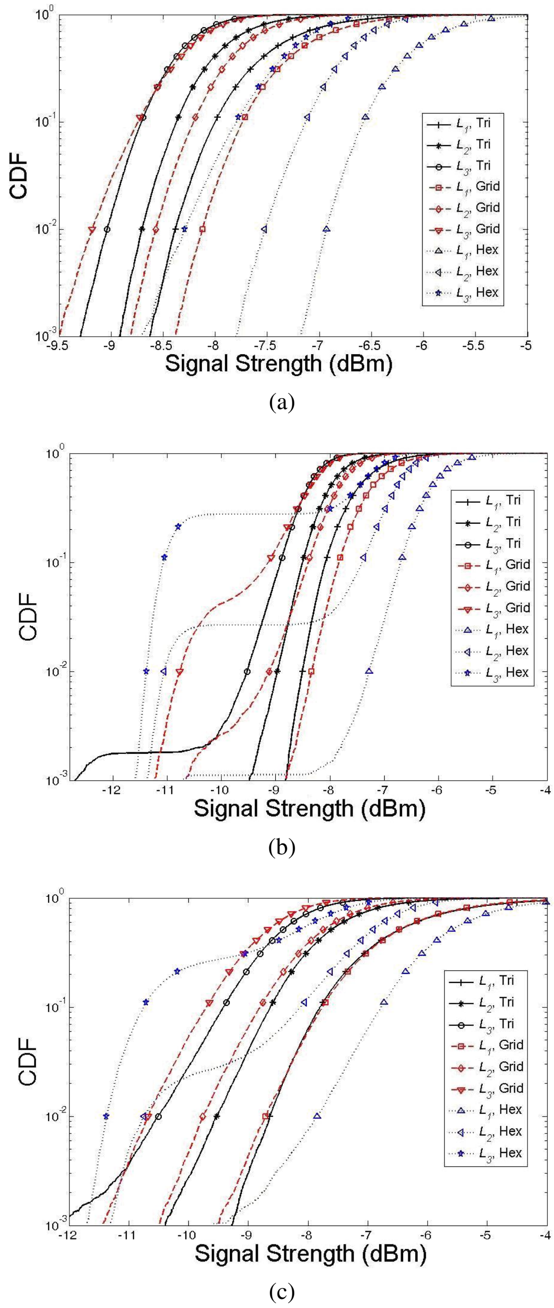
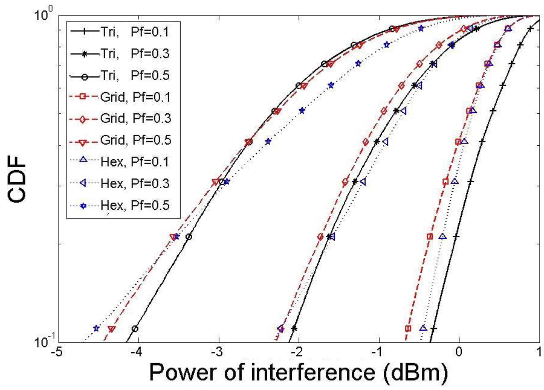


Fig. 2. Comparisons of the RSS of three strongest links for three topologies with the normalized variation σ_N =0.05 for different failure rate (a) no failure (b)P_f=0.1, σ_N =0.05 (c)P_f=0.1, σ_N =0.07

