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Research Article

Reliability Evaluation of a Wireless Sensor Network in Terms of Network Delay and Transmission Probability for IoT Applications

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Abstract: Reliability is a crucial performance metric for wireless sensor networks (WSNs) because it ensures network functionality even with degraded sensor nodes and wireless connections. Due to the limited availability of power resources associated with the sensor nodes, their efficacy is reduced. In addition, parameters such as the number of neighbours, packet success rate, packet size, and node capacity have a significant impact on how sensor nodes function. Similarly, inter-node distance and signal-to-noise ratio (SNR) have the greatest influence on the functioning of wireless communications in WSNs. Before evaluating the reliability of a WSN, therefore, the node and link reliability must be computed. This paper evaluates the reliability of sensor nodes by taking into account all of the parameters previously mentioned. In addition, the lifetime of each sensor node is estimated in terms of the fractional energy consumed for each wake-up operation and the transmission of packets, respectively. Using the inter-node distance and SNR values, each wireless link's reliability is determined. Following this, a proposed algorithm evaluates the reliability of WSN by first enumerating all minimal paths between the sensor node and the base station and then converting these minimal paths into their sum-of-disjoint-product terms. Making use of a suitable example network, every step of the proposed method is illustrated. For evaluating the reliability of WSN, the proposed method is simulated in different environments. In addition, the influence of parameters such as inter-node distance, SNR, number of neighbours, packet success ratio, and time on the reliability values of WSN is portrayed and analysed.

***Keywords*:** WSN, node reliability, link reliability, SNR, fault-tolerant network

MSC: 68M15, 68M18

Nomenclature

A	Target area in m
α	The node's capacity and type
β	The packet size

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d	Euclidean distance
E_i	Initial energy associated with sensor node s_i
e_i	Energy consumed by a node to wake up
e_T	Energy consumed to transmit packets
G	Probabilistic graph representing WSN
g_i	The number of neighbor nodes of node i
γ	Packet success rate
k	Propagation power loss exponent
λ	The node failure rate
$p_N(i)$	Reliability of ith sensor node
$pT(i)$	Transmission probability of ith sensor node
pw_j	Node wake-up probability
ρ_j	Wake-up rate of jth sensor node
S_i	ith sensor node
SNR	Signal-to-noise ratio
T_i	Lifetime of a node
t_A, t_B, t_C	Time period

1. Introduction

The Internet of Things (IoT) is an emerging technology with a variety of application domains, including smart cities, smart manufacturing, and smart healthcare, to mention a few. Fundamentally, the successful implementation of IoT applications requires a wireless sensor network (WSN) because it connects geographically dispersed sensor modules to the base station. The preponderance of such a network is made up of sensor nodes with limited energy resources [1, 2]. Additionally, wireless connections are used to transmit data in this network type. Today, the WSN is used in a variety of crucial applications, such as healthcare, military operations, and industry. Under such critical conditions, a WSN with the utmost level of reliability is required. However, the limited availability of power resources hinders the functionality of sensor nodes. In addition, wireless communications are highly susceptible to failure due to fading and other physical parameters. This, in turn, necessitates the evaluation of the WSN's reliability from its deployment to its operation in order to guarantee the successful delivery of sensitive data to its intended recipients.

Reliability is of the utmost importance when evaluating the performance of various networks, as it defines the operational probability of a network over a specific period of time and in a specified working environment [1]. Based on how the nodes are connected, a network can be abstractly divided into two types: fixed networks, such as distributed networks [2], and wireless networks, such as WSNs. The literature contains numerous techniques for evaluating the reliability of wired networks. For computing the reliability of wired networks, the majority of these techniques [3-7] employ minimal cut-set (MCS) [2], minimal path set (MPS) [3], inclusion-exclusion principle [4], binary decision diagram, etc. However, wireless networks are more susceptible to failure due to wireless links than wired networks. However, very little emphasis is given to the evaluation of wireless network reliability [1].

In terms of reliability, the WSN is not robust, but the literature is far behind existing solutions to this problem. As previously stated, a WSN may exist in a variety of operational states dependent on wireless links and sensor nodes. As a result, determining the node and link reliability is the first step before assessing the WSN's reliability using these parameters. In addition to the aforementioned, other parameters that contribute to the failure of such networks include network delay, packet size, packet success ratio, etc. Consequently, the reliability of WSNs must be evaluated based on the aforementioned parameters. In turn, this necessitates assessing the reliability of the WSN as a whole or as a function of its fundamental components, such as sensor nodes and wireless connections. This paper addresses this issue and proposes a new method for evaluating the reliability of WSNs that takes into account both node and link failures. The following is a list of this paper's most important contributions:

1. The reliability of each node is evaluated in terms of node wake-up probability and packet transmission probability.
2. The lifetime of each sensor node is estimated in terms of residual energy and network delay.

3. The reliability of the link is computed by considering the inter-node distance and SNR as the parameters.
4. A minimal path-based algorithm is used to find the reliability of each sensor node and the base station.
5. A detailed analysis is carried out to show how different parameters, as stated earlier, affect the reliability of WSNs.

The workflow adopted in this paper is presented graphically (Figure 1), and the list of abbreviations used in this paper is listed in Table 1.

The rest of the paper is organized as follows: Related works are discussed in Section 2. Section 3 proposes a method for evaluation of reliability of WSN. The proposed method is illustrated in Section 3. Simulated results and discussion are presented in Section 4 while Section 5 concludes the paper with its future scope.

