Network Restoration in Wireless Sensor Networks for Next-Generation Applications

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***Abstract*—This paper investigates highly efficient network restoration models for wireless sensor networks (WSNs) to be deployed for next-generation (xG) applications. The developed network restoration models are designed with two main goals in mind. The first goal is to optimise network resource utilisation, the second is to protect the network against failures. In realising the goal of optimising resource usage, a peculiar feature of WSNs is exploited, namely, their ability to remain in active service even when one or more of their active elements (sensor nodes and/or connecting links) fail. To achieve the second goal of network protection, we leverage the advantage of p-cycle-based restoration solutions - the fact that they can provide ring-like recovery speeds with mesh-like capacity efficiencies - in developing optimal p-cycle restoration models that provide sufficient protection for the network against both link and node failures. In the restoration models developed, we employ a selection process that jointly considers the shortest lengths, best topologies and capacity requirements of the available p-cycles in achieving new capacity-optimal p-cycle-based restoration solutions for the network. Comparative results obtained show that our developed selection-based capacity-efficient p-cycle restoration solutions for WSNs outperform other similar approaches for both network realisation and protection, making them particularly ideal for xG applications.**

***Index Terms*—Network failures, network restoration, next-generation communication, p-cycles, wireless sensor networks**

I. Introduction

THE wireless sensor network (WSN) is a well-established and frequently researched wireless communications paradigm. To date, WSNs have been one of the most successfully deployed and significantly effective wireless communications concepts. As a basic description of WSNs, sensing devices (or sensors) are attached to objects and deployed within a geographical area to sense certain localised conditions and to send in timely reports. In the distributed topologies of WSNs, reports of sensed local conditions are sent from sensor to sensor(s) in the network, while in the centralised topologies, reports are sent from each sensor to a centrally located controlling unit. In both cases, the reports are used to make important network decisions, which can help the network in taking swift action(s) for the overall operation and sustenance of the communication system for which the WSNs have been deployed [1], [2]. Although WSNs are no longer a new technology, their relevance continues to grow exponentially with the advent of new and/or improved technologies that require sensing, observation and feedback in carrying out their operations. In today's field of wireless communications, WSNs have become one of the most important technologies in driving next-generation (xG) wireless communications possibilities.

In recent times, there has been significant progress in the development of new and modern WSNs prototypes. However, there are still limitations of size, quality, durability, etc. of the sensor nodes (SNs) being developed and deployed for WSNs. Most SNs are still battery-powered, hence they have a limited lifetime. Again, probably because of their size, the processing capacities and memory spaces of most SNs are still very low, limiting their resource capability. These and other limitations of SNs and WSNs mean that failures in the deployment and applications of WSNs are still a possibility. Failures can affect the performance and reliability of WSNs negatively if they are not properly managed [3]. The effects of failures in WSNs applications are exacerbated for xG technologies where the desired level of latency, throughput, reliability etc. are highly critical. For instance, failure of SNs in WSNs can result in the loss of the network's shortest path for transmission. This can elongate the transmission's path, which could then result in an increase in the transmission delay or in the overall energy consumption of the network [4]. Hence, if not adequately addressed, failures can have catastrophic effects on WSNs, especially when such WSNs are to be employed or deployed for xG applications.

To address the potential damage of network failures in WSNs employed for xG applications, developing network restoration models that provide adequate backup and/or recovery for such networks in the event of a failure is imperative [5]. A good network restoration model, when incorporated into the WSNs designed for xG applications, can help in ensuring that communication is not severely disrupted as a result of the occurrence of a failure, because alternative transmission routes are almost instantaneously provided to continue network operation while the failed elements are being repaired or replaced [6], [7]. Usually, the alternative routes are either quickly computed at the point of failure (reactive restoration) or they could have been pre-planned in the network design (proactive restoration) [8]. The important point is that the network restoration designs to be employed must be such that they are both time and resource efficient, and that they are capable of actively providing the needed backup for the

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network [9].

In this paper, we address the problem of network failures in WSNs for xG applications by developing appropriate and highly efficient network restoration solutions against both link and node failures. The network restoration models investigated leveraged an important advantage that WSNs have over most other types of wireless communication, namely, their ability to remain fully active even when one or more of their network elements fail at any given time. Exploiting this possibility, the WSNs are designed to keep some of their SNs inactive methodically for some intermediate periods of time. This makes it possible for the overall network resource usage to be fully optimised, while at the same time providing sufficient protection and/or recovery for the network when failures occur. Results are obtained to show improvement in the performance of the WSNs for xG applications when appropriate network restoration strategies are inculcated. The improvements achieved are very significant in helping xG networks achieve their much-acclaimed promises of providing reliable, secure and timeous autonomous wireless communication services in the near future. The contributions of the paper are summarised as:

- developing an appropriate WSNs model that is designed particularly for xG applications. The model considers and incorporates the peculiar properties of xG communication technologies in its WSNs design;
- investigating a capacity-efficient network restoration model that addresses link failures in the WSNs model designed for xG applications. The restoration model achieves optimal capacity efficiency by selecting only the best protection paths among all the possible and/or available paths for each link in the network;
- developing and analysing a new, capacity-efficient network restoration model that addresses node failures in the WSNs model designed for xG applications. The new restoration model jointly combines the ideas of shortest path lengths, the best topologies and the most capacity-efficient designs in selecting the best protection paths for the network.

The remainder of this paper is organised as follows: Section 2 provides a review of relevant literature on failures and network restoration in WSNs for xG applications, Section 3 presents the basic ideas in our network restoration models for WSNs xG applications, Section 4 provides the analysis of the developed network restoration models, Section 5 discusses the results obtained and Section 6 gives the concluding remarks.

II. Review of Related Literature

In this section, we explore the important aspect of network failures and the restoration/protection of networks against failures in wireless communications. Particularly, we examine current/ongoing efforts that are being developed in the research space to ensure that communication networks are protected against failures through current network restoration ideas and solutions.

A communication failure can be defined as a forced, temporary modification of a network, typically as a result of a disruption to actual design of flow or traffic, which usually results in a decrease in the capacity of affected links and/or nodes in the network, sometimes decreasing their capacity completely to zero [10]. Failures can generally be classified into two types - link failures and node failures. In wireless communication, a link failure is deemed to have occurred when the connection between two nodes in the network (or a node and the central control unit for the network) fails [11]. Solving a link failure problem is usually achieved by redirecting and/or redistributing the traffic of the failed link to some neighbouring functional links that have sufficient capacity to carry the additional traffic from the failed link. On the other hand, a node failure is said to have occurred when one or more nodes (switches, routers, control hub, etc.) fail [12].

As a general observation, there seem to have been a lot more work on protection and/or restoration of communication networks from link failures than from node failures. This may be due to a number of reasons. One such reason is the understanding that solving node failure problems is much more demanding and usually requires more resources than solving link failure problems. Another possible reason is the preconception that since link failures occur more frequently, they are of more importance than node failures. However, in modern wireless communication designs (such as new-generation WSNs), node failures may occur equally frequently as link failures. Node failures are therefore of equal significance, if not even more, than link failures. Besides, newly-evolving xG applications of wireless communication simultaneously combines the use of various technologies such as the internet-of-things (IoT), fifth-generation, cloud computing and heterogeneous networks technologies. A very good example of the application of such combined technologies is vehicle-to-vehicle communication. In such xG applications, the requirements of very high accuracy, low latency and undisrupted service provisioning demand that the occurrence of any and all types of failures (link or node) is equally undesirable and must be kept at the barest minimum, if not completely eliminated. Furthermore, these xG demands require that all failures (whether link or node) must be quick to detect, while complete network restoration must be achievable in very short time frames if/when such failures occur. In the remaining part of this section, we review recent works on failure detection and possible network restoration solutions, particularly the ones that have some relevance to our discourse on WSNs for xG communications.

