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A Neighbour Disjoint Multipath Scheme for Fault Tolerant Wireless Sensor Networks

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***Abstract*—In this paper, we propose a "Neighbour Disjoint Multipath (NDM)" scheme that increases resilience against node or link failures in a wireless sensor network (WSN). Our algorithm chooses the shortest path between a sensor and the sink as the primary path, thus ensuring the algorithm is energy efficient under normal circumstances. In selecting the backup paths, we utilise the disjoint property to ensure that i) when there are k paths between source and sink, no set of k node failures can result in total communication break between them, and ii) by having $(k-1)$ *spatially separated* backup paths w.r.t. the primary path, the probability of simultaneous failure of the primary and backup paths is reduced in case of localised poor channel quality or node failures. Our algorithm not only ensures the node disjointedness characteristics of the constructed paths, but also tries to minimise the impact of localised node or link failures where a localised portion of the network may be unusable. We analyse the motivation behind our idea clearly, and discuss the algorithm in detail. We also compare the NDM scheme with other common multipath techniques such as node-disjoint and edge-disjoint approaches, and point out its effectiveness through simulation.**

***Keywords*—Neighbour disjoint multipath, wireless sensor networks, node-disjoint multipath, edge-disjoint multipath, resilience.**

I. Introduction

With the advent of sensor technology, a new class of multi-hop wireless sensor network (WSN) emerged which is generally characterised by resource-constraint failure-prone architecture, and subsequently has given rise to new challenges in order to provide robustness or resilience. Among many applications, these types of WSN are used in battlefield surveillance (e.g., enemy vehicle/troop movements), natural disaster monitoring, and for industrial process monitoring and control where a certain reliability should be ensured while providing robustness in the presence of harsh surroundings [1], [2].

The WSN architecture may fail to supply *important* data *fast* enough in the presence of *hostile* wireless environments due to i) transient failures, or ii) permanent failures [3]. Transient failures usually affect communication links between sensors, and may be caused by interference, multi-path fading, and other environmental factors. Permanent failures might occur due to hardware malfunction/destruction or energy depletion of sensors. Both types of failures can be detrimental for a WSN application having stringent reliability requirements, since they might cause system failures which can result in economic loss, environmental damage or other serious consequences.

In this paper, we propose a "Neighbour Disjoint Multipath (NDM)" scheme that increases resilience against node or link failures. The NDM scheme chooses the shortest path between a sensor and the sink as the primary path, thus ensuring the algorithm is energy efficient under normal circumstances. Then it tries to select a set of backup paths that have no node that is inside the primary path or even a neighbour to any node of it except source or sink. In selecting the backup paths, we utilise the disjoint property to ensure that i) when there are k paths between source and sink, no set of k node failures can result in total communication break between them, and ii) by having $(k-1)$ spatially separated backup paths w.r.t. the primary path, the probability of simultaneous failure of the primary and backup paths is reduced in case of localised poor channel quality or node failures. The first property ensures node disjointedness characteristics of the constructed paths, thereby, incorporating the associated advantages that comes with node-disjoint paths. The second property tries to minimise the impact of co-located node or link failures where a localised portion of the network might be unusable.

We make the following contributions: first, we provide a generalised concept of radio disjointedness property utilised by prior research [4]–[6] to construct multiple paths in terms of neighbour. For example, an n-neighbour disjoint multipath algorithm may be defined as the one that selects the backup paths with nodes that are n radio range away from the primary path's nodes. In this paper, we only concentrate on neighbour (i.e., 1-neighbour) disjoint multipath algorithm. Second, we provide an assessment of performance compared to well-known node-disjoint and edge-disjoint multipath approaches. We use two different failure models: i) *isolated* node failures where each sensor may die independently of each other, and ii) *co-located/localised* node failures where all nodes within a fixed radius fail simultaneously. It attempts to model the idealised wave propagation of most physical phenomena [7]. Various types of activities such as interference inside a building affecting multiple nodes within an area, or other environmental effects such as rain fades or fire may destruct sensors confined to a specific region. These phenomena acted as a motivation to choose this failure model. We utilise two important metrics in order to compare their performance – i) *resilience* which measures the likelihood that, when the primary path fails, a backup path is available between source and sink, and ii) *excess energy expenditure factor* that gives a measure of energy efficiency of the multipath scheme that is a function of number of paths, and the path lengths.

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The rest of the paper is organised as follows. We discuss our motivation of NDM scheme in Section II. The NDM algorithm is discussed in detail in Section III with an illustrative example. In Section IV, we present experimental findings pointing out the effectiveness of our NDM approach. We provide a brief description of related work in Section V. Finally, we depict in Section VI the conclusions drawn, and our future work.

II. Motivation

In this section, we discuss the motivation behind our NDM approach by first analytically showing that in order to improve the resilience against node or link failures using multipath approach, one needs to choose shorter and uncorrelated paths.