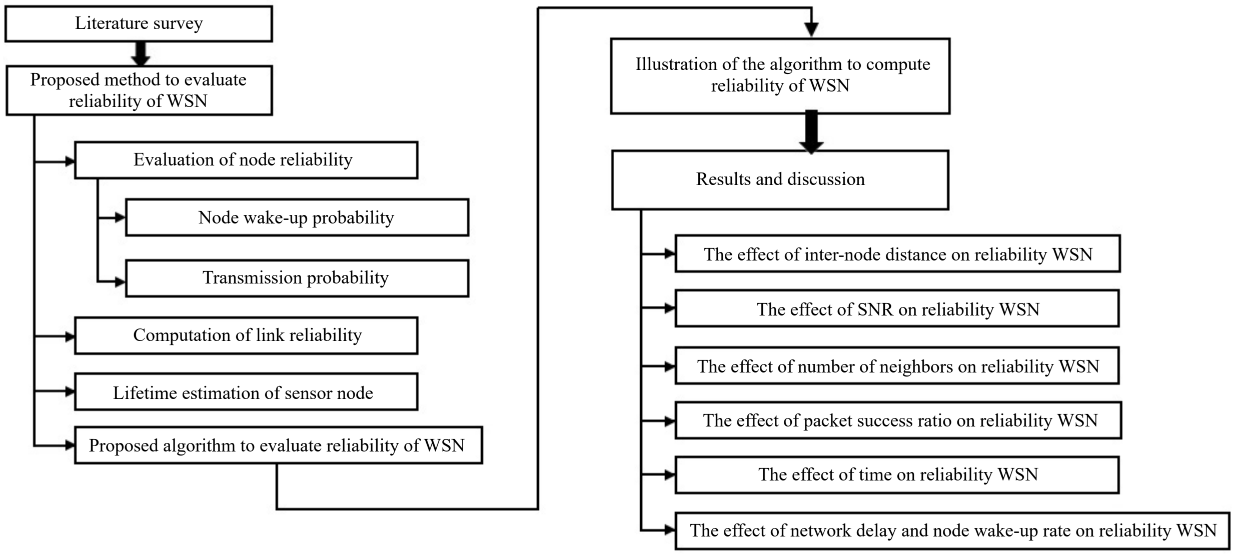

Figure 1. A graphical representation of the workflow adopted in this paper

Table 1. List of abbreviations

Abbreviation	Meaning
BS	Base station
CA	Carrier aggregation
CGC	Centralized genetic-based clustering
DS	Dempster-Shafer
EERA	Energy-efficient and reliable routing approach
FD	Full duplex
IoT	Internet of Things
LG	Line graph
LWSN	Linear wireless sensor networks
MP	Minimal path
PL	Path loss
RDTP	Reliable data transport protocol
RRNS	Redundant residue number system
RRP	Reliable routing protocol
SDP	Sum-of-disjoint product
WSN	Wireless sensor network

2. Related work

For large-scale WSN, Guo et al. [8] introduced an RRP that maximised reliability in terms of data collection and control message delivery. This paper lists numerous sensor nodes and sink nodes along bidirectional routes. The routing topology was constructed by the sink node by first generating a route with an illegitimate node as the destination. The findings of this paper's experiments demonstrated that the packet delivery rate was 100%, exceeding the current routing protocols in terms of routing overhead, end-to-end packet delay, and packet delivery rate. Although end-to-end delay, routing costs, and packet delivery rates are all used to describe reliability, there is no clear reliability expression used in the study to assess WSN reliability. The paper [9] created a mobile node-adaptive reliability-based transport protocol that may be adapted to the needs of novel reliable data applications for sensor networks. Clusters are created using this technique to minimise energy consumption. But this method lacks any method for computing the reliability of WSN.

In order to extend the lifespan and improve the reliability of WSNs, the work carried out [10] developed a unique strategy based on a RRNS. The objective of this work is to increase reliability without addressing how to determine the lifespan of individual sensor nodes or the lifespan of WSNs in general. A new approach based on the RRNS was suggested in the work [11] to make WSN as energy-efficient and error-free as possible. Thus, this technique improves the WSN's general level of reliability. However, reliable packet delivery does not necessarily depend only on energy-efficient and error-free packet delivery, as wireless links and sensor nodes also play a role in reliability.

A CGC system was developed [12] to guarantee reliable data transfer. For the selection of cluster heads, a genetic algorithm was used as a dynamic technique. This methodology, called the onion approach, was adopted. In addition, a novel onion technique that divides WSN into numerous onion layers has been suggested in this work to reduce communication overheads between cluster heads. When resolving the reliability issue, additional elements like network delay, the number of neighbours each node has, the packet success ratio, etc. have not been taken into account. By using an effective moduli set in the RRNS, the paper [13] suggested a novel RDTP for wireless sensor networks. According to the simulation results in this paper, the proposed method uses significantly less energy than alternative methods. Energy efficiency is not the only factor to consider while ensuring reliable data connections between the BS and sensor nodes. Other factors that were previously stated are not taken into account for trustworthy data communication.

DS evidence theory was employed by Tang et al. [14] to make their proposal for DS-EERA for WSNs. This method chooses the subsequent hops by primarily taking into account network parameters such as the residual energy of nearby nodes, network activity, the shortest path, etc. Like earlier research, it does not evaluate reliability by taking into account the reliability of sensor nodes and wireless links. A more effective framework for behavior-driven reliability modelling was given in [15] for the effective reliability analysis of complex WSN-based smart systems. The suggested approach may deal with the consequences of dependent behaviours affecting several smart system components in a combinatorial manner. In order to sustain efficacy, it also enhances the use of single-area dependability strategies. Although dependability has been extensively addressed in this work, there is no technique to assess the WSN's reliability. A method for configuring, designing, and deploying low-power WSNs was provided by Brini et al. [16]. The sensor node is given an energy model and a plausible PL model.