In both [13] and [14], the authors established that node failures in WSNs can result in multiple nodes being disconnected from the network and can potentially cause the network to separate into segments. The authors promulgated that to avoid such problem, faulty SNs must be detected quickly during normal operations of WSNs so as to ensure the preservation of the network's quality of service, and to avoid further degradation in network operations. The authors in [13] presented two low-cost fault detection approaches, which they claimed can work independently without creating any hindrance to actual data packet routing in the WSNs operations. The main idea in the algorithms developed was to use an agent to carry out the detection. The agent created a query path that led to dead or faulty nodes, while also providing feedback on the status of each node. The feedback received from the nodes revealed their health status, and further decisions could then be made by the network based on the reported health status received via the query path. The authors in [14] developed a bi-connected inter-partition topology which minimised the maximum path length between pairs of partitions, and then deployed the least count of relay nodes in achieving full recovery of the network.

A failure detection model for identifying permanent and intermittent faults in WSNs was developed in [15]. In the model, a node was declared faulty if it did not broadcast its own sensed reading so that other neighbouring nodes could receive it within a given time. Furthermore, a node was still to be declared faulty even though it broadcast its readings if such readings were deemed to be incorrect. This was achieved by comparing each node's readings with those from a set of other neighbouring nodes. The authors used multi-objective particle swarm optimisation to simultaneously minimise detection latency and energy overhead, while a fuzzy-based mechanism was also used to determine the best compromised solution on the optimal Pareto front. The authors claimed that their model achieved failure detection with high accuracy within a short time with as few message exchanges as possible and a minimal energy overhead. Particle swarm optimisation based on random weight was also employed in [16] to address the performance degradation problem caused by node failures in photovoltaic monitoring network.

Authors in [17] proposed an energy-efficient failure recovery scheme for WSNs. The model used a coverage preserving failure recovery mechanism to achieve energy-efficient network restoration when a failure occurred. The authors argued that the proposed scheme was able to diagnose failures with a very low false alarm rate and was able to recover failures by maintaining coverage above a given acceptable threshold value. Similarly, the authors in [3] developed a failure recovery model for WSNs based on grade diffusion. The model used the saved shortest path approach to determine the best recovery path with minimal energy consumption for WSNs. The grade diffusion method kept the sensors working for the longest period possible, thus increasing the lifetime of the network. The authors argued that the grade diffusion, enhanced by the shortest path approach, which used routing tables with saved shortest paths, was able to identify faulty nodes quickly and to recover the network in good time. Genetic algorithm was employed by the authors in [18] for achieving effective network restoration against failures.

In [19], the authors proposed a recovery method to deal with the failure of an articulation node (a node whose failure can lead to the network being broken into different segments, isolated from one another) in a multi-channel WSNs scenario. The problem was formulated as a multi-objective optimisation problem. In the centralised solution approach developed, the sink carried out the entire recovery procedure from failure detection to the reallocation of channels after the connectivity had been restored. The recovery solution developed used graph theory heuristics, such as graph colouring and Steiner points, to rearrange the nodes around the failed node, recover the network from network partitioning and to restore network

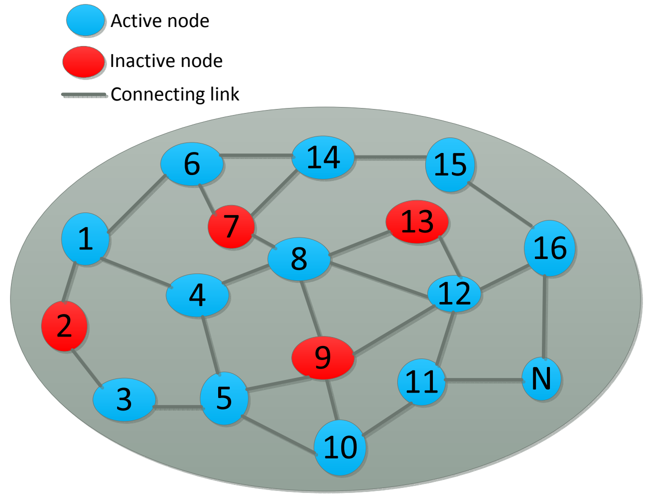

Fig. 1. A simple network model of WSNs adaptable for xG applications such as the IoT. The model is distributed and designed to conserve resources by keeping some selected nodes inactive over certain time periods.

connectivity. In [20], the articulate nodes were referred to as actors. A proactive-reactive hybrid restoration model was proposed to protect such nodes. A backup node was pre-assigned to each actor among its one-hop neighbours. If the actor failed, the backup node, in a reactive manner, moved quickly to the best position to restore the connectivity of the failed node's neighbours, which triggered a local recovery process at the backup node. The process was repeated until network connectivity was restored.

In the failure detection and/or network restoration solution models for WSNs developed in the works reviewed above, we note that the peculiarities of xG communications were not adequately considered were consequently not sufficiently designed for xG applications. Furthermore, the restoration strategies developed and/or employed in these works may not be able to provide sufficient protection and/or backup for the high-demand, low-latency expectations of xG networks. To bridge this research gap, therefore, in this paper, we develop network restoration models for WSNs that are designed particularly for xG applications. The models leveraged the peculiarities of WSNs and the understanding of the demands and expectations of xG networks in designing network restoration strategies that optimise resource usage and provide adequate protection for the network, thus helping to achieve the expectations and promises xG communications.

III. Network Model

The developed network model shown in Fig. 1 is a general WSN model that is adaptable to, and applicable to, most xG communication networks such as the IoT, advanced WSNs, cognitive radio networks and so on. In this paper, to make the model practical, the WSNs model is particularly adapted for the IoT application. However, the model can be adapted for other xG networks as well. In the IoT network set-up, the SNs represent the objects in the network. This is a realistic consideration, since each object employs one or more sensors in communicating with other neighbouring objects. Each SN can transmit over multiple channels within a sufficiently large communication area. The communication model assumed for the IoT network is the device-to-device communication model. With this communication model, two or more devices can directly connect and communicate with one another without the need of an intermediary. The IP-based protocols are used to establish connection among devices and to minimise messaging cost for the IoT application. In IoT networks, as in most other xG technologies, traffic loads are heterogeneous and wireless link conditions can fluctuate. Therefore, in the xG model developed and studied, autonomous network services provided by the network are achieved by transmitting data via the SNs in a distributed manner. The distributed network topology is adopted for most xG networks, particularly for IoT applications, because of its advantages over centralised network topology. The advantages of distributed topology over centralised topology are threefold: cost-effectiveness, the possibility of keeping multiple components for each function in order to achieve quick recovery from failures and finally, the possibility of sharing the entire workload over multiple components, thereby improving the scalability of the network [21]. These advantages make a distributed network the better topology for most xG applications, particularly IoT networking.

The two main design goals for the WSNs for xG applications investigated in this paper are optimising overall network resource usage and providing sufficient restoration and/or recovery for the network in the event of failure of one or more SNs or their connecting links. Next, we present the description of how the network is designed in order to achieve these two goals.

A. *Resource Optimisation Design*

To achieve the goal of resource optimisation, we devise a network strategy that is most effective in conserving network resource usage for the WSNs designed for xG applications. The strategy is that, at every given time in the overall network lifetime, only an appropriate number of SNs that are required for data transmission and network restoration are engaged and/or activated. This implies that only the SNs that are needed for both data transmission and network recovery/backup are set in an active state, while the other SNs that are not used for either data transmission or backup remain inactive during that period, thus conserving their limited resources. Then, at other times, some or all of the formerly inactive SNs become active for transmission and backup, allowing the initially active SNs to go into the inactive state to conserve their own resources as well. The network is then designed in such a way that the 'active' and 'inactive' timing for different SNs are flexible and can overlap. Hence, if/when the need arises (for instance, in cases of emergency or unexpected high/low traffic demand), the SNs are swiftly informed to change their status from either active to inactive or vice versa. The implication of this is that, through proper design of the network, each SN can help the network achieve constant, continuous data transmission, as well as protecting the network against failure, while optimising its resource usage.