Suppose X_i is a Bernoulli random variable with parameter $0 < p_i < 1$ that models whether the i^{th} path between a sensor and the sink fails. X_i is 1 if the path fails, and 0 otherwise. The probability mass function can be written as:

$$f_{X_i}(x_i) = p_i^{x_i}(1-p_i)^{(1-x_i)} \quad x_i = 0, 1.$$

Let another path, j exists between the sensor and sink. We investigate the *resilience improvement* against path failures if we consider both the i^{th} and j^{th} paths compared to a single one. For simplicity, we assume the failure probability of each of the i^{th} and j^{th} path is, $p_i = p_j = p$. The joint failure probability of both paths is q. Subsequently, we have, $E(X_i) = E(X_j) = p,$ and $E(X_iX_j) = q$. The correlation ρ between X_i and X_j,

$$\rho = \frac{\text{cov}(X_i, X_j)}{\sqrt{\text{var}(X_i)}\sqrt{\text{var}(X_j)}} = \frac{q-p^2}{p-p^2}. \tag{1}$$

Using (1), the joint failure probability of both paths, q can be expressed as,

$$q = p^2 + \rho(p - p^2).$$

The resilience improvement, rI by using both paths compared to a single one can be calculated as,

$$rI = \frac{p-q}{p} = (1-p)(1-\rho), \tag{2}$$

where $q \leq p$ and $0 \leq \rho \leq 1$. From (2), following inferences could be made:

- $p \downarrow \implies rI \uparrow$, which suggests that choosing a lower failure probability (p) path improves the resilience. In various prior research, it has been analytically and experimentally shown that under similar channel conditions, a shorter hop-count path exhibits lower failure probability compared to a longer one [8]–[10]. Therefore, choosing a shorter path compared to a longer one improves resilience.
- $\rho \downarrow \implies rI \uparrow$, which suggests that choosing an uncorrelated alternative path ($\rho \approx 0$) compared to the initial path improves resilience. We term the initial path as the primary path, and all the alternative ones as the backup paths.

We take both the above observations into consideration while designing our multipath scheme. We first choose the shortest path as the primary path, and then incrementally select the backup paths in order of their rI gains when used together with the primary path. An application might utilise all the backup paths that might be available using our approach, or may use only a subset of them. In order to quantify the correlation between the primary path and the backup ones, we utilise the spatial placement diversity among the nodes so that both types of paths do not get affected simultaneously by localised node or link failures which are commonplace in WSN [5], [6]. A detailed description of the measurement of ρ appears in the following section.

On another note, by assuming the path failures to be independent Bernoulli random variables, it can be shown that the resilience parameter, rI increases monotonically with the number of backup paths. Hence, adopting multipath approach to fight against path failure events is also justified. Using the result obtained in Appendix A, we have, $E(\prod_{i=1}^{k} X_i) = p^k$. Plugging the value inside (2),

$$rI = \frac{p - p^k}{p},$$

which increases monotonically with k (i.e., the number of backup paths).

A. Measure of Correlation, ρ

Suppose X_i is the primary path, and X_j be a path considered to be chosen as a backup path. The correlation between X_i and X_j is ρ. Assume the set S_i contains the nodes of the path X_i except the source s and sink t where $|S_i| \geq 0$, and the set S_j contains the nodes of path X_j except source and sink. Now, let $S_i{}'$ comprises of the nodes of S_i where $S_i{}' \subseteq S_i$ that are either inside S_j or neighbours to at least one node of S_j.

If $|S_i| = 0$, $\rho = 0$. Otherwise ρ is defined as,

$$\rho = \frac{|S_i{}'|}{|S_i|}, \quad |S_i| > 0. \tag{3}$$

By choosing such a neighbour-disjoint backup path, we try to spatially separate the backup path from that of primary path with the intention that if the primary path suffers from bad channel quality or localised node failures, it may have little or no effect on the latter.

III. Neighbour Disjoint Multipath (NDM) Scheme

A. Definition

The Neighbour Disjoint Multipath (NDM) constructs a primary path, and a set of alternative or backup paths between a source and the sink. It strives to achieve a set of backup paths that are neighbour-disjoint w.r.t primary path, i.e., they have no node that is inside the primary path or even neighbour to any node of it. The primary path between a source and the sink is generally the shortest path between them [1], [2]. We also retain this concept of primary path in the design of NDM scheme. In exploring the alternative or backup paths, we try to exploit spatial placement diversity among the nodes: i) no node except the source and sink of these paths is part of the primary path, and ii) any node except the source and sink of these paths is preferably not a neighbour to any other nodes of the primary path. Because of the design principles used, these backup paths are expected to be unaffected by localised path failures, i.e., simultaneous destruction of sensors confined to

Algorithm 1 NDM (G, s, t, w, ρ, K)

s = source, t = sink, and K = number of paths computed so far. The *colour* variable associated with each vertex indicates if it is already a part of the previously computed paths (BLACK), inside the queue (GREY) or unexplored (WHITE). Weight w is obtained from topology information where $w(u, v) = 1$ if $(u, v) \in E(G)$ and $w(u, v) = 0$ otherwise. Correlation factor $\rho[v]$ of each node v is defined as, $\rho[v] = 1.0$ if v is neighbour to any node of the primary path except source or sink, and $\rho[v] = 0.0$ otherwise.

```
1: INITIALISE (G, s, t, ρ, K)
2: Q ← {s}
3: colour[s] = GREY
4: while Q ≠ ∅ do
5:    u ← EXTRACT-MIN(Q)
6:    colour[u] ← BLACK
7:    for each vertex v ∈ Adj[u] do
8:       RELAX(u, v, w, ρ)
9:       if colour[v] = WHITE then
10:         Q ← Q ∪ {v}
11:         colour[v] = GREY
12:      end if
13:   end for
14: end while
```

a specific area or correlated bad channel conditions. However, these backup paths can potentially be less desirable in terms of latency or energy-efficiency, e.g., they may be longer than the primary path. They are only meant to be used when the communication via primary path fails. We show that our NDM scheme is more resilient to both isolated and co-located failures compared to the node or edge disjoint approaches.