The network coverage reliability of WSNs has been calculated based on Monte Carlo simulations in [17]. Further, the impact of different parameters, like coverage reliability, has also been discussed in this work. Important reliability measures like two-terminal reliability are not addressed in this work.

The work in [18] presented a method to transform the time-aggregated graph model of a dynamic network into an LG. Reliability is then evaluated by generating the time-stamped MP sets and time-stamped minimal cut sets. However, the reliability of hardware components like sensor nodes has not been incorporated while evaluating the reliability of WSN. The work in [19] explained how to maximise the reliability of WSN by considering the number of sensor nodes as a constraint.

Jia et al. [20] proposed an industrial WSN with FD relays and the CA technique to increase the reliability of sensor nodes. This work further maximises reliability by decomposing the resource allocation problem into sub-problems through the distributed decision-making (DDM) process. The solution to each sub-problem has been obtained by employing the bee colony algorithm. Though this work mainly deals with the reliability maximisation problem, there is still a lack of an efficient method to evaluate it for WSN. The importance of reliability for IoT has been discussed in [21].

The work in [22] developed a reliable algorithm to minimise the higher overhead that occurs due to flooding. Two protocols are designed: one for unicast and another for multicast. Unicast is used to minimise the routing path, while multicast is used to minimise the throughput of the long routing path. The results show that the algorithm improves throughput and packet delivery rate by avoiding flooding but fails to provide a method or an expression to find the reliability of WSN.

Xu et al. [23] proposed a model using different discrete distributions like Poisson distribution, Weibull distribution, and binomial distribution to reduce network overhead, improve security, and enhance query efficiency. Like other works, it also fails to address other aspects of reliability, like the computation of hardware-dependent reliability. A reliable intelligent model has been proposed in [24] for the deployment of sensor nodes in IoT applications. The reliability was evaluated by enumerating all node-disjoint paths between each sensor node and the BS. This work does not consider any parameters for evaluating node reliability and link reliability, which must be included while evaluating the reliability of WSN. A hybrid approach has been proposed in [25] that uses decision trees to estimate the reliability of both plain-based and cluster-based LWSNs. Based on hybrid models of binary decision diagrams and divide-and-conquer schemes, the work in [26] presented a practicable method for concurrent reliability analysis in terms of connectivity and coverage for LWSNs. However, these methods do not consider node reliability or link reliability, and they also lack a general method to compute the reliability of WSN.

3. Proposed method for reliability evaluation of WSN

The following assumptions are made for the proposed method for reliability evaluation of WSN:

1. The source and destination nodes are known.
2. All nodes are homogeneous.
3. Every node and every pair of nodes within the range of wireless communication are considered to be linked within the wireless network.
4. The development of the host is based on the random-way point versatility model.

Initially, N numbers of sensor nodes are deployed randomly over the target area (A m^2). The WSN that constitutes these N numbers of sensor nodes can be viewed as a probabilistic graph G. The wireless link in this graph can have two states, as defined below:

$$\begin{aligned} I_{i,j} &= 1 \text{ if} \sqrt{(S_i.X - S_j.X)^2 + (S_i.Y - S_j.Y)^2} \\ &= 0 \text{ otherwise} \end{aligned} \tag{1}$$

3.1 *Computation of reliability of node*

The work proposed in this paper considers mainly the following two factors while evaluating the reliability of the sensor node:

i. Node wake-up probability

ii. Packet transmission probability

3.1.1 *Computation of node wake-up probability*

A sensor node i transmits a beacon signal and an identity (ID) signal to its neighbouring nodes during the respective time intervals t_B and t_C. It awaits an acknowledgement signal for t_A seconds. When a neighbouring node j awakens and detects the beacon signal, it remains awake and awaits the subsequent ID signal to identify the sender. When node j awakens during an ID signal, it remains alert and awaits the next ID signal. If node j recognises the sender successfully and is a next-sensor node of node i, it communicates with node i to receive the packets. Node j can then use a similar procedure to wake up the next sensor node in its network. The establishment of the link between nodes i and j is depicted in Figure 2. The time instants that a node j wakes up follow a Poisson random process with rate ρ_j [27].

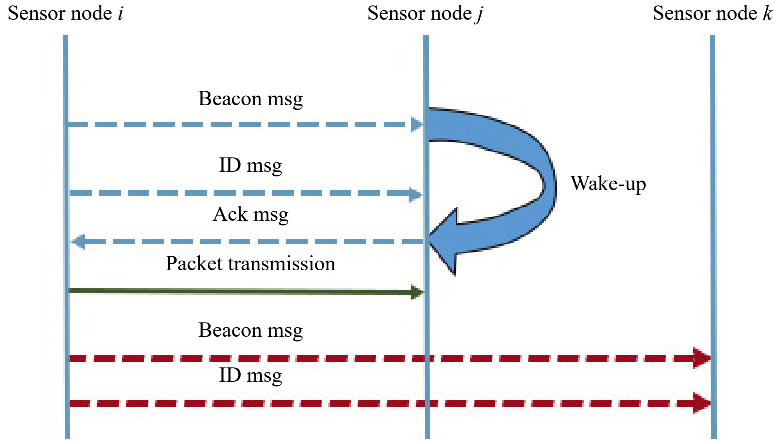

Figure 2. Link establishment between node i and node j for data transmission

The node wake-up probability can be calculated as

$$pw_j = 1 - e^{-\rho_{j(t_A + t_B + t_C)}} \tag{2}$$

3.1.2 *Computation of packet transmission probability*

The node's reliability depends on the following parameters [28]:

i. The node's capacity and type (α)

ii. The packet size (β)

iii. The number of neighbour nodes of node i (g_i)