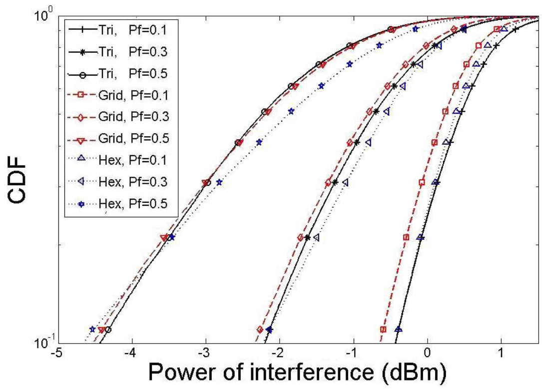
In Fig. 2, we compare the cumulative distribution functions (CDF) of the RSS of the nodes for three topologies with deployment variation and different failure rates. From Fig. 2(a) of no failure, it is observed that with σ_N =0.05 the RSS of three links in hexagon (Hex) is stronger than that of both grid and triangle (Tri) due to its shortest distance between the neighbor nodes. Similarly, the RSS of L_1 and L_2 in grid is stronger than that of triangle. However, the RSS of L_3 in grid is weaker than that of triangle. The reason is that the number of links in triangle is six which is more than the four in grid. Then the probability of the distance between the nodes becoming closer is higher than that of grid. Moreover, when parts of nodes suffer failure, then the RSS of three links in three topologies would suffer degradations as shown in Figs. 2.(b)-(c). In a slight failure rate P_f=0.1, the third strongest link of hexagon is degraded first and the most severe as shown in Fig. 2(b). Then, the third strongest link of grid suffers and then the second strongest link of hexagon is the next one. The last sufferer, the third strongest link of triangle is afflicted comparatively minor. However, in a moderate failure rate P_f=0.3 to 0.5, both the third strongest links of grid and triangle topologies suffer more than that of hexagon due to the shorter distance between nodes as shown in Fig. 2(c).

The CDF of the power of interference (MAI) of the nodes for different topologies can be obtained and compared in Fig. 3. From Figs. 3(a) and 3(b), for the first two strongest links, L1 and L2, with different failure rate and variation of σN =0.05, among the three topologies the power of MAIs in Tri is strongest and the weakest is in Hex. However, for the third strongest links, L3, among the three topologies the power of MAIs in Hex becomes higher than that of Grid for failure rate P_f =0.1 and is the strongest for failure rate P_f =0.3, 0.5 as shown in Fig. 3(a). Moreover, with the larger the variation of σ_N =0.07, for the third strongest links, L_3, among the three topologies the power of MAIs in Hex is the strongest no matter which failure rate P_f =0.1, 0.3 or 0.5 as shown in Fig. 3(b).

Fig. 4 shows the CDFs of SIR of the three strongest links L_1, L_2 and L_3 of the nodes for different topologies with variation σ_N = 0.05 and 0.07. From Fig. 4(a), it can be observed that with P_f =0.1 the third strongest link of hexagon topology exhibits the worst link quality due the most fragile with only three neighbor node in hexagon topology. While both the third strongest link of Tri and Grid topologies exhibit fault tolerance with P_f =0.1 as shown in Fig. 4(a). However, when the failure rate increases by P_f =0.5, the SIR of the third strongest link of Tri topology is degraded more than the other two topologies due its most severe MAI. Moreover, when the failure rate increases to P_f =0.5, the link quality of the third strongest link of Grid topology is degraded to slightly better than the other two as shown in Fig. 4(b). Besides, from the results with higher variations of σ_N =0.07 as shown in Fig. 4(c), it can be observed that the hexagon topology still exhibits worst link quality of L_3 and L_2 than both triangle and grid topologies with moderate failure rates P_f =0.3.



(a)

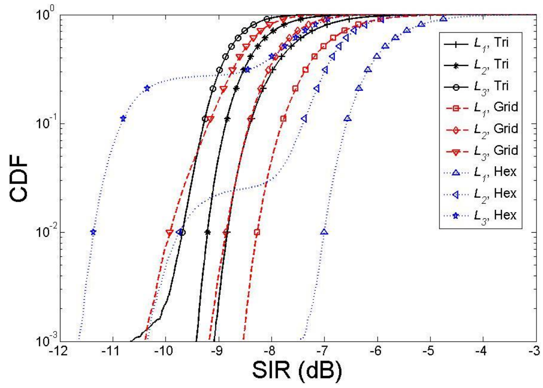


(b)

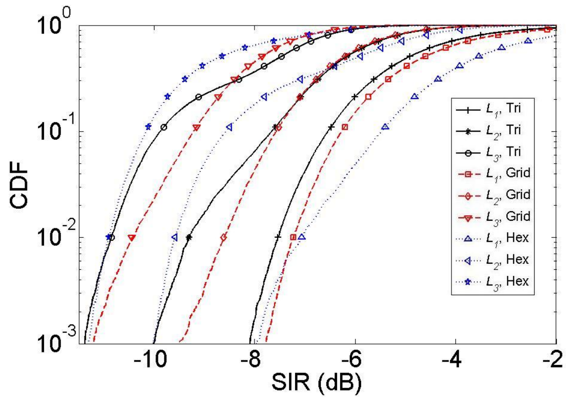
Fig. 3. The comparison of CDF of the power of MAIs of the nodes for different topologies with variations: (a)σ_N =0.05, (b)σ_N =0.07