B. NDM Construction Algorithm

The NDM algorithm assumes global knowledge of the network topology in terms of neighbour information, and works in the following manner:

- First, the primary path which is the shortest path between source and sink is computed.
- Then a set of backup paths that are neighbour-disjoint w.r.t. primary path is constructed incrementally until no other such path exists. The backup paths may consist of two different types of NDM: i) pure and ii) impure. We define a *pure* NDM as the one that has correlation $\rho = 0$ of Eq. (3), i.e., the backup path where there is no node that is inside the primary path or even neighbour to any node of it. An *impure* NDM's $\rho > 0$.
- In the end, we obtain a primary path, and a set of backup paths in descending order of their preferences.

The pseudo-code of the NDM scheme is shown in Algorithm 1. It is similar to the Dijkstra's shortest path algorithm [11] with a modified RELAX procedure that appears in Algorithm 3. In Dijkstra where only the hop-count metric is used to select the routes, here both correlation ($d\rho$) and hop-count (d) metrics are jointly utilised. Based on (3), a node specific correlation factor $\rho(v) \in \{0.0, 1.0\}$ is assigned to each v that quantifies whether

Algorithm 2 INITIALISE (G, s, t, ρ, K)

```
1: for each vertex v ∈ V[G] do
2:    d[v] ← MAX
3:    dρ[v] ← MAX
4:    π[v] ← NIL
5:    colour[v] ← WHITE
6:    if v ∈ any of the K paths then
7:       colour[v] ← BLACK
8:    else
9:       Compute ρ[v] w.r.t. primary path
10:   end if
11: end for
12: d[s] ← 0
13: dρ[s] ← 0.0
14: colour[s] ← colour[t] ← WHITE
```

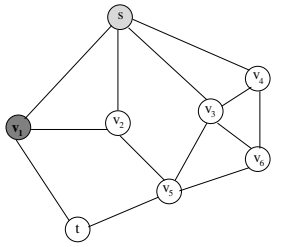
Algorithm 3 RELAX (u, v, w, ρ)

```
1: if dρ[v] > dρ[u] + ρ[v] then
2:    dρ[v] ← dρ[u] + ρ[v]
3:    d[v] ← d[u] + w(u, v)
4:    π[v] ← u
5: else if dρ[v] = dρ[u] + ρ[v] and d[v] > d[u] + w(u, v)
   then
6:    dρ[v] ← dρ[u] + ρ[v]
7:    d[v] ← d[u] + w(u, v)
8:    π[v] ← u
9: end if
```

it is a neighbour to any node of the primary path. $d\rho$ defines the cumulative $\rho(v)$'s from source s upto node v. Priority is first given to disjointedness (i.e., correlation factors) in choosing the nodes along a backup path. In case of equal disjointedness while considering two different nodes, the smaller hop-count route is preferred. This is in view with our analysis done in Section II where uncorrelated shorter paths are shown to provide more resilience against failures. The primary path is computed in the first run of Algorithm 1 when $K = 0$.

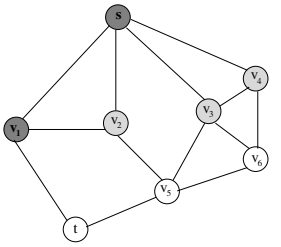
1) Complexity Analysis: The following analysis provides an upper bound on the computational costs for running the complete NDM algorithm. It is similar to the complexity of Dijkstra's shortest path algorithm for a single source-sink pair. The complexity primarily depends on lines 4, 5, 7 and 8 of algorithm 1. If the EXTRACT_MIN procedure (i.e., priority queue) is managed with a binary heap, then the cost of retrieval of a minimum weight vertex (line 5) is $\mathcal{O}(\log_2 V)$. There will be $|V(G)|$ such operations. All the edges $E(G)$ will be traversed in line 7, and for each traversal, the RELAX procedure's operation (implicit in algorithm 3) on the binary heap will cost $\mathcal{O}(\log_2 V)$. Therefore, for a single path calculation between source and sink, the upper bound can be computed as $\mathcal{O}((V + E) \log_2 V)$. If there exists K paths between the source and sink, algorithm 1 will be run for K times. Consequently, the running time is $\mathcal{O}(K(V+E) \log_2 V)$. This running time corresponds to a single node's identification of its primary and backup paths towards the sink using the global network topology information.

2) An Illustrative Example: Consider the network topology of Fig. 1 where the source and sink are denoted by s and



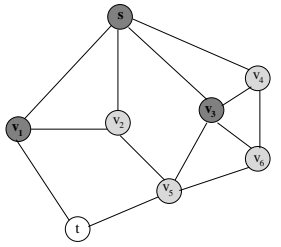
	s	v_1	v_2	v_3	v_4	v_5	v_6	t
d	0		MAX	MAX	MAX	MAX	MAX	MAX
$d\rho$	0.0		MAX	MAX	MAX	MAX	MAX	MAX
π	NIL		NIL	NIL	NIL	**NIL**	NIL	NIL

(a) After initialisation.