Two critical conditions are necessary for these WSNs resource optimisation design strategy to work efficiently for xG communication, such as the IoT. The first condition is the right decision on the selection of the active SNs necessary for data transfer and network protection at any given time. The other condition is the proper decision on the time appropriation within each time frame for which selected SNs are to remain active before going into the inactive state (conversely, this also defines the time appropriation for which the inactive SNs would remain in their inactive state within the time frame). The optimal decisions on the above-mentioned conditions can be investigated by the use of network scheduling or queueing theory. The solutions must take several factors of the network into consideration, such as the network demand, network policy, etc. With this arrangement, the first goal (that is, optimising resource usage in the WSNs for xG communication) is successfully achieved. Further discussions on the use of scheduling or queueing theory in achieving this goal are not conducted in this paper. Rather, more work is dedicated to achieving the second goal of providing network restoration solutions for the developed WSNs to be employed for xG communication.

B. *Network Restoration Design*

Once the goal of optimising network resource usage has been achieved, the other goal of providing adequate restoration for the network to mitigate the effects of either link or node failures has to be realised as well. To accomplish this second goal, appropriate network restoration models have to be investigated and incorporated in the network design. In the remaining parts of this section, we investigate an appropriate network restoration solution that can achieve optimal capacity efficiencies in the WSNs employed for xG applications.

1) p-Cycle-based Restoration: The network restoration strategy being deployed to achieve optimal network restoration for the WSNs designed for xG communications is the preplanned or pre-configured cycle (referred to as the p-cycle) restoration strategy. The p-cycle-based restoration strategy is a well-developed restoration strategy for providing protection against network failures. A p-cycle is defined as a preconfigured cycle formed out of the spare capacities of links in a network. Notably, there is already a sizeable amount of literature that has discussed and employed p-cycles as the method for achieving network protection and/or restoration, especially for transport networks.

2) Approaches and Advantages of p-Cycle-based Restoration: The decision to employ p-cycle protection as the preferred network restoration strategy for the WSNs designed for xG applications is based on its advantages over most other network restoration strategies that have been developed and/or are currently employed to recover and protect networks against failures. The authors in [22] have already documented a detailed review of the characteristics, approaches and potential benefits of p-cycles over most other types of protection mechanisms for communication networks. In summary, the p-cycle design methods or approaches can be centralised or distributed, while p-cycles can be used to protect nodes, paths and segments of a network. More so, the major benefit of p-cycle restoration over other types of restoration schemes is the fact that p-cycles make it possible to achieve recovery from failures at speeds that are comparable to ring-based protection, while ensuring that the capacity efficiencies are as good as in mesh-based protection [22], [23]. Arguably, this makes p-cycles the ideal restoration mechanism for xG networks.

In their designs, p-cycle-based restorations are able to achieve near-perfect network protection by pre-connecting the spare capacities of the network to form a ring-like structure. As a result, in the event of a failure, only two switching actions (as in rings) at the end nodes of the failed link are needed to switch the traffic to the restoration route provided by the p-cycles [22]. Another important advantage of p-cycles that makes them particularly ideal for protecting WSNs designed for xG applications is that, in the network they protect, p-cycles have the capacity not only to protect spanning (or on-cycle) links, but also their straddling links. The final benefit of p-cycles is that since they are constructed on virtual and not real paths, they do not consume any capacity during normal operation of the network they are protecting. It is only when the p-cycles are actively employed in protection and restoration of the network that they use up any capacity at all.

3) Added Benefits of the Proposed p-Cycle Approach: As promising and beneficial as p-cycle-based restoration solutions are, there are some challenges that have to be overcome if they are to be the ideal restoration strategy in the WSNs designed for xG applications. Two main challenges of p-cycles that are most critical when considering them for providing restoration in the WSNs designed for xG applications have been identified: firstly, the observable fact that p-cycles tend to provide restoration routes with many hops, which may then result in less-than-optimal backup paths for the network, and secondly, the fact that p-cycles are mostly designed to provide protection against link failures only, whereas both link and node failures are of great relevance in WSNs. These two concerns must be properly addressed in the p-cycle design for restoring WSNs being employed for xG communication. Addressing the two problems will provide capacity-efficient, optimal p-cycle-based protection against link and node failures in the WSNs designed for xG applications. In the next section, we develop and analyse solution approaches for addressing these two concerns and discuss them in greater detail.

In concluding this section, it is important to note that in our design of p-cycle-based network restoration solutions for the WSNs employed for xG applications, we have assumed that the WSNs being considered are planar networks or that, at the least, they can be easily converted to planar networks. This is important, because it is only in planar networks that all possible candidate p-cycles can be obtained, and from which the 'best' ones can be selected. Well-established methods are already developed in the literature for obtaining the set of all possible p-cycles available in planar networks. Therefore, by simply employing one of those established methods, all possible p-cycles for the WSNs being considered can be determined.

IV. Network Analysis

In the developed WSNs designed for xG applications, we represent the set of available nodes (that is, all the SNs) in the network by N and represent the set of connecting links by L. Simply, the link ij connects the two SNs i and j. The working capacity on link ij is represented as w_{ij}, its spare capacity is represented as s_{ij} and its total capacity is represented as t_{ij}, $(\forall ij \in L)$. It is assumed that within each short time frame, the network conditions are stationary, therefore, the capacities for each time frame and total traffic do not change with time. The network contains a set of source nodes N_s and destination nodes N_d $(N_s, N_d \in N)$, which make up the end-nodes. Let r_{sd} be the traffic demand from the node $s \in N_s$ to node $d \in N_d$. The paths that are originally assigned to transmit traffic from s to d are referred to as the working paths (WPs). The paths that are assigned to protect or restore traffic from s to d in case of a failure along its WPs are referred to as the restoration paths (RPs) for the network. The total traffic flow on any link ij is the sum of all the traffic flows between the source and destination nodes that passes through that link and is represented by f_{ij} $(f_{ij} \leq t_{ij})$. In the subsequent subsections, we present and analyse the techniques for achieving optimal protection (restoration) for the network against both link and node failures using the p-cycle-based restoration strategy.

A. Link Failure Restoration in the WSNs designed for xG Applications

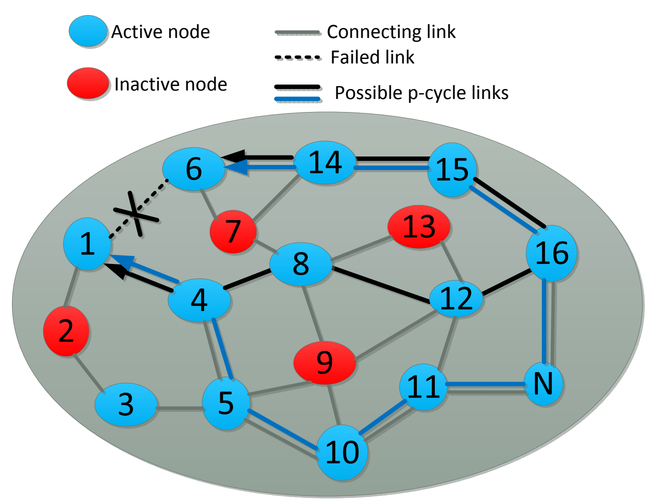

Fig. 2. P-cycle employed for link failure restoration in WSNs designed for xG applications.

Fig. 2. is an example of a p-cycle employed to protect a network from link failure. The goal is to investigate a p-cycle-based restoration that overcomes the multi-hop challenge, thereby providing optimal restoration for the network against link failures. To achieve this goal, we explore the concept of selecting the ideal candidate p-cycles from all the available p-cycles for the network. The selected p-cycles are such that they achieve complete network restoration at optimal cost in

the WSNs designed for xG communications. This concept of selecting some candidate p-cycles from among all available p-cycles for network restoration evolves from a previous work of one of the authors of this paper [24]. The main ideas in this concept are presented as follows:
The optimal set of p-cycles to be selected are the p-cycles that minimise the costs associated with selecting them. This is subject to the constraint that the traffic flow that can be restored over a given link cannot be greater than the maximum available spare capacity on that link.

Let:

P	be the set of all possible p-cycles from which the RPs can be selected; $P(ij)$ is the set of distinct cycles selected for restoring link ij.
c_p	be the cost associated with selecting p-cycle p; c_{ij} be the cost of selecting link ij.
$s_{ij,p}$	be the maximum available spare capacity for traffic flow f_{ij} on the p-cycle p for link ij.
$X_p \in \{0,1\}$	be the parameter that encodes which p-cycle is selected. $X_p = 1$ if p-cycle p is selected and $X_p = 0$ otherwise.