Considering the parameters mentioned above, the reliability of the node can be defined as:

$$p_T(i) = \frac{\gamma}{2 \times e^{\propto(g_i - \beta)} + 1} \tag{3}$$

The wake-up probability for the node i can be written by using equation (2) as:

$$p_w(i) = 1 - e^{-\rho_{i(t_A + t_B + t_C)}} \tag{4}$$

3.1.3 *Computation of node reliability*

The node reliability can be calculated by defining the two following dependent events:

i. Event 1: The node wakes up with probability $p_W(i)$.

ii. Event 2: The node transmits packets with probability $p_T(i)$.

The occurrence of event 2 depends on the occurrence of event 1 as the sensor node must wake up first, and then only it can start transmitting the packets. Hence, the reliability of node i can be expressed in terms of wake-up probability $p_W(i)$ and packet transmission probability [29] $p_T(i)$ as

$$\begin{aligned} p_N(i) &= (p_W(i) \cup p_T w(i)) \\ &= (1 - e^{-p_{j(t_A + t_B + t_C)}}) + \frac{\gamma}{2 \times e^{\propto(g_i - \beta)} + 1} - (1 - e^{-p_{j(t_A + t_B + t_C)}}) + \frac{\gamma}{2 \times e^{\propto(g_i - \beta)} + 1}. \end{aligned} \tag{5}$$

3.2 *Estimation of lifetime of sensor nodes*

Let E_i be the initial energy associated with sensor node S_i. If node S_i needs e_i units of energy to wake up [27] and e_T energy to transmit packets, the ratio of energy consumption can be expressed as:

$$r_i = \frac{e_i \times e_T}{E_i} \tag{6}$$

The lifetime of the node can be defined as [27]:

$$T_i = \frac{t_A + t_B + t_C}{r_i ln \frac{1}{(1 - p_w) \times (1 - p_T)}} \tag{7}$$

The node reliability in terms of node failure rate and overall lifetime of the sensor node can be written as:

$$p_N(i, T) = e^{-\lambda T} \tag{8}$$

where T represents the lifetime of sensor node, λ is the node failure rate.

3.3 *Computation of link reliability*

The reliability of a wireless link ($p_{i,j}$) is determined by the probability that the signal is successfully received, and it depends mainly on the following factors [28]:

i. Transmission power
ii. The Euclidean distance between two sensor nodes (d)
iii. The SNR and the reliability of wireless links $p_{i,j}$ between any two sensor nodes i and j can be expressed as

$$p_{i,j} = e^{-d^k / SNR} \tag{9}$$

where k is the propagation power loss exponent whose value is assumed to lie between 2 to 4.

3.4 *Computation of reliability of WSN*

The reliability of the WSN is computed by following the following steps:

i. All the MPs are enumerated between the sensor node (S) and the BS.
ii. These MPs are transformed into their equivalent disjoint MPs by using the SDP technique.
iii. Reliability is then evaluated by replacing all indicator variables (like node name and link name) by their probability values and logical sum and product operators by their arithmetic counterparts like addition and multiplication, respectively.

The algorithm to calculate the reliability of WSN is presented in Algorithm 1.

Algorithm 1: Computation of reliability of WSN

Deploy randomly N number of sensor nodes for the target area A m^2
for *each sensor node* S_i , i = 1, 2, ... N **do**
for *each sensor node* S_j , i = 1, 2, ... N **do**
  if $i \neg j$, **then**
    $d(S_i, S_j) = \sqrt{(S_i.X - S_j.X)^2 + (S_i.X - S_j.X)^2}$
    if $d \leq T_r$, **then**
      $Si.nebh.append\ (S_j)$

Link establishment for packet transmission
for *each sensor node* S_i **do**
  $S_i.send\ (beacon)$ each S_i, $S_j \in S_I.nebh$
  $S_j.send\ (ID)$ each S_i, $S_j \in S_I.nebh$
  if $wake\_up\ (S_j) == true$, **then**
    $S_j.send(ack)$
  Link $(S_i, S_j) = true$

for *each sensor node* S_i **do**
  Calculate $p_N\ (S_i)$ by using equation (5)

for *each link* $l_{i,j}$ **do**
  Calculate $p_{i,j}$ by using equation (9)

for *each sensor node* S_i **do**
  Generate all MPs between S_i and the BS
  Convert the MPs to their SDP terms
  S_{dis} = SDP terms of MPs
  $R = (S_{dis})_{a,\bar{a},\cup,\cap \to p,q,+,x}$

4. Illustration

Each step of the proposed method is illustrated by taking a suitable network as an example (Figure 3). The wireless links are named alphabetically. The weight of each link represents the Euclidean distance between its associated nodes. For example, the link between sensor nodes 0 and 1 is named 'a' with a weight of 3, which is the Euclidean distance between the nodes 0 and 1. The details of wireless links along with their computed reliability values by using equation (9) are presented in Table 2 (k and SNR are assumed to be 2 and 20 dB, respectively).