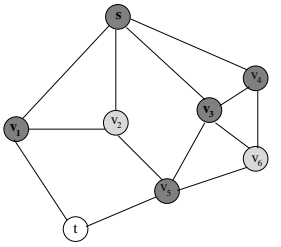
	s	v_1	v_2	v_3	v_4	v_5	v_6	t
d	0		1	1	1	MAX	MAX	MAX
$d\rho$	0.0		1.0	0.0	0.0	MAX	MAX	MAX
π	NIL		s	s	s	**NIL**	NIL	NIL

(b) After iteration 1: s's edges are relaxed.



	s	v_1	v_2	v_3	v_4	v_5	v_6	t
d	0		1	1	1	2	2	MAX
$d\rho$	0.0		1.0	0.0	0.0	0.0	0.0	MAX
π	NIL		s	s	s	v_3	v_3	NIL

(c) After iteration 2: v_3's edges are relaxed.



	s	v_1	v_2	v_3	v_4	v_5	v_6	t
d	0		1	1	1	2	2	MAX
$d\rho$	0.0		1.0	0.0	0.0	0.0	0.0	MAX
π	NIL		s	s	s	v_3	v_3	NIL

(d) After iteration 4: v_5's edges are relaxed.

Fig. 1: An illustrative example showing NDM algorithm's computation steps in order to find a backup path between source (s) and sink (t).

t, respectively. We will explain the computation steps of a backup path using the NDM algorithm. Assume the primary path $< s, v_1, t >$ has already been computed. Fig. 1a depicts the network's state after the initialisation step of algorithm 1. Note that, the dark shaded vertices are the ones that have already been explored while lightly shaded ones correspond to the nodes currently inside the priority queue, Q. The rest are the unexplored ones. Fig. 1b depicts the network's state after the first iteration of *while loop* at line 4 where the edges of the source (s) are traversed (or relaxed). The tables under each network state of the figures list some important metrics, e.g., the hop-count distance (d), correlation factor ($d\rho$), and the predecessor (π) associated with each vertex. During second iteration, the EXTRACT_MIN procedure of algorithm 1 might choose either v_3 or v_4 from Q. However, v_2 would not be chosen because of its high correlation factor ($d\rho = 1.0$). Suppose, v_3 is chosen, and the network's state after the iteration appears in Fig. 1c. During iteration 3 (the state after which is not shown in Fig. 1), vertex v_4 will be chosen. Note that, two other candidates v_5 and v_6 having the same correlation factor as v_4 can not be selected in this step. This is because v_4's hop-count distance metric ($d = 1$) is lower than theirs ($d = 2$). After iteration 3, either v_5 or v_6 could have been chosen. Suppose v_5 is chosen, and Fig. 1d represents the network state after iteration 4. Even if v_6 were chosen in this step, the obtained backup path would have been the same ultimately. In subsequent iterations, vertex v_6, v_2 and t will be chosen respectively that will yield no changes in the network states. The backup path $< s, v_3, v_5, t >$ can be retrieved by traversing the predecessors (π's) of the vertices starting from sink t.

Note that there exists another completely uncorrelated NDM path $< s, v_4, v_6, v_5, t >$. However, our algorithm selected the shorter distance path among the two. In other words, between two NDM paths having similar correlation factors, our algorithm would always choose the shorter distance path. This is in accordance with the findings of Section II. If both the metrics (d and $d\rho$) are the same between two paths, then one is randomly chosen.

IV. Experiments, Results and Discussion

A. Evaluation Criteria

In this section, we first define the two performance metrics that we use to evaluate the multipath algorithms, and briefly discuss the two failure models adopted. We then explain the simulation environment, and the parameters that are varied to assess the multipath schemes' performances.

1) Performance Metrics:

i) Resilience: The resilience of a multipath scheme measures the likelihood that, when the primary path fails, a backup path is available between source and sink. For example, a resilience value of 0.8 indicates that when the primary path between the source and sink fails, a backup path may still be available 80% of the times.

ii) Energy Efficiency: The energy efficiency of a multipath approach gives an indication of how energy efficient it is in terms of quickly disseminating the event information from source to sink. For example, in order to achieve this property, an application may need to periodically probe the backup paths with keep-alive traffic [1], [2]. Alternatively, it may just send multiple copies of the same data by both the primary and backup paths [12]. In either scenario, the energy consumption through the backup paths will be dependent on the number of backup paths, and their path lengths. If L_p and L_i are the lengths of primary and the i^{th} backup path, respectively, then the path length ratio between them, $r_i = \frac{L_i}{L_p}$. Note that, the primary path is generally the shortest path between source and sink. The excess energy consumption through the backup paths compared to the primary path would then be proportional to $E_f = \sum_{i=1}^{m_b} r_i$, where m_b is the mean number of backup paths.