In selecting the optimal subset of p-cycles to be used as RPs for the network, appropriate costs are assigned to each p-cycle in consideration of possible selection. The total cost of using a p-cycle is determined by evaluating the cost on each link that makes up that ring. The goal is then to select the subset of the p-cycles that minimise the total cost of restoring the network, while also guaranteeing that every link can be restored once a failure occurs. The optimisation problem is given as:

$$\min_{X_p} \sum_{\forall p \in P} c_p . X_p, \tag{1}$$

subject to

$$f_{ij} \leq \sum_{\forall p \in P(ij)} s_{ij,p} . X_p \quad \forall ij \in L, \tag{2}$$

$$X_p \in \{0,1\} \quad \forall p \in P. \tag{3}$$

In the developed optimisation problem above, the RPs to be employed must be such that traffic being restored does not interfere with the original traffic in the links that are selected to form the p-cycles for restoration or backup. We explain how this is achieved. The total amount of traffic that can be restored by a selected p-cycle p without interference is determined by the link with the minimum unused capacity on each RP. In p-cycles, each spanning (on-cycle) link ij has only one RP, that is, there is only one route for restoring the node pair i and j when the link ij fails. However, the straddling links usually have two distinct routes. Hence, if ν represents the possible level of diverse routes for p-cycle p, $\nu = 1$ for spanning links and $\nu = 2$ for straddling links. For each diverse route ν, the amount of flow that can be restored with p-cycle p on link ij, represented as $\alpha^p_\nu(ij)$, is obtained as [24];

$$\alpha^p_\nu(ij) = \min\{t_{gh} - f_{gh} + f_{gh,ij}\} \ \forall gh \in \epsilon^p_\nu(ij), \tag{4}$$

where $\epsilon^p_\nu(ij)$ are all the links along path ν, excluding ij ($\epsilon^p(ij) = \epsilon^p_1(ij) \cup \epsilon^p_2(ij)$).

When link ij fails, the total amount of traffic that can be restored through p-cycle p without interference $\alpha_{ij,p}$ for spanning link ij is simply;

$$\alpha_{ij,p} = \alpha^p_1(ij) \tag{5}$$

while for straddling link ij, the total amount of traffic that can be restored is;

$$\alpha_{ij,p} = \alpha^p_1(ij) + \alpha^p_2(ij). \tag{6}$$

Hence, when link ij fails, the maximum available spare capacity for restoration of all the traffic on the failed link ij without interference by all the p-cycles selected for the RPs is given as;

$$\alpha_{ij} = \sum_{\forall p \in P(ij)} \alpha_{ij,p}. \tag{7}$$

B. Node Failure Restoration in the WSNs designed for xG Applications

In WSN technology, node failures may occur as frequently (and probably even more frequently) as link failures. In a practical sense, a node failure can be seen as the simultaneous failure of all the links connected to that failed node. Therefore, to provide sufficient 'recovery' for a failed node, all traffic that should have been routed through the failed node from all the links connected to it must be instantaneously rerouted. This makes the task of addressing node failures somewhat more complicated and/or demanding than that of addressing link failures. We note here that in reality, the actual recovery of failed nodes is technically impossible, except for instance in the type of WSNs application where the network is designed in such a way that some SNs are deliberately temporarily made inactive for some time periods and can therefore be put back to active service at other time periods, or if the failure is due to battery depletion. If the failure is due to low battery, the SNs may be recharged. However, some data transmission may occur between the period of battery depletion and its recharge, while the failure may also be due to other causes apart from battery depletion as well, hence, the need for network restoration. It must be said that the task of developing appropriate p-cycle-based solutions that can achieve optimally efficient network restoration against node failures in WSNs for xG applications is quite a demanding task.

In this paper, we employ the concept of node-encircling p-cycles (NEPCs) in achieving network restoration and protecting the network against node failures in the WSNs designed for xG applications. The original idea on NEPCs was proposed in [25]. Fig. 3. is an example of NEPC. The NEPC restoration is considered ideal for xG networks because it is well equipped to provide restoration for IP-based networks, the likely protocol for most xG networks such as the IoT. The underlining condition for any NEPC to be able to restore a failed node sufficiently is simply that the NEPC must traverse all adjacent (one-hop) neighbour nodes of the failed node that it is meant to restore, but not the failed node itself. The NEPC restoration also have the advantage that, if two or more nodes fail simultaneously, the selected NEPCs can protect the network against such multiple node failure, as long as there

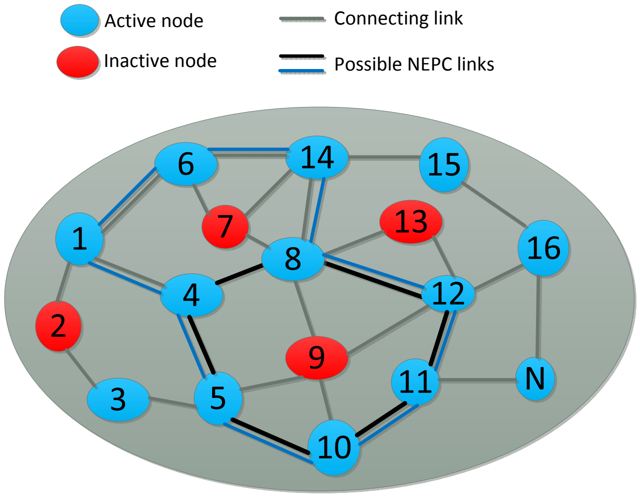

Fig. 3. Node-encircling p-cycle employed for node failure restoration in WSNs designed for xG applications.

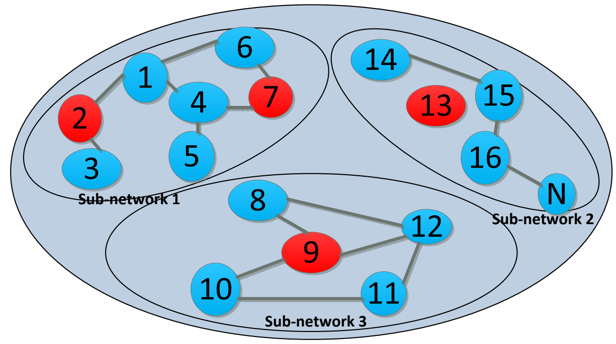

Fig. 4. Graphical depiction of a network divided into sub-networks.

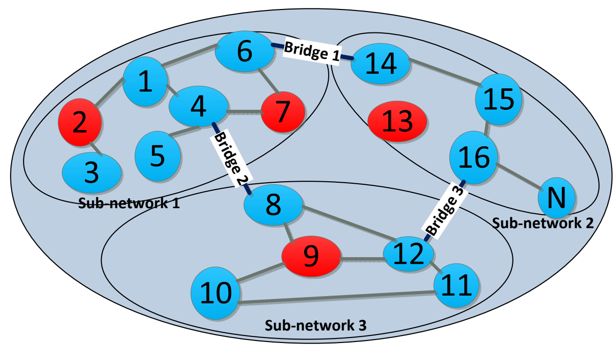

Fig. 5. Graphical depiction of the interlink of sub-networks through bridge nodes.

is sufficient capacity to carry out the restoration. The NEPC solutions developed and employed in this paper are designed to be capacity-efficient, making them ideal for addressing multiple node failures in xG networks.

In our developed network, the failed or inactive nodes are first identified or detected before the restoration can be achieved. The assumption is that these inactive nodes are easily identifiable in the network. Indeed, there are already a number of works that have investigated methods for detecting failed or inactive nodes in WSNs. As an example, the authors in [13] investigated a technique for identifying inactive (or failed) nodes by sending regular queries to all nodes in the network. The responses (or lack thereof) by the nodes were then used to detect the health status of the nodes. In [15], the periodic signals transmitted by each SN were used directly for detecting failed nodes in good time (better latency) and with less energy overhead. The recent work of [26] employed a technique whereby each SN broadcasts an alert message whenever it becomes energy deficient. Its neighbouring nodes having sufficient energy can temporarily make up for the energy deficiency of the SN by increasing their transmission range. We assume that the most efficient methods for detecting the inactive or failed nodes in the network are already incorporated in the network design (the failure detection technique in [15] is employed in this work) and therefore keep focus on the restoration strategies being investigated.