In order to easily find the SIR_0 performed the network 3-connectivity, $SIR_{0,3\text{-con}}$, we transfer the CDFs of SIR of the links to the $P_{k\text{-con}}$ for k=1,2 and 3 in fault environments as shown in Fig. 5. Moreover, in CDMA systems the longer PN sequence obtains higher processing gain and suppresses MAIs. If the minimum SIR requirement SIR_0 is obtained, the useful length of PN codes can be designed to perform required network connectivity. Thus, the connectivity performance in deployment variation is investigated. We depicted the comparison for the three topologies as shown in Fig. 5.

When the variation is small with σ_N=0.05 and the failure rate is minor with P_f=0.1 as shown in Fig. 5(a), the SIR_0 to reach 3-connectivity is -11.4, -10 and -9.8dB for hexagon, grid and triangle topologies respectively. Moreover, when the failure rate increases to P_f=0.5 as shown in Fig. 5(b), the SIR_0 for the three topologies to reach 3-connectivity are almost the same and about -11dB.



(a)



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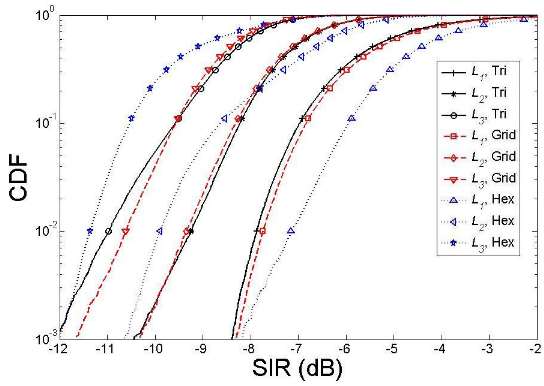
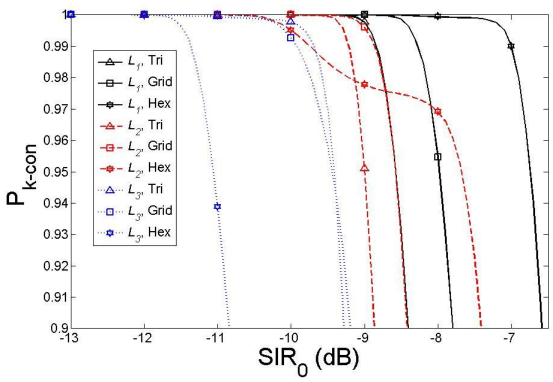


(c)

Fig. 4. The CDFs of SIR for the three strongest links in three different topologies with σ_N =0.05: (a) P_f=0.1 (b) P_f=0.5 and σ_N =0.07: (c) P_f=0.3.

Fig. 6 shows the comparisons on 3-connectivity performance $SIR_{0,3\text{-con}}$ vs. failure rate P_f for the three topologies with σ_N =0.05, 0.07 and 0.1. From Fig. 6(a), it is observed that the 3-connectivity performance of Hex suffers severe degradation for failure rate P_f=0.1 with σ_N =0.05, 0.07 due to the only three neighbor links in Hex. However, when failure rate P_f increases from 0.1 to 0.5, the $SIR_{0,3\text{-con}}$ seem not falling down but slightly uprising due to the MAI reduction. Therefore, the 3-connectivity performance of Hex exhibits fault tolerance for P_f =0.2 to 0.5.

As regards the 3-connectivity performance of Tri and Grid topologies, it is observed that the fault tolerance performance is superior to that of Hex with σ_N =0.05, 0.07 and P_f =0.1 to 0.5 as shown in Figs. 6(b)-6(c). Moreover, from Fig. 6, with larger variation of σ_N =0.1, the 3-connectivity performance of three topologies possess good fault tolerance performance.