2) Failure Models: We adopt two fundamentally different failure models, namely, the geographically co-located failures and the independent node failures to evaluate our approach's performance across different types of failures. We term the failure models as *localised* and *isolated* failure models, respectively.

i) Localised failures: A localised failure corresponds to the failure of all nodes within a circular region of R_l. It attempts to model the idealised wave propagation of most physical phenomena [7]. Various types of activities such as interference inside a building affecting multiple nodes within an area, or other environmental effects such as rain fades or fire may destruct sensors confined to a specific region. The centre of the localised failure's region R_l is assumed to be uniformly distributed over the sensor field. Furthermore, we assume the number of such failures within a time interval is Poisson

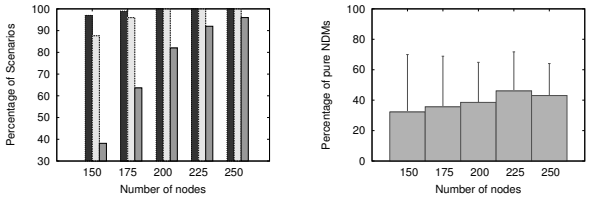
distributed with parameter λ_l.

i) Isolated failures: Isolated failures may correspond to the depleted energy events of sensors, hardware malfunction, or even sensor failures due to localised environmental effects discussed previously but inside a much lower density deployment scenario. In other words, the physical activity of such localised failures would be so small that it may affect only an individual sensor rather than a group of them.

3) Simulation Environment: We choose the object oriented NS-3 platform [13] since one can also easily set up different propagation characteristics even specific for indoor environment using the simulator. We conduct the experiments under two different propagation characteristics – i) unit disk model [14] and ii) hybrid buildings propagation model involving rooms and concrete walls supported by NS-3 [13]. This hybrid model includes Hata model [14], COST231 [14], ITU-R P.1411 (short range communications), ITU-R P.1238 (indoor communications), which are combined in order to be able to evaluate the pathloss under different scenarios. The disk model simulation area is $400m \times 400m$, and each node's transmission radius is fixed at $50m$ whereas the indoor environment's size is $50m \times 50m$. 802.11b standard is used as the MAC protocol, and the optimised link state routing (OLSR) daemon is utilised to retrieve the neighbour information of each node. Afterwards the NDM algorithm is run inside a centralised entry (e.g., the source). The Ford-Fulkerson algorithm [11] is utilised to compute the node-disjoint and edge-disjoint paths. Note that, only the network topology information is required for the path computation of various schemes including NDM. The algorithms' outputs (i.e., computed paths) are not affected by the underlying MAC or network layer protocol used here.

For every experiment, each data point is averaged over 100 independent trials where a different seed is chosen for each run. The source and sink are chosen randomly in each trial that are separated by $6 \sim 7$ hops in all the experiments except Section IV-B4. All other nodes are randomly distributed over the whole area, thereby, forming a different topology for each run. The parameters that we vary to evaluate our NDM multipath scheme with node-disjoint (termed as NODE henceforth) [1], [2], [11], and edge-disjoint (termed as EDGE henceforth) [1], [2], [11] multipath schemes are: i) density of nodes, ii) source-sink separation (in terms of hop distance), iii) the arrival rate, λ_l and the radius, R_l of localised failures, and iv) the number of backup paths, k. Each run lasted long enough to retrieve the neighbour information via OLSR tables.

To compute the resilience metric for localised failures: i) we first pick a non-zero integer l from Poisson distribution with parameter λ_l. ii) We then randomly choose a node on the primary path except source or sink, and select the first failure region's centre randomly that is spread uniformly over the communication radius of the selected node. This ensures the primary path to fail in each run of our simulation. iii) We then randomly place the rest $(l-1)$ failure points, and fail all nodes within radius R_l of each point of the l failure events. We compute the resilience metric for isolated failures as follows: i) for each localised failure scenario (i.e., 100 trials), we run a corresponding isolated failure scene as well where the network topology and the total number of failed nodes are kept the same. ii) We first randomly choose and kill a node on the primary path, and then the rest are chosen randomly over the whole sensor set and killed except source or sink.



(a) Percentage of scenarios where primary (black), at least one backup path (light grey) and at least one pure NDM path (dark grey) exists.

(b) Percentage of pure NDMs w.r.t. total backup paths found.

Fig. 2: Existence of primary, backup and pure NDM paths between source (s) and sink (t) with varying node density.

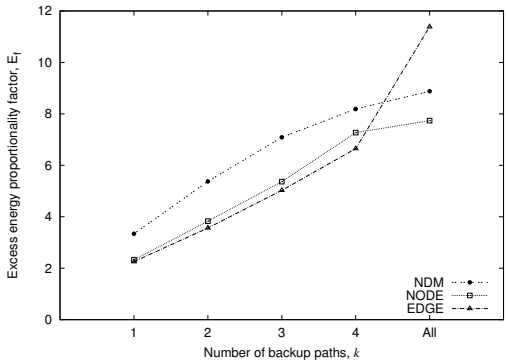
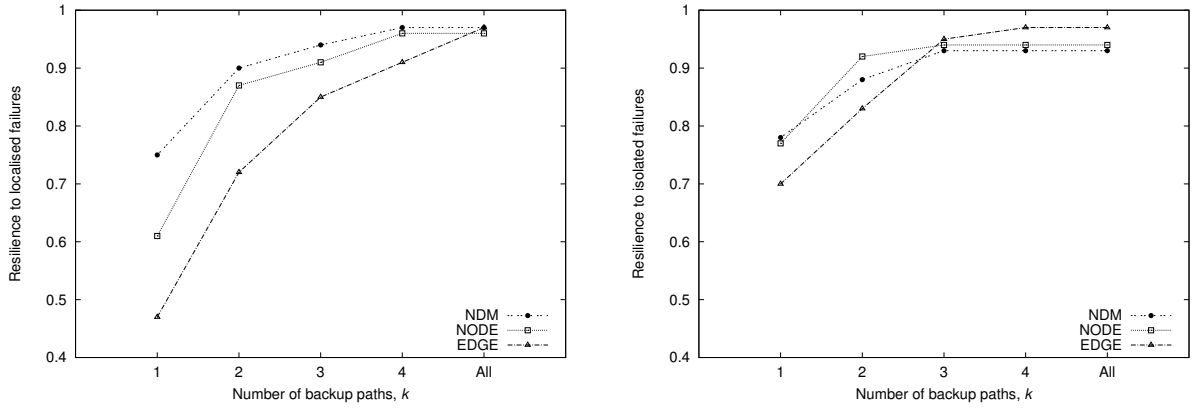