1) Base Heuristic for Network Restoration using NEPC: First, we present a base heuristic that generates NEPCs capable of achieving network restoration against node failures in the WSNs designed for xG applications. The heuristic is developed to generate one protecting NEPC for each SN in the network. The base heuristic concept was originally proposed in [25]. The main idea in the heuristic is to split the network into subregions within which simple cycles are possible, after which a final, possibly non-simple cycle that has the desired p-cycle properties is formed by merging the simple cycles together. In the heuristic, the important condition for any NEPC restoration must be obeyed, which is that the p-cycle must cover all the nodes that are one-hop adjacent to the node being restored, while not touching on the failed node itself.

To help understand the base NEPC heuristic, the following concepts are defined (pictorial depictions of the concepts are presented in Fig. 4. and Fig. 5.):

Sub-network: A sub-network is a separately identifiable part of a larger network that can effectively represent the entire network even though it contains a lower number of network elements. Fig. 4. is a pictorial description of a network from which a number of sub-networks are derived.

Subgraph: A subgraph is a graph whose links and nodes are derived from (that is, are a subsets of) a main graph or network. Fig. 4. can be used to describe the concept of subgraphs. If it is possible to have subgraphs 1 and 2 such that all their nodes and links are members of sub-network 1, then, subgraphs 1 and 2 are subsets of sub-network 1.

Bridges: A bridge is the only link that connects two distinct parts (e.g., subgraphs or sub-networks) of a network. If this link fails, the different parts of the network will not have any possible connection between them. Thus, a bridge node is that node that directly connects (through a bridge) other nodes that would otherwise have been disconnected from the network. In Fig. 5. for example, the link $(6, 14)$ is a bridge because it is the only connection between sub-networks 1 and 2. If this

TABLE I
BASE HEURISTIC FOR ACHIEVING NEPC RESTORATION IN WSNS FOR XG COMMUNICATION. THE RELEVANT REFERENCE WORK IS [25].

Step 1	For each SN to be restored, identify and mark all SNs that are adjacent (one-hop connected) to it.
Step 2	Remove the SN and all the links attached to it to form a sub-network of the original network.
Step 3	In the sub-network that remains after removing the to-be restored node and the links attached to it, check if any bridge nodes are discovered along with the associated subgraphs 'hinged' on the bridge nodes.
Step 4	If no bridge nodes are discovered, perform Step 5 in the entire sub-network.
Step 5	Find the p-cycle that traverses all of the previously marked SNs (and bridge nodes, if bridge nodes are discovered), which the subgraph may contain.
Step 6	Merge the p-cycles from all the subgraphs to form the restoring NEPC.

link fails, sub-networks 1 and 2 will not have any possible connection between them.
The NEPC base heuristic is presented in Table 1.

The base heuristic for NEPC restoration against node failures presented in Table 1. is straightforward, simple to implement and capable of providing very good candidate NEPCs. However, the NEPCs provided using the heuristic presented above may not be capacity efficient, especially for large WSNs designed for xG communications such as the IoT. We therefore investigate approaches by which the capacity efficiency of NEPCs for network restoration in the WSNs for xG applications can be improved. There are already some ideas in the literature for improving the capacity efficiency of NEPCs. We classify the most common approaches into two categories - the contraction approach and the topology improvement approach. Further, we develop a new, improved approach called the capacity efficiency optimisation approach. This new approach achieves better capacity efficiency in the NEPCs for network restoration than in previous approaches in the literature, making it the most adequate NEPCs solution for the WSNs being employed for xG applications.

2) Contraction of the Candidate NEPCs: The first approach used for improving NEPCs is referred to as the contraction approach. The main idea in the contraction approach is to reduce the selected candidate NEPCs to their smallest possible sizes with the lowest number of hops. When using the contraction approach, the candidate NEPCs are reduced to smaller NEPCs by removing the on-cycle paths and replacing them with the distance-based shortest paths between the two end nodes of the on-cycle paths. The shortest paths should be node-disjoint with the remaining parts of the intermediate p-cycle (excluding the on-cycle paths). If there are such on-cycle paths that can be replaced, the resultant smaller p-cycle is the intermediate p-cycle. Then, all redundant on-cycle segment paths from this p-cycle are deleted and a new contracted p-cycle is formed. This new p-cycle still contains all the adjacent nodes of the node to be restored, resulting in a more capacity efficient-candidate NEPC. An example of the use of this approach can be found in [27].

3) Topology Improvement with Joint Restoration: The second approach being used to improve NEPCs is called the topology improvement approach. In this approach, the candidate NEPCs are selected in an attempt to improve the network by following two main steps. The first step is the same as in the fist approach described earlier; that is, the contraction of the candidate NEPCs. During this first step, the candidate NEPCs for each node in the network are defined under the constraint that the length for each NEPC must be the shortest possible. In the second step, the chosen NEPCs are optimally sized in a joint link and node restoration design. The topology of the candidate NEPCs are determined by selecting a specific sequence of chain-like segments of links and nodes, where a chain represents a possible route between a specified pair of end nodes. Chains are treated as the decision variables in an integer linear programming (ILP) model where they now represent all the possible combinations of node pairs terminating onto the set of nodes adjacent to the failed node. Then, by combining a specific set of chains together, which is accomplished by matching the end nodes of each chain, an improved physical topology of the candidate NEPCs is achieved. An example of the use of this approach can be found in [28].

4) Capacity Efficiency Optimisation: To improve further on the solutions realised by using NEPCs, a third approach, called the capacity efficiency optimisation approach, is developed in this paper. This approach achieves even higher capacity efficiency than in the previous two approaches already presented. In this approach, to select the best NEPCs that will achieve optimal capacity efficiency for the network, the candidate NEPCs are determined after jointly considering three different defining criteria: the shortest lengths, the best topologies and the most capacity-efficient of all the NEPCs. The first two criteria are the same as the criteria employed in the previous two approaches already discussed.

To implement the third criterion introduced in this approach, the p-cycle-based restoration is designed in such a way that it empowers any of the selected NEPCs to be shared by multiple nodes as may be required, while also ensuring that each node is permitted to make use of as many different NEPCs as are needed to achieve the optimal capacity efficiency for the network [28]. By so doing, the approach not only achieves capacity efficiency optimisation using the selected (best candidate) NEPCs, but also has the important advantage of employing the NEPCs that can sufficiently and fully protect all links and nodes in the network against both link and node failures. The analysis of the approach is as follows:

Recall that
N represents the network's SNs,
L represents the possible links for the network,
P is the set of all p-cycles in the network indexed by p,
$w_{ij} \geq 0$ represents the working capacity on link ij,
$s_{ij} \geq 0$ represents the spare capacity on link ij,
$f_{ij} \geq 0$ represents the total traffic flow on link ij, and
c_{ij} represents the cost associated with using link ij.