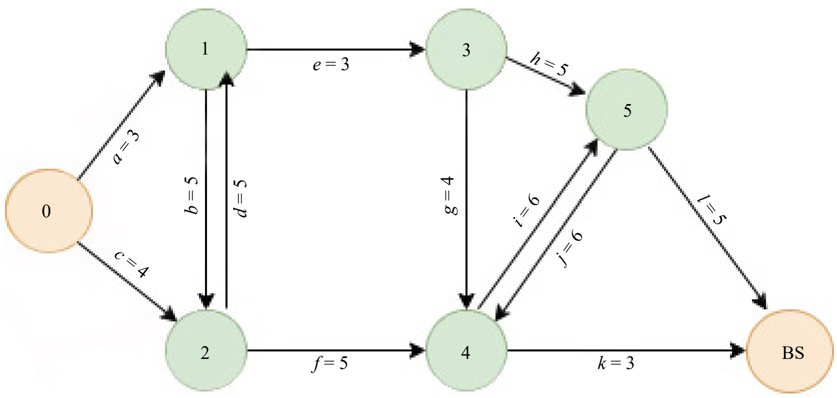

Figure 3. An example WSN with five number of sensor nodes

Table 2. Wireless links and their computed reliability values

Nodes	Link	*d*	Reliability
0,1	*a*	3	0.905
1,2	*b*	4	0.875
0,2	*c*	5	0.846
2,1	*d*	5	0.846
1,3	*e*	3	0.905
2,4	*f*	5	0.846
3,4	*g*	4	0.875
3,5	*h*	5	0.846
4,5	*i*	6	0.818
5,4	*j*	6	0.818
4,6	*k*	5	0.846
5,6	*l*	3	0.905

The node reliability is calculated by using equation (5) with a packet success ratio rate of 0.9, a packet size of 10, and the neighbour nodes as shown in Table 3.

Table 3. Calculation of node reliability

Nodes	g_i	Reliability
0	2	0.9626
1	2	0.9626
2	2	0.9626
3	2	0.9626
4	2	0.9626
5	2	0.9626

The MPs generated by the proposed algorithm are converted to their equivalent SDP terms, which are presented in Table 4. The reliability calculated for each path is shown in the third column of this table.

Table 4. Calculation of reliability of WSN considering only link failure

Path	Link	Reliability
1	*Pb Pe Pj*	0.64775375
2	*Pb Pe Phqj Pi*	0.11034355263
3	*Pa qbqe qhqj Pk Pl*	0.00023061802
4	*Pa qbqc Pf Pg qh Pj qk ql*	0.00001466151
5	*Pa qb Pc Pe qf qg qh Pj qk ql*	0.01222410095
6	*qa Pbqc Pd qe Pf qg qhqj Pk Pl*	0.00000233473
7	*qa Pbqc Pd qe Pf Pg qh Pj qk ql*	0.00000140359
8	*Pa qbqc qd qe Pf qg qh Pi Pj Pk ql*	2.23215995e-7
9	*Pa qbqc qd qe Pf Pg Phqi qj qk Pl*	7.36859173e-7
10	*Pa qb Pc qd Pe qf qg Phqi qj qk Pl*	0.00000100279
11	*qa Pbqc Pd qe Pf Pg Phqi qj qk Pl*	0.00000297445
12	*qa Pbqc Pd qe Pf qg qhqi Pj Pk Pl*	0.00000190981

The computed reliability values are shown in Table 4. The reliability of all the links in the possible paths is calculated, and the reliability is 0.77057726855.

The sensor nodes can be viewed as connected in series with the associated links, and thus, the incorporation of the failure of sensor nodes towards calculating the path reliability is presented in Table 5.

Table 5. Calculation of the reliability of WSN, considering both node failure and link failure

Path	Node and link	Reliability
1	0*Pb* 2*Pe* 4*Pj*	0.57776004901
2	0*Pb* 2*Pe* 4*Ph* 5*qj Pi*	0.09473934804
3	0*Pa* 1*qbqe qhqj* 3*Pk* 5*Pl*	0.00020569835
4	0*Pa* 1*qbqe Pf* 3*Pg qh* 4*Pj qk ql*	0.00001258816
5	0*Pa qb* 1*Pc* 2*Pe qf qg qh* 4*Pj qk ql*	0.00000263821
6	0*qa Pbqc* 2*Pd qe* 1*Pf qg qhqj* 3*Pk* 5*Pl*	0.00000192959
7	0*qa Pbqc* 2*Pd qe* 1*Pf* 3*Pg qh* 4*Pj qk ql*	0.00001443372
8	0*Pa qbqc qd qe* 1*Pf qg qh* 3*Pi* 5*Pj* 4*Pk ql*	0.00000253954
9	0*Pa qbqc qd qe* 1*Pf* 3*Pg* 4*Phqi qj qk* 5*Pl*	6.08995076e-7
10	0*Pa qb* 1*Pc qd* 2*Pe qf qg* 4*Phqi qj qk* 5*Pl*	0.00000663026
11	0*qa Pbqc* 2*Pd qe* 1*Pf* 3*Pg* 4*Phqi qj qk* 5*Pl*	0.00000236636
12	0*qa Pbqc* 2*Pd qe* 1*Pf qg qhqi* 3*Pj* 5*Pk* 4*Pl*	0.00000151937

The overall reliability, i.e., the reliability of the total path, including the connecting paths and nodes, is shown in Table 5. The reliability of all the possible paths is calculated, and the overall reliability is 0.67325095255.

5. Simulated results and discussion

The proposed method to evaluate the reliability of WSN in terms of network delay and packet transmission is simulated in a Google Colab environment with Python. The parameters set for the purpose of simulation are presented in Table 6. Fifty nodes are randomly deployed over a target area of 100 m^2 (Figure 4). The wake-up probability of each node is calculated by adopting the wake-up protocol [27]. In addition to this, the transmission probability of each node is calculated (Table 7). The number of neighbours for each node is also shown in this table. The reliability is then calculated between each sensor node and BS by using the proposed method in two situations: considering only link failure (Figure 5) and considering node failure and link failure (Figure 6).