Fig. 3: Excess energy expenditure factor E_f vs. the number of backup paths, k.

B. Simulation Results and Discussions

1) Inspecting NDM's characteristics: We first look at the various characteristics of the NDM constructed paths. We conduct the experiments inside both the disk and indoor propagation simulation environment with varying node densities. Only the disk model's results are shown in Fig. 2. For this experiment, 200 nodes were required to have the primary path, and at least one backup path in all scenarios (see Fig. 2a). This initial experiment also gives us an indication about the deployed number of nodes (e.g., 200 but not 150) in this particular scenario to investigate the NDM's properties effectively. As seen in Fig. 2a, the number of NDM paths increases monotonically with the node densities for a given area. Fig. 2b reveals that a significant portion of the backup paths are pure. A pure NDM is the one where there is no node that is inside the primary path or even neighbour to any node of it except for source and sink. We feel this is an important characteristics of the NDM to possess. The more the pure NDMs among the backup paths, the better its probability to fight against the failure incidents, especially the localised ones.

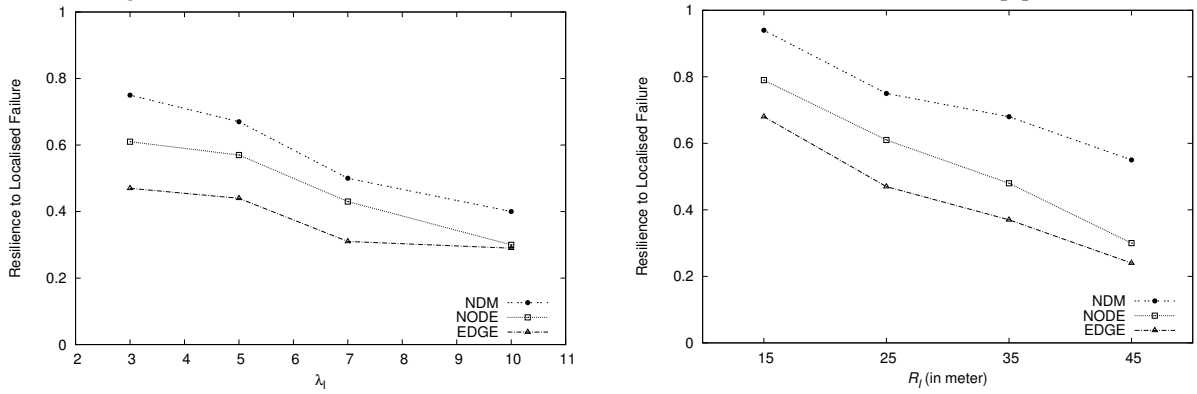
2) Impact of number of backup paths, k: We consider the resilience/energy trade-off with the increment of number of backup paths that might be utilised by an application. Resilience of k-disjoint backup paths measure the likelihood that if a primary path between the source and sink fails, one of the k backup paths is still available. Fig. 4 depicts that the resilience improves with the number of backup paths with its energy expenditure factor E_f (defined in Section IV-A)



(a) Resilience to localised failures (source-sink separation $6 \sim 7$ hops, 200 nodes and $\lambda_l = 3$).

(b) Resilience to isolated failures (source-sink separation $6 \sim 7$ hops and 200 nodes).

Fig. 4: Resilience to localised and isolated failures increases with the number of backup paths, k.



(a) Impact of frequency of localised failures, λ_l ($R_l = 25m$).

(b) Impact of radius of localised failures, R_l ($\lambda_l = 3$).