Let:

$X_p^n \in \{0,1\}$	be the parameter that encodes which cycles can act as NEPCs for which node. If $X_p^n = 1$, p-cycle p can be an NEPC for node n. If $X_p^n = 0$, it cannot.
$\phi_r^n \in \{0,1\}$	be the parameter that encodes the end-nodes of each demand. $\phi_r^n = 1$ if node n is an end-node of demand r and $\phi_r^n = 0$ otherwise.
$\rho_{ij}^{r,q} \in \{0,1\}$	be the parameter that encodes WPs by link. If $\rho_{ij}^{r,q} = 1$, WP q used for demand r crosses link ij. If $\rho_{ij}^{r,q} = 0$, WP q used for demand r does not cross link ij.
$\sigma_n^{r,q} \in \{0,1\}$	be the parameter that encodes WPs by node. If $\sigma_n^{r,q} = 1$, WP q used for demand r crosses node n. If $\sigma_n^{r,q} = 0$, WP q used for demand r does not cross node n.
$\pi_{ij,p} \in \{0,1\}$	be the parameter that encodes the p-cycles that crosses a link. $\pi_{ij,p} = 1$ if p-cycle p crosses link ij, and $\pi_{ij,p} = 0$ otherwise.
$\kappa_{ij,p} \in \{0,1,2\}$	be the parameter that encodes the number of protection relationships provided to link ij by a unit-sized copy of p-cycle p. This implies that $\kappa_{ij,p} = 2$ if link ij is a straddle link for p-cycle p, $\kappa_{ij,p} = 1$ if link ij is an on-cycle link for p-cycle p and $\kappa_{ij,p} = 0$ in all other cases. For the special case of non-simple p-cycles, $\kappa_{ij,p} = 0$ when link ij is an on-cycle link but it is crossed twice by the p-cycle.

If:

r	is the traffic demand on the WP route.
D	is the set of WPs for a traffic demand.
d^r	is the number of WPs available for traffic demand r.
Q^r	is the set of all distinct predetermined eligible routes available to transmit the demand r of the WP.
$g^{r,q} \geq 0$	is the amount (integer) of traffic flow (or demand units) assigned to WP q used for demand r.
$\tau_n \geq 0$	is the amount (integer) of traffic flow that passes through node n.
$0 \leq \mu \leq 1$	is the proportion of paths that must be restored in the event of a node failure, that is, μ makes it possible for only a desired percentage of the traffic flows to be restored and can thus be used to specify the number of paths that require node-failure restorability.

Then, the ILP problem becomes:

$$\min_{(w_{ij}, s_{ij})} \sum_{ij \in L} c_{ij}(w_{ij} + s_{ij}), \tag{8}$$

subject to

$$d^r = \sum_{q \in Q^r} g^{r,q} \quad \forall r \in D, \tag{9}$$

$$f_{ij} \leq \sum_{p \in P} s_{ij,p}.X_p \quad \forall ij \in L, \tag{10}$$

$$w_{ij} = \sum_{r \in D} \sum_{q \in Q^r} \rho_{ij}^{r,q}.g^{r,q} \quad \forall ij \in L, \tag{11}$$

$$w_{ij} \leq \sum_{p \in P} \kappa_{ij,p}.n_p \quad \forall ij \in L, \tag{12}$$

$$s_{ij} = \sum_{p \in P | \kappa_{ij,p}=1} \pi_{ij,p}.n_p \quad \forall ij \in L, \tag{13}$$

$$\tau_n = \sum_{r \in D | \phi_r^n = 0} \sum_{q \in Q^r | \sigma_n^{r,q}=1} \mu.g^{r,q} \quad \forall n \in N, \tag{14}$$

$$\tau_n \leq \sum_{p \in P | X_p^n = 1} 2.n_p \quad \forall n \in N, \tag{15}$$

$$n_p \geq 0, \quad X_p \in \{0,1\} \quad \forall p \in P, \tag{16}$$

$$w_{ij} \geq 0, \quad s_{ij} \geq 0, \quad \forall ij \in L. \tag{17}$$

The objective function (8) minimises the total cost of providing both working and spare capacities for the network (that is, it minimises the total capacity required for routing all WPs and for providing adequate network protection through the RPs). The constraint in Equation (9) ensures that there is sufficient traffic flow to route all the network's working demands fully. The constraint in Equation (10) ensures that the traffic flow to be restored over a given link is not above the maximum available spare capacity on that link. The constraint in Equation (11) places enough working capacity to accommodate all the working flows. The constraint in Equation (12) ensures that the RPs provided by all the p-cycles of the solution set are sufficient to protect all the working capacities for the network. Constraint (13) ensures that there is enough spare capacity to accommodate all p-cycles involved in the design. Constraint (14) is used to obtain the amount of traffic flow that passes through node n. The use of the multiplier μ helps to manipulate whether the demands are fully or partially restored. In other words, it shows how much of the traffic flow passing through node n will contribute to the final restoration traffic calculation. The constraint in Equation (15) ensures that the number of NEPCs is sufficient to fully reroute all the traffic flow that passes through each node n (the multiplier 2 indicates that each NEPC provides two possible RPs for traffic that passes through a failed node). Constraints (16) and (17) ensure that the number of available p-cycles, as well as the working and spare capacities, are all non-negative.

The capacity efficiency optimisation problem presented in Equations (8) - (17) is an ILP problem that can be solved optimally, proving that the goal of providing optimal network capacity efficiency is achievable. Furthermore, the most important criteria of shortest lengths, best topologies and capacity-efficiency optimisation for the selected NEPCs are all incorporated in realising this goal. From the analyses presented in this paper, it can therefore be concluded that when properly developed, WSNs are sufficiently capable of achieving optimal capacity efficiency and network protection against both link and node failures in their design and deployment for xG communication applications.

V. Results and Discussion

The designed WSNs for xG applications is implemented by simulating a test network containing a high volume of SNs (acting as objects in an IoT network) and links between SNs, all deployed within a given geographical area. In the design, the total IoT network is divided into sub-networks, each sub-network containing an average of 20 SNs with an average nodal degree of 4.0 (similar to the network set-up in [28], the reference used in validating the results). The traffic model used is the packet switched traffic model, following the IEEE standards on machine-to-machine communication, as supported by the IP-based protocols. Reference [28] is used as a basis for comparing and validating the developed restoration model because it presented the initial ideas which we improved upon and employed in the xG applications being considered. The results obtained in this work could have been compared with more recent works that have employed NEPC such as the works in [29], [30], [31]. However, none of these more recent works have provided an improved solution for the NEPC which could have then been used as a basis for comparison in this work. Such works have only used the NEPC concept in achieving their varying goals in each case.

In our developed model, request for links and nodes to help establish communication and restoration between the source and the destination nodes are evenly distributed among all nodes in the network. The network is simulated in MATLAB, while the ILP developed to achieve optimal network realisation is solved using YALMIP, a MATLAB-based tool for solving optimisation problems [32]. The simulation is carried out on a Core i5 processor running at 3.2GHz with 8G memory. The computational complexity is given as the number of arithmetic operations carried out before arriving at the solution. The average runtime before arriving at solutions was always within a minute. For the purpose of validation, the p-cycle design solutions obtained in this paper are compared with the results presented in [28]. Hence, the designed WSNs considers the shortest source-destination routes for each demand (that is, shortest by length of links) as the eligible WPs, while the best 10 NEPCs are selected as the candidate NEPCs to achieve network restoration. Again, just as in [28], capacity costs are normalised to the lowest cost network design; that is, the point at which the lowest cost is achieved for the network, which in this case is at an average nodal degree of 4.0 for $\mu = 0$ (link-failure protection only). In the results presented, the data points therefore correspond to the normalised total capacity cost of the 'optimal' solution for the network.

A. Performance Metrics

Two important performance measures are evaluated for the link and node restoration solutions investigated in this work; the *total capacity cost* and the *average path length*. The total capacity cost is the cost of using the working paths plus the cost incurred by using the p-cycle for restoring the network from a failure. To determine the capacity cost of the p-cycle, the cost of each link on the cycle is evaluated. The total cost for the p-cycle is the sum of the costs for all links on the chosen cycle. The average path length is defined by the number of links that combine to form the p-cycle for the restoration. It is measure of the number of hops in the selected p-cycle for restoring the network from a failure.