Table 6. Parameter setting for simulation purpose

Parameter	Value/Range
T_r	25 m
β	10
γ	0.9
ρ	0.01
α	1
k	2
SNR	20 dB
t_A	1 ms
t_B	1 ms
t_C	1 ms

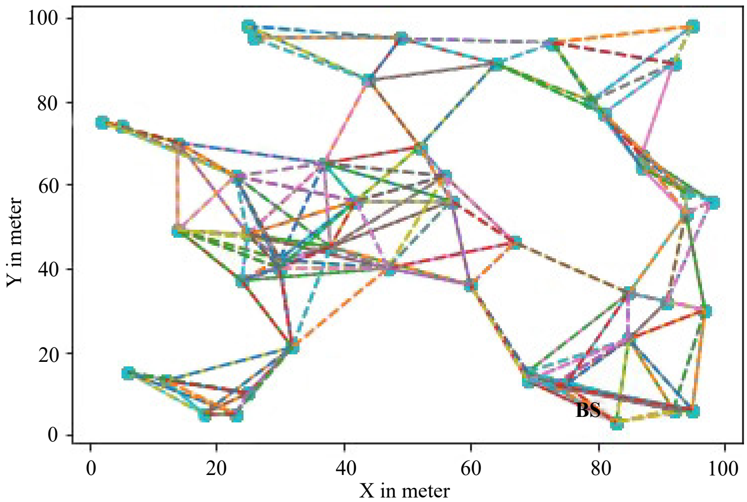

Figure 4. Random deployment of sensor nodes over target area

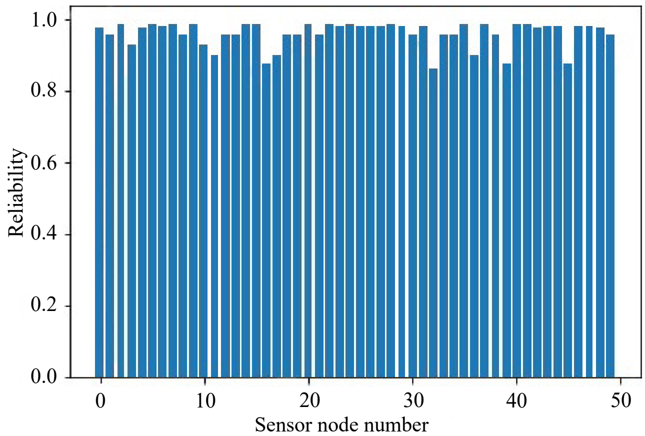

Figure 5. Computed reliability between each sensor node and the BS, considering only link failure

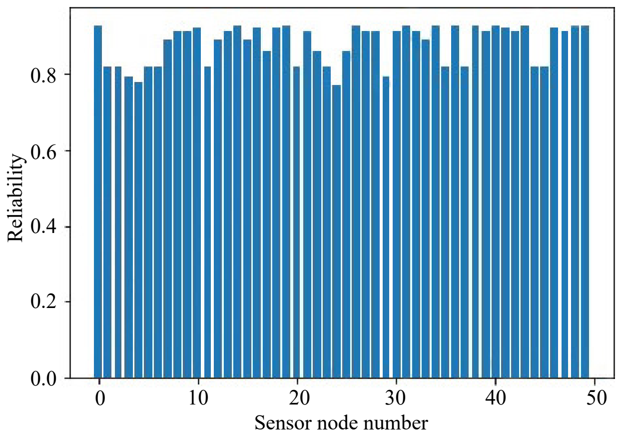

Figure 6. Computed reliability between each sensor node and the BS, considering both link failure and node failure

Table 7. Calculation of sensor node reliability

Node	No. of neighbours	Transmission probability	Awake probability	Node reliability	Lifetime
0	7	0.82	0.93	0.99	5503
1	8	0.71	0.93	0.98	3583
2	5	0.89	0.93	0.99	7886
3	9	0.52	0.93	0.97	2044
4	7	0.82	0.93	0.99	5503
5	3	0.90	0.93	0.99	8402
6	6	0.87	0.93	0.99	7041
7	3	0.90	0.93	0.99	8402
8	8	0.71	0.93	0.98	3583
9	3	0.90	0.93	0.99	8402
10	9	0.52	0.93	0.97	2044
11	10	0.30	0.93	0.95	1166
12	8	0.71	0.93	0.98	3583
13	8	0.71	0.93	0.98	3583
14	4	0.90	0.93	0.99	8256
15	3	0.90	0.93	0.99	8402
16	11	0.14	0.93	0.94	729
17	10	0.30	0.93	0.95	1166
18	8	0.71	0.93	0.98	3583
19	8	0.71	0.93	0.98	3583
20	5	0.89	0.93	0.99	7886
21	8	0.71	0.93	0.98	3583
22	4	0.90	0.93	0.99	8256
23	6	0.87	0.93	0.99	7041
24	4	0.90	0.93	0.99	8256
25	6	0.87	0.93	0.99	7041
26	3	0.90	0.93	0.99	8402
27	6	0.87	0.93	0.99	7041
28	5	0.89	0.93	0.99	7886
29	6	0.87	0.93	0.99	7041
30	8	0.71	0.93	0.98	3583
31	6	0.87	0.93	0.99	7041
32	12	0.06	0.93	0.94	506
33	8	0.71	0.93	0.98	3583
34	8	0.71	0.93	0.98	3583
35	5	0.89	0.93	0.99	7886
36	10	0.30	0.93	0.95	1166
37	4	0.90	0.93	0.99	8256
38	8	0.71	0.93	0.98	3583
39	11	0.14	0.93	0.94	729
40	3	0.90	0.93	0.99	8402
41	5	0.89	0.93	0.99	7886
42	7	0.82	0.93	0.99	5503
43	6	0.87	0.93	0.99	7041
44	6	0.87	0.93	0.99	7041
45	11	0.14	0.93	0.94	729
46	6	0.87	0.93	0.99	7041
47	6	0.87	0.93	0.99	7041
48	7	0.82	0.93	0.99	5503
49	8	0.71	0.93	0.98	3583