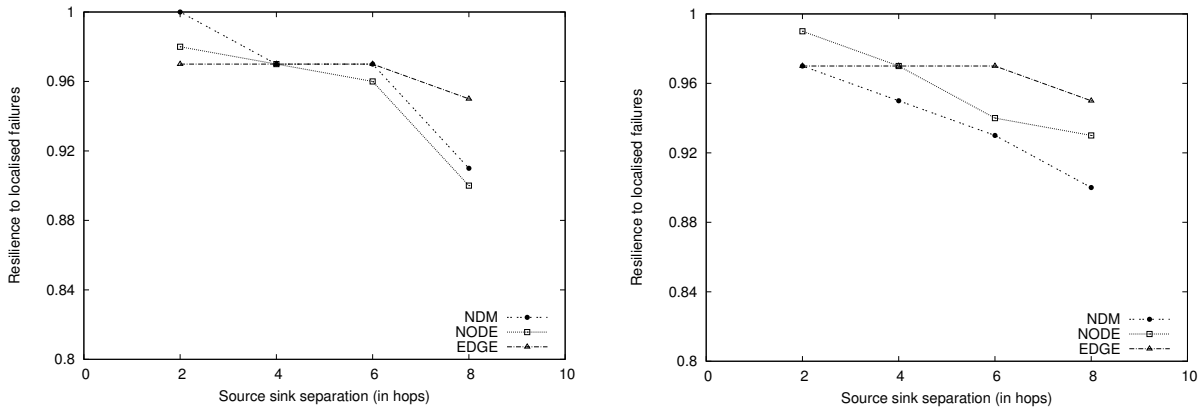
Fig. 5: The impact of λ_l and R_l on resilience to localised failures (200 nodes and source-sink separation $6 \sim 7$ hops).

increasing as well for all the three approaches, namely, NDM, node-disjoint (NODE) and edge-disjoint (EDGE). Our NDM approach is more resilient than NODE or EDGE for localised failures as shown in Fig 4a while EDGE performs slightly better with higher values of k for isolated failures (see Fig. 4b). EDGE is more energy efficient compared to both NDM and NODE for lower values of k as depicted in Fig. 3. However, it is the least energy efficient one when all the available paths are considered as backup paths. This is because EDGE produces a lot more paths than NDM and NODE since it is free from the node disjointedness property which consequently attributes more weight to E_f. For both NODE and EDGE schemes, when choosing a subset of backup paths among all the available ones, the paths are selected in ascending order of their hop distances. NDM is generally less energy efficient than NODE since it tries to select uncorrelated neighbour-disjoint path that might be longer over a shorter node-disjoint one.

Fig 4 shows that for a modest improvement in resilience (15% for localised and 13% for isolated) by choosing two backup paths ($k = 2$) compared to one ($k = 1$), the energy expenditure factor increases by about 61% for NDM (Fig. 3). For NODE and EDGE, the energy expenditure factor increment is by about 64% and 58%, respectively. Thus, one can generally improve the resilience by considering more disjoint paths, however, the gain might come at a higher energy cost.

3) Impact of R_l and λ_l on resilience to localised failures: With increasing frequency of failure, λ_l or larger failure radius, R_l, the resilience is expected to decrease for all approaches which is verified in Fig. 5. Our NDM approach outperforms both NODE and EDGE in all the cases. We have considered only one backup path, i.e., $k = 1$ for this experiment. Similar observations were perceived for other values of k. However, the performance gain of NDM becomes lower compared to NODE and EDGE for increasing k. For fixed λ_l and R_l, this can be observed in Fig. 4a as well.

4) Impact of Density and Source-Sink Separation: We present the results obtained from the indoor propagation simulation environment here. All the available backup paths are considered which gave the lowest performance gain of NDM compared to EDGE and NODE. Considering lower k values, the observed gains were much higher – the results of which have been omitted for brevity. Here, the failure frequency λ_l and radius R_l are set in such a way that at least 15% nodes die in each run. Resilience generally decreases for all the approaches with increasing separation (see Fig. 6). As separation increases, path length increases, so does the number of ways a failure event can affect a path. Similarly, as density increases, the number of backup paths increases



(a) Impact of source-sink separation to localised failures.

(b) Impact of source-sink separation to isolated failures.

Fig. 6: The impact of source sink separation to resilience to localised and isolated failures (200 nodes).

and their path lengths decrease, resulting in fewer ways for severing both primary and all the backup paths simultaneously. Consequently, the resilience increases as seen in Fig. 7. At lower densities (Fig. 7a), NDM's performance is worse than both NODE and EDGE because the number of pure NDMs is much less in lower densities (see Fig. 2).

For all the separation cases, the number of NDM paths is around 67% less than EDGE, and 50% less than NODE. The average path length ratio is 33% and 16% higher for the smallest separation scenario (i.e., 2 hops) and only 0.5% and 1.5% higher for the longest (i.e., 8 hops) compared to EDGE and NODE, respectively. Therefore, NDM can actually be more energy efficient than both EDGE and NODE in a relatively dense network using all the available backup paths. However, when all the backup paths are used, its resilience gain is not that significant compared to EDGE and NODE.

V. Related Work

Various approaches exist in the literature to ensure resilience against node or link failures, e.g., i) the retransmission based strategy where both the sender and receiver might instigate the retransmission, and ii) by introducing redundancy in the form of antenna/node duplication [15], sending same information multiple times [12] or incorporating error correction codes inside the packet, multipath approaches, etc. Multipath routing for fault tolerance and load balancing has been studied both in traditional (ATM [16], OSPF [17], etc.) and ad-hoc networks (DSR [18], TORA [19], etc.). The literature on multipath routing in WSN is also vast, and we do not aim to be comprehensive in our survey. A recent detailed survey on multipath techniques in WSN could be found in [1], [2]. We review the related work here that are deemed to be more closer to our NDM approach, i.e., utilising disjointedness property to explore multiple paths.