B. Results for Total Capacity Cost

Fig. 6. compares the capacity costs for the traditional link failure restoration (e.g. as obtainable in [28]) with the developed selection-based link failure restoration in the WSNs designed for xG applications. In the plots presented, both the traditional link-failure restoration and the selection-based link failure restoration achieve 100% link protection. This means that, for all the links in the network, the restoration solutions incorporated provide one or more p-cycles to protect each link. Furthermore, the developed selection-based link failure restoration leveraged its ability to select the best and/or most-appropriate p-cycles from the set of possible p-cycles for the

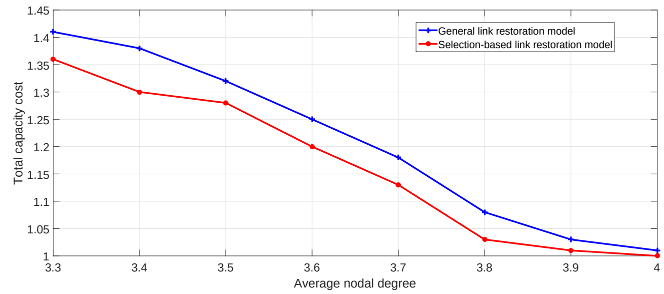

Fig. 6. Link failure restoration using p-cycles. Capacity costs for the traditional restoration solutions (such as in [28]) are compared with the newly developed selection-based restoration solutions.

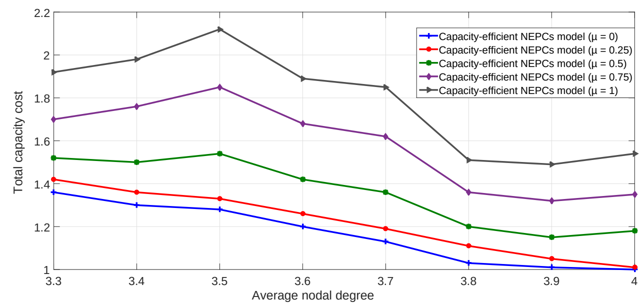

Fig. 7. Node failure restoration using NEPCs. The solutions presented achieves 100% link failure restoration as well as varying levels of node failure restoration using the developed capacity-efficient NEPCs design.

protection of the network against link failure. As a result, the selection-based restoration solutions achieve better capacity cost efficiency than the traditional link-failure restoration the network.

Fig. 7. presents the results for the network design when the selection-based restoration, alongside the developed capacity-efficient NEPCs, are combined to achieve both link and node failure restorability for xG networks. In all the cases presented, the selection-based link failure restoration design incorporated achieves 100% link protection. At the same time, the network provides varying levels of node failure protection through the capacity-efficient NEPCs incorporated. The $\mu = 0$ plot is equivalent to the developed selection-based link failure restoration model. This is so because, setting $\mu = 0$ effectively sets $\tau_n = 0$ for all nodes, thereby eliminating the constraints related to node failure protection. The problem is then reduced to the selection-based link failure restoration problem presented in Section 4.1. The other plots show different levels of restoration against node failures through the capacity efficiency NEPCs design (indicated by the varying values of μ).

From the results, it can be observed that the incorporation of selection-based node failure restoration (through NEPCs) increases capacity costs for the network more than when only the selection-based link failure restoration design is considered. However, as shown in Fig. 8., the capacity cost achieved through the developed selection-based capacity-efficient NEPCs is significantly lower than previously obtained in the NEPCs solutions achieved in the reference work [28].

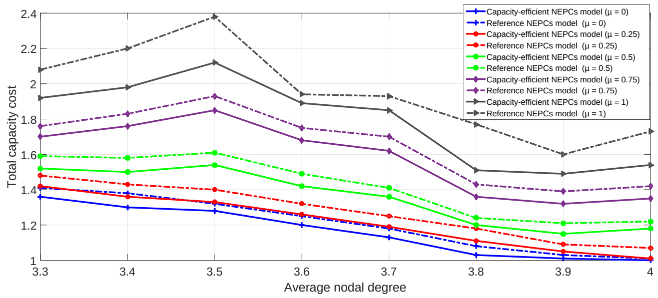

Fig. 8. Traditional restoration solutions using NEPCs (the relevant reference work being [28]) are compared with the newly developed capacity-efficient NEPCs solutions.

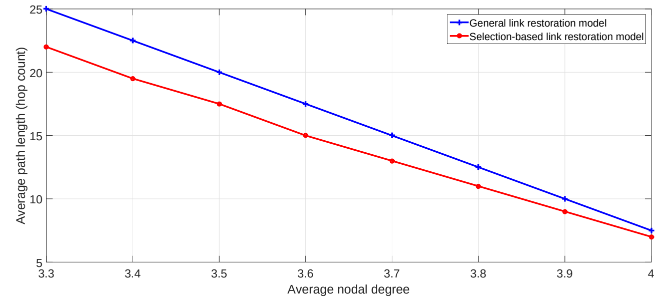

Fig. 10. Link failure restoration using p-cycles. Average path length for the traditional restoration solutions (such as in [28]) are compared with the newly developed selection-based restoration solutions.

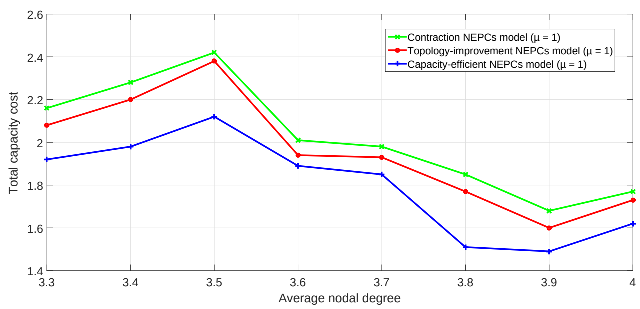

Fig. 9. Solutions from the various NEPCs investigated are compared. The newly developed capacity-efficient NEPCs approach outperforms both the contraction NEPCs approach and the topology-improvement NEPCs approach.

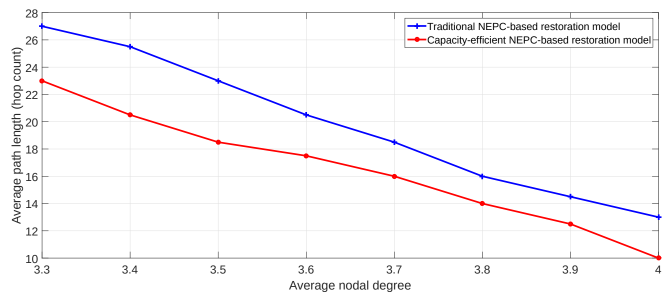

Fig. 11. Node failure restoration using NEPCs. Average path lengths for the traditional restoration solution from [28] are compared with the newly developed selection-based restoration solution.

This is because the selection of the best candidate NEPCs is based on the cost implications of each NEPC. The introduction of this selection process in the optimisation problem helps to reduce the overall cost of the network significantly. Finally, it is observed that if only a limited amount of node failure restoration is required (i.e., low μ values), capacity costs are reduced, approaching those for link failure protection only.

In Fig. 9., the capacity cost results for the various NEPCs restoration solutions considered in this paper are compared. It can be observed that, in terms of capacity costs for the network, the topology improvement approach outperforms the contraction approach, while the developed capacity efficiency optimisation approach outperforms both the contraction and the topology optimisation approaches. It is noted that all three approaches can significantly outperform solutions obtained through the base heuristic for NEPCs. The results show that the newly developed capacity-efficient NEPC-based restoration model outperforms the traditional NEPC-based solution because it achieves significant improvement in the total capacity cost incurred by the network to achieve optimal network restoration.

C. Results for Average Path Length

Fig. 10. compares the average path length for the traditional link failure restoration (e.g. as obtainable in [28]) with the developed selection-based link failure restoration in the WSNs designed for xG applications. In the plots presented, both the traditional link-failure restoration and the selection-based link failure restoration achieve 100% link protection. Furthermore, the developed selection-based link failure restoration leveraged its ability to select the best and/or most-appropriate p-cycles from the set of possible p-cycles for the protection of the network against link failure. As a result, the selection-based restoration solutions achieve significant improvement in the average path length (implying a shorter delivery latency) than the traditional link-failure restoration the network.

In Fig. 11., the average path length results obtained for the traditional NEPCs solution are compared with the developed capacity-efficient NEPCs solution. The results show that the newly developed capacity-efficient NEPC-based restoration model outperforms the traditional NEPC-based solution because it achieves significant improvement in the average path length for optimal network restoration.