(a)

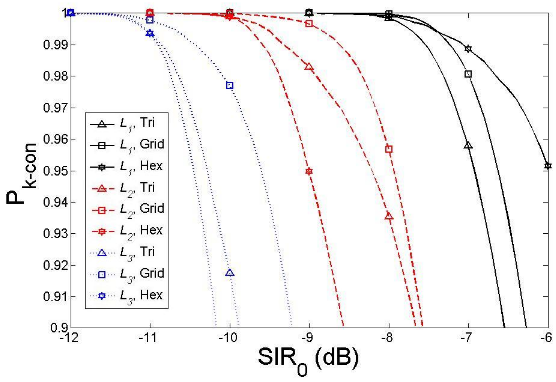


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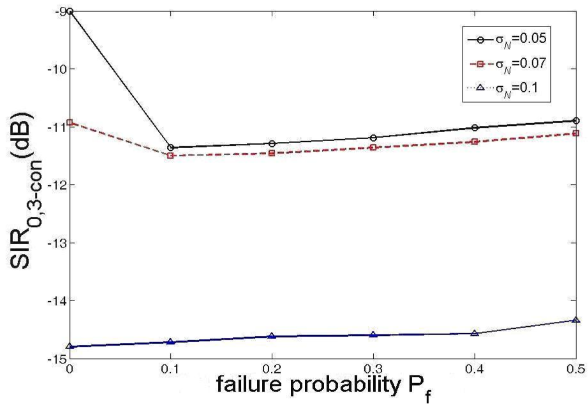
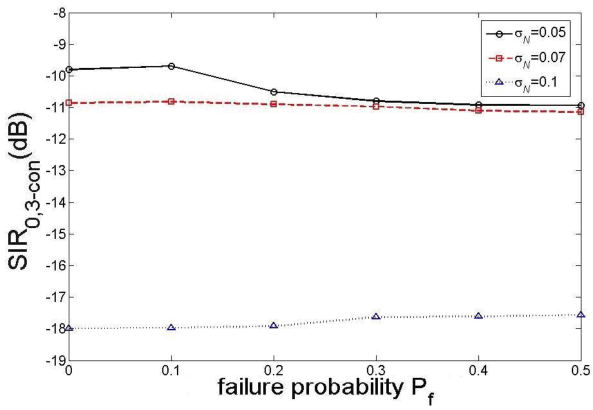
Fig. 5. The comparison on connectivity performance for the three strongest links with σ_N =0.05: (a) P_f=0.1 (b) P_f=0.5 and σ_N =0.07



(a)



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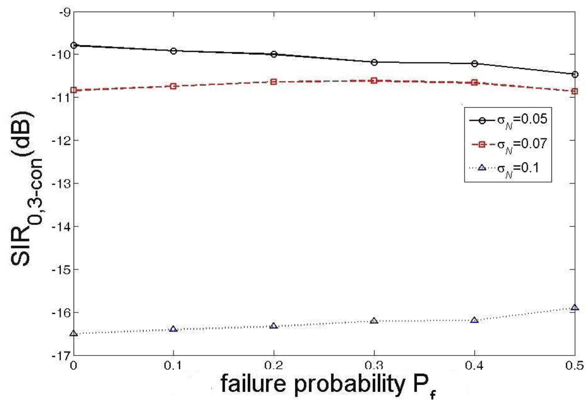

(c)

Fig. 6. The comparison on fault tolerance of 3-connectivity with $SNR_{0,3\text{-con}}$ for (a)Hex, (b)Tri, (c) Grid topologies with σ_N =0.05

5 Conclusion

In wireless CDMA sensor networks, the received signal strength and the MAIs depend on the network topologies and the variations of deployment. In this paper, the fault tolerance of connectivity performance of three topologies, hexagon, grid and triangle topologies is investigated with variations of deployment. We evaluate the connectivity performance with $SIR_{0,3\text{-con}}$, the minimum requirement of SIR, SIR_0 for the 3-connectivity. Simulation results show that the hexagonal and grid topologies suffer a degradation of -2.4 and -0.5 dB, respectively, when the failure rate from 0 to 0.1 with σ_N=0.05. However, the triangular topology shows a robustness of fault tolerance, when the failure rate from 0 to 0.5 with $\sigma_N \leq 0.1$.

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