A plethora of work on node and edge disjointedness exist in the literature [1], [2] that we do not cover explicitly here. We briefly outline some research that utilise spatial diversity for finding multiple paths. Maximally radio-disjoint multipath routing (MR2) [4] adopts an incremental approach to construct the minimum interfering paths in satisfying an application's bandwidth requirements. [5] proposes a weighted interference multipath metric that takes into account the spatial diversity through introducing the number of neighbours in estimating interferences. Wu and Harms [18] try to select least-correlated paths using the number of link connectivity among the paths.

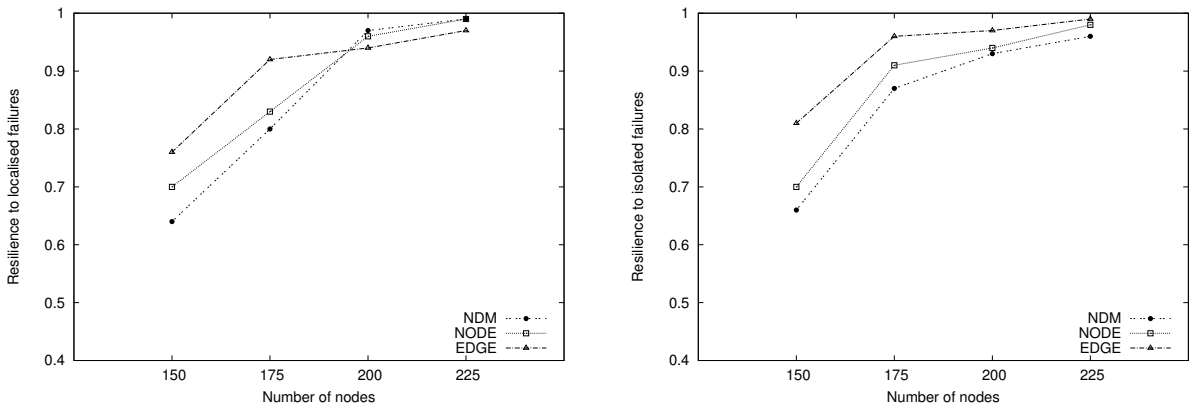
Interference minimised multipath routing (I2MR) tries to construct zone-disjoint paths with the requirement of localisation support inside the sensors [6]. A few others also try to achieve zone-disjointedness using directional antennae [20]. However, all these zone-disjointed schemes require special hardware/service inside the resource constrained sensors.

All these papers try to adopt spatial diversity in order to find multiple paths like us. However, they are generally designed with specific application in mind. They are protocol driven scheme with the goal of achieving a specific application's requirement, e.g., high-speed multimedia streaming, higher throughput, etc. Our work is more fundamental in the sense that could be utilised in a setting just like the basic node or edge disjoint algorithms. Furthermore, we take both the radio disjointedness (i.e., spatial diversity) and hop distance property into account in designing our NDM algorithm.

VI. Conclusion and Future Work

In this paper, we propose a neighbour disjoint multipath (NDM) scheme that utilises spatial diversity and hop distance metrics to increase resilience against node or link failures. In general, NDM performed better than both NODE and EDGE in case of localised failures, and comparatively with NODE in scenarios with higher node densities for isolated failures. However, it tends to be the least energy efficient one since it gives higher priority towards spatially uncorrelated paths compared to the shorter ones. These findings are in accordance with the concept shared by other research that a small number of proper non-interfering paths allows for better performance than a large number of interfering ones both in terms of resilience and energy efficiency [4], [6].

An interesting future work direction would be to design an n-neighbour disjoint algorithm ($n > 1$), i.e., the backup path's nodes would be n radio range away from all nodes of the primary path, and assess its viability across different network topology. Furthermore, the correlation factor, ρ of Eq. (3) could be defined incrementally as a measure of disjointedness w.r.t. primary and the backup paths computed so far.



(a) Impact of density to localised failures.

(b) Impact of density to isolated failures.

Fig. 7: The impact of density to resilience to localised and isolated failures (source-sink separation $6 \sim 7$ hops).

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APPENDIX A
THE PRODUCT OF k INDEPENDENT BERNOULLI RANDOM VARIABLES IS BERNOULLI.

Suppose $X_1, X_2, \ldots, X_k$ are mutually independent Bernoulli random variables with parameters $p_1, p_2, \ldots, p_k$, respectively. We have to prove that $\prod_{i=1}^{k} X_i$ is Bernoulli.

Proof: Basis: Consider $k = 2$, and $Y = X_1 X_2$. The probability mass function of the product of two independent Bernoulli random variables Y is, $f_Y(y) = 1 - p_1 p_2$ if $y \equiv 0$, and $f_Y(y) = p_1 p_2$ if $y \equiv 1$, which can be rewritten as,

$$f_Y(y) = (p_1 p_2)^y (1 - p_1 p_2)^{1-y} \quad y = 0, 1. \tag{4}$$

(4) is the probability mass function of a Bernoulli random variable with parameter $p_1 p_2$.

Hypothesis: $\prod_{i=1}^{k} X_i$ is Bernoulli.

Induction: We have to prove that $\prod_{i=1}^{k+1} X_i$ or $\prod_{i=1}^{k} X_i \times X_{k+1}$ is Bernoulli. $\prod_{i=1}^{k} X_i$ is Bernoulli (Hypothesis step) and X_{k+1} is also Bernoulli. Their product is also Bernoulli (Basis step). Therefore, $\prod_{i=1}^{k+1} X_i$ is Bernoulli. ■

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