VI. Conclusion

In this paper, appropriate WSN models applicable to xG communications (particularly the IoT) were developed and analysed. The models incorporated and examined a number of network restoration strategies to help address and solve the problem of network failures. The peculiar feature of WSNs, which is its ability to remain in active service even if one or more of its elements have failed, was leveraged in developing the xG WSNs models. The network restoration solutions investigated for the network were p-cycle-based restoration solutions because of their advantage of providing sufficient network recovery at fast speeds while also achieving optimal resource usage for the network. The results obtained show that, by incorporating appropriate network restoration solutions, WSNs can indeed achieve remarkable improvement in their performance indices, thereby positioning them for highly effective xG applications.

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REFERENCES

[1] M. Kumar and V. Gupta, "A review paper on sensor deployment techniques for target coverage in wireless sensor networks," in *2016 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT)*, Dec 2016, pp. 452–456.

[2] G. Verma and V. Sharma, "A survey on hardware design issues in RF energy harvesting for wireless sensor networks (WSN)," in *2016 5th International Conference on Wireless Networks and Embedded Systems (WECON)*, Oct 2016, pp. 1–9.

[3] S. Abuelenin, S. Dawood, and A. Atwan, "Enhancing failure recovery in wireless sensor network based on grade diffusion," in *2016 11th International Conference on Computer Engineering Systems (ICCES)*, Dec 2016, pp. 334–339.

[4] A. E. Zonouz, L. Xing, V. M. Vokkarane, and Y. L. Sun, "Reliability based optimization in hybrid wireless sensor networks," in *2015 Annual Reliability and Maintainability Symposium (RAMS)*, Jan 2015, pp. 1–7.

[5] S. Han and K. G. Shin, "Efficient spare-resource allocation for fast restoration of real-time channels from network component failures," in *Proceedings Real-Time Systems Symposium*, Dec 1997, pp. 99–108.

[6] W. Lau and S. Jha, "Failure-oriented path restoration algorithm for survivable networks," *IEEE Transactions on Network and Service Management*, vol. 1, no. 1, pp. 11–20, April 2004.

[7] R. Dighe, Q. Ren, and B. Sengupta, "A link based alternative routing scheme for network restoration under failure," in *Global Telecommunications Conference, 1995. GLOBECOM '95., IEEE*, vol. 3, Nov 1995, pp. 2118–2123 vol.3.

[8] B. S. Awoyemi, A. S. Alfa, and B. T. Maharaj, "Network restoration for next-generation communication and computing networks," *Journal of Computer Networks and Communications*, vol. 2018, no. 4134878, pp. 1–13, April 2018.

[9] G. Panza, A. Capone, D. Pinarello, and P. Belotti, "Engineering robust next-generation networks," in *2009 IFIP/IEEE International Symposium on Integrated Network Management-Workshops*, June 2009, pp. 237–240.

[10] P. H. Franklin, I. Tavrovsky, and R. Ames, "A strategy for optimal management of spares," in *2016 Annual Reliability and Maintainability Symposium (RAMS)*, Jan 2016, pp. 1–6.

[11] X. Zhang and Z. Zhang, "Link fault identification using dependent failure in wireless communication networks," *Electronics Letters*, vol. 52, no. 2, pp. 163–165, 2016.

[12] W. P. Tay, J. N. Tsitsiklis, and M. Z. Win, "On the impact of node failures and unreliable communications in dense sensor networks," *IEEE Transactions on Signal Processing*, vol. 56, no. 6, pp. 2535–2546, June 2008.

[13] Z. Rehena, R. Mukherjee, S. Roy, and N. Mukherjee, "Detection of node failure in wireless sensor networks," in *2014 Applications and Innovations in Mobile Computing (AIMoC)*, Feb 2014, pp. 133–138.

[14] S. Lee, M. Younis, and M. Lee, "Connectivity restoration in a partitioned wireless sensor network with assured fault tolerance," *Ad Hoc Networks*, vol. 24, pp. 1 – 19, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1570870514001437

[15] A. Mahapatro and P. M. Khilar, "Energy-efficient distributed approach for clustering-based fault detection and diagnosis in image sensor networks," *IET Wireless Sensor Systems*, vol. 3, no. 1, pp. 26–36, March 2013.

[16] Z. Fu, Z. Liu, Y. Yuan, M. Zhao, and Q. Li, "Coverage restoration method for wireless sensor networks of distributed pv system," *International Journal of Distributed Sensor Networks*, vol. 11, no. 2, p. 738237, 2015. [Online]. Available: https://doi.org/10.1155/2015/738237

[17] K. P. Sharma and T. P. Sharma, "CPFR: Coverage preserving failure recovery in wireless sensor networks," in *2015 International Conference on Advances in Computer Engineering and Applications*, March 2015, pp. 284–289.

[18] H. Ghanbari and M. Jahanshahi, "A new distributed method based on genetic algorithm for connectivity restoration in wireless sensor networks," in *2016 IEEE International Conference on Information and Automation (ICIA)*, Aug 2016, pp. 1893–1900.

[19] S. Chouikhi, I. E. Korbi, Y. Ghamri-Doudane, and L. A. Saidane, "Articulation node failure recovery for multi-channel wireless sensor networks," in *2015 IEEE Global Communications Conference (GLOBECOM)*, Dec 2015, pp. 1–7.

[20] K. Yan, G. Luo, L. Tian, Q. Jia, and C. Peng, "Hybrid connectivity restoration in wireless sensor and actor networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2017, no. 1, p. 138, Aug 2017. [Online]. Available: https://doi.org/10.1186/s13638-017-0921-4

[21] W. Miyazaki, K. Kinoshita, H. Tode, K. Murakami, S. Kikuchi, S. Tsuchiya, A. Sekiguchi, and T. Katsuyama, *An Efficient Failure Recovery Scheme for Next Generation Network Services Based on Distributed Components*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 51–60. [Online]. Available: https://doi.org/10.1007/978-3-540-88623-5_6

[22] R. Asthana, Y. N. Singh, and W. D. Grover, "P-cycles: an overview," *IEEE Communications Surveys Tutorials*, vol. 12, no. 1, pp. 97–111, First 2010.

[23] W. D. Grover and D. Stamatelakis, "Bridging the ring-mesh dichotomy with p-cycles," in *Proc. of DRCN workshop*, 2000, pp. 92–104.

[24] G.-Q. Wang and A. S. Alfa, "Cycle-based restoration in mesh networks utilizing bandwidth and flow considerations," June 28 2011, US Patent 7,969,862.

[25] D. Stamatelakis and W. D. Grover, "IP layer restoration and network planning based on virtual protection cycles," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 10, pp. 1938–1949, Oct 2000.

[26] K. Mahmood, M. A. Khan, M. ul Hassan, A. M. Shah, S. Ali, and M. K. Saeed, "Intelligent on-demand connectivity restoration for wireless sensor networks," *Wireless Communications and Mobile Computing*, vol. 2018, no. 9702650, pp. 1–10, 2018.

[27] T. Zhao, L. Li, and H. Yu, "Finding good candidate node-encircling pre-configuration cycles in survivable WDM mesh networks," in *2006 International Conference on Communications, Circuits and Systems*, vol. 3, June 2006, pp. 1877–1881.

[28] J. Doucette, P. A. Giese, and W. D. Grover, "Combined node and span protection strategies with node-encircling p-cycles," in *5th International Workshop on Design of Reliable Communication Networks, 2005.*, Oct 2005, pp. 1–9.

[29] M. Molnr, "Non-elementary routes for multicasting in transparent optical networks," in *2017 19th International Conference on Transparent Optical Networks (ICTON)*, July 2017, pp. 1–4.

[30] A. Jarray and A. Karmouch, "Cost-efficient mapping for fault-tolerant virtual networks," *IEEE Transactions on Computers*, vol. 64, no. 3, pp. 668–681, March 2015.

[31] A. Jarray, , and A. Karmouch, "p-cycle-based node failure protection for survivable virtual network embedding," in *2013 IFIP Networking Conference*, May 2013, pp. 1–9.

[32] J. Lofberg, "YALMIP : a toolbox for modeling and optimization in MATLAB," in *Proc. IEEE Int. Symposium on Computer Aided Control Systems Design*, Sept 2004, pp. 284–289.