5.1 *The effect of inter-node distance on reliability of WSN*

Figure 7 illustrates the effect of inter-node distance on the reliability of WSNs with varying SNR. This graph shows that as the distance between nodes increases, the link reliability decreases, thereby decreasing the overall reliability of WSN. However, this effect can be mitigated by increasing the SNR whenever feasible. Figure 7 also indicates that the WSN reliability reaches zero for an inter-node distance of approximately 17 metres and a SNR of 10. However, the reliability values for strong signal strengths, such as SNR values 20 and 30, are 0.2% and 0.5%, respectively. Figure 7 demonstrates that reliability varies inversely with respect to inter-node distance and directly with respect to SNR value.

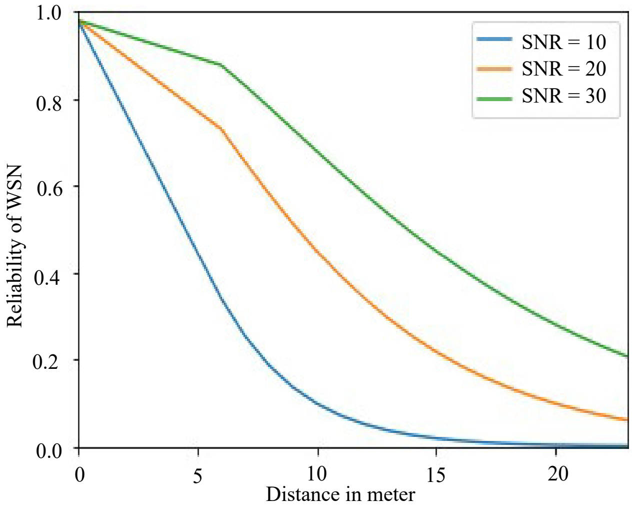

Figure 7. The effect of inter-node distance on reliability of WSN

5.2 *The effect of SNR on reliability of WSN*

Figure 8 depicts the computed WSN reliability in terms of SNR for various inter-node distances. The main takeaway that can be drawn from this graph is that the WSN is more reliable when operating over excellent signal strength, i.e., when SNR values are optimal. This observation is straightforward, as a diminishing effect causes data loss for weaker signals. In addition, this number implies that the inter-node distance should be shorter to achieve a higher reliability value.

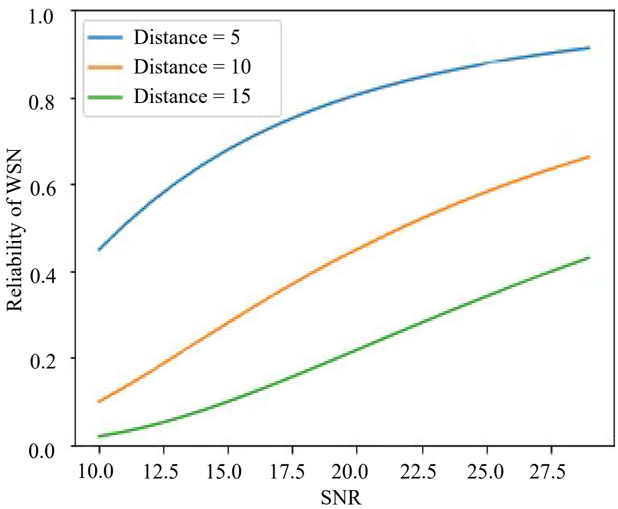

Figure 8. The effect of SNR on reliability of WSN

5.3 *The effect of number of neighbours on reliability of WSN*

Figure 9 illustrates the influence of the number of neighbours on the reliability of a WSN with varying transmission packet sizes. This graph illustrates that as the number of neighbours increases, so does the decrease in dependability. For instance, the reliability of a WSN reaches 0.96 when the number of neighbouring nodes is close to eight for a transmission packet size of 10, whereas the same reliability value can be attained for a larger transmission packet size, such as 20, even if the number of neighbouring nodes increases to 18. For packets with a size of 30 or 40 bytes, the reliability of a WSN becomes stagnant regardless of the number of neighbours.

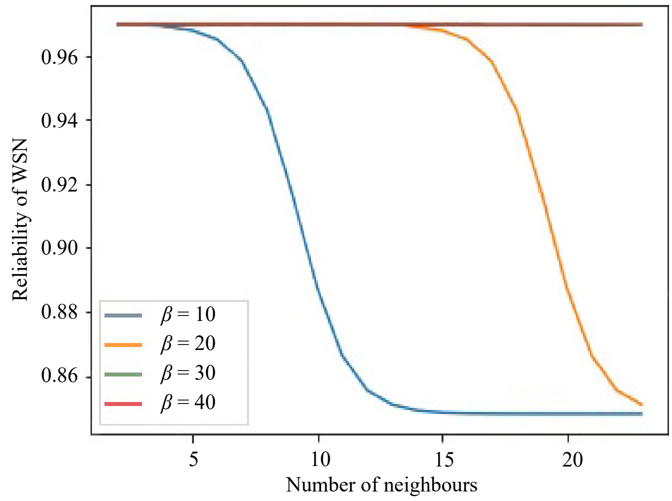

Figure 9. The effect of number of neighbours on reliability of WSN

5.4 *The effect of packet success ratio on reliability of WSN*

Figure 10 shows the effect of packet success rate on the computed reliability of a WSN with varying numbers of neighbours. This graph demonstrates that as the packet success rate increases, so does the reliability, which in turn increases the WSN's overall reliability. This graph also shows that as the number of neighbours increases, the reliability increases marginally compared to the steady increase in reliability values when there are fewer neighbours.

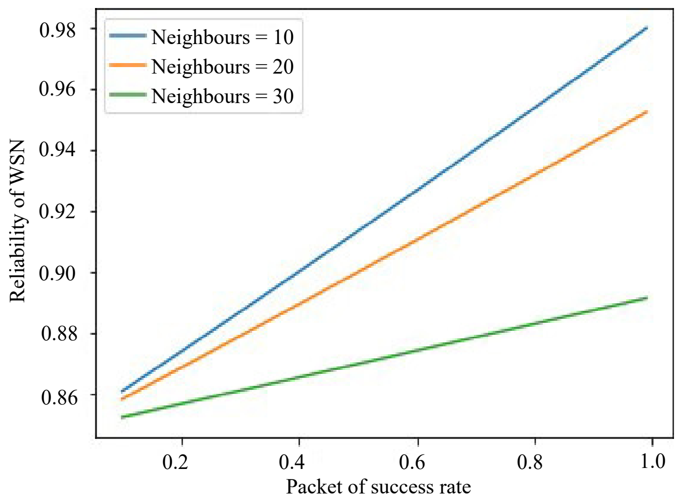

Figure 10. The effect of packet success ratio on reliability of WSN

5.5 *The effect of time on reliability of WSN*

The lifetime of WSN is computed by averaging the life time of sensor nodes (Table 6). The reliability of WSN is computed by using equation (8) under three node failure rates (λ), viz., 0.0025, 0.005, and 0.001, respectively (Figure 11). From this figure, it can be revealed that WSN becomes non-operational during 400 time units and 600 time units for node higher node failure rate, such as $\lambda = 0.0025$ and $\lambda = 0.005$, respectively. However, it is found to be operational with an approximate reliability value of 0.1 even beyond 1,000 time units for a low link failure rate like $\lambda = 0.001$.

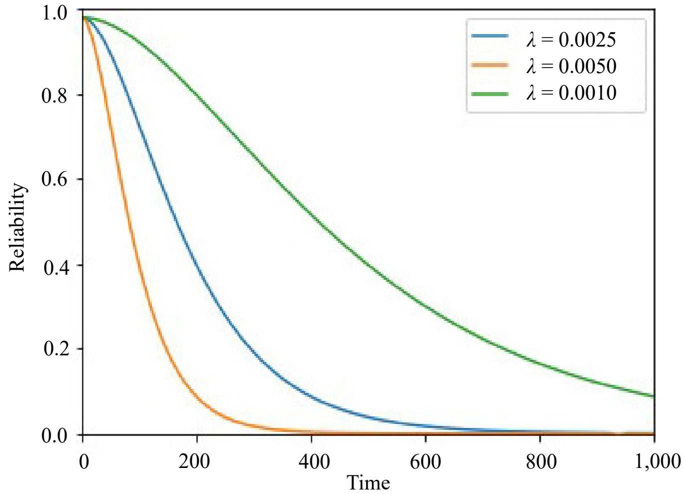

Figure 11. The effect of time on reliability of WSN

5.6 *The effect of network delay and node wake-up rate on reliability of WSN*

The reliability values are computed using different wake-up rates and network delays (Table 8). The considered wake-up values are 0.01, 0.05, and 0.09, respectively. The network delay for each node is computed by summing up t_A, t_B, and t_C. With an increase in wake-up rate, the overall energy consumption by each node increases, which in turn results in low reliability values. Further, the reliability value is also decreased significantly upon increased network delay.

Table 8. The effect of network delay and wake-up rate on reliability of WSN

Network delay	Reliability of WSN		
	$\rho = 0.01$	$\rho = 0.05$	$\rho = 0.09$
0	1	1	1
3	0.99	0.99	0.99
6	0.98	0.87	0.70
9	0.97	0.66	0.36
12	0.94	0.46	0.16
15	0.91	0.30	0.07
18	0.87	0.19	0.03
21	0.83	0.12	0.01
24	0.79	0.08	0.00
27	0.75	0.05	0.00
30	0.70	0.03	0.00

6. Conclusion

The research presented here suggests a novel approach for assessing WSN reliability that takes into account both link and node failure. Each node's reliability is calculated as a function of crucial factors such as end-to-end packet delay, neighbour count, packet size, and packet success rate. The inter-node distance and SNR are taken into account while assessing each link's reliability. It also computed the lifetime of each sensor node. The reliability is then calculated by listing every MP that can be used to connect every sensor node to the BS. An appropriate sample network is used to demonstrate the suggested technique. The reliability of WSN is evaluated and then analysed. A detailed illustration and discussion of the effects of neighbour count, packet size, packet success rate, SNR, and inter-node distance are provided. Other reliability indices, such as network reliability and broadcast reliability, can be evaluated using the work done in this research. Further, the network coverage probability can also be incorporated while evaluating the reliability of WSN. Additionally, the proposed method can be modified, which will provide an end-to-end, RRP for IoT applications.

Conflict of interest

The authors declare no conflict of interest.

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