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Improving link failure restoration in next-generation wireless sensor networks

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ABSTRACT

Next-generation wireless sensor networks (xWSN) have applications in many emerging wireless technologies, such as fifth-generation, internet-of-things, device-to-device communications, e-health, e-agriculture, etc. For most of these xWSN applications, network reliability and robustness against failures are crucial considerations. In this paper, an appropriate network restoration model is developed to help achieve network protection and/or restoration for xWSN in the event of link failures. In the model, effective network restoration is achieved by investigating efficient pre-configured-cycle (p-cycle)-based restoration solutions for the xWSN. Furthermore, to achieve significant improvement in the capacity efficiency of the p-cycle solutions realised, the concepts of p-cycle selectivity, load redistribution and the use of single p-cycles for double failure restoration are investigated and incorporated in the network restoration design. The restoration model developed, alongside the various improvement concepts incorporated, is shown to achieve better performance in terms of average path length and total capacity cost when compared with similar restoration models for modern wireless communication applications.

1. Introduction

Emerging next-generation (xG) wireless communication technologies such as fifth-generation (5G) and beyond, internet-of-things (IoT), cognitive radio networks, etc. promise fast speed, high capacity, low latency and impressive reliability, among others [1,2]. Wireless sensor networks (WSN), despite no longer being a new technology, are also developing modern models and prototypes that are being designed and deployed to help achieve the promises and expectations of xG wireless communication. The new WSN designs for modern applications are referred to as next-generation wireless sensor networks (xWSN) [3]. Alongside other xG technologies, these modern xWSN models and prototypes do have practical applications in smart cities, device-to-device (D2D) communications (such as machine-to-machine and vehicle-to-vehicle communications), e-health, e-agriculture, e-transportation, e-education, and several other modern sensor-dependent xG wireless communication applications.

As the xWSN evolve, one main challenge with their development is the possibility of network failures, especially when they are to be employed or deployed for highly sensitive xG communications. In reality, even in very robust modern network designs, it is quite difficult to completely eliminate the possibility of the occurrence of network failures in communication networks. Therefore, for xWSN, although there are significant improvements over conventional WSN, failures may still occur. A network failure in the xWSN may be a result of the limitations in size, quality, durability, storage capacity, processing capability or lifetime of the sensor nodes (SNs) being deployed for network operations [4]. Network failures in the xWSN may also be caused by complexities in the network operations or difficulty in the terrain or location of deployment and usage of the SNs [5], or by some other foreseen or unforeseen factors [6].

The negative impact of network failures on the performance of xWSN has been alluded to in [7]. Importantly, network failures in xWSN, if uncontrolled, can frustrate the realisation of the promise of high reliability in the xG network applications for which they are deployed. Therefore, to help mitigate the effects of network failures in xWSN, appropriate network restoration models must be incorporated in the network design. Such network restoration models would effectively anticipate the occurrence of failures and provide timeous backup and/or recovery plans for the network in which they are incorporated. Developing network restoration models for xG communication applications is an important area of research in modern telecommunications.

In this paper, we present an appropriate network restoration model that can provide the necessary protection and/or restoration for the xWSN in the event of network failures (link failures, particularly). We

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then investigate and analyse some important concepts to achieve significant improvement in the restoration solutions of the network restoration model being employed for xWSN applications. The important contributions in this paper are summarised as follows:

- We advance an appropriate network restoration model that is most applicable for restoring and protecting xWSN against link failures.
- We present practical concepts to achieve significant improvement in the solutions of the network restoration model that is developed and advanced for xWSN applications.
- We analyse optimal restoration solutions for the restoration model developed for xWSN and present comparative results for the various improvement concepts incorporated in the network restoration model.

The remaining parts of this paper are organised as follows: Section 2 gives a brief review of related literature on network restoration in xWSN, Section 3 presents the system model for network restoration against link failure in xWSN applications, Section 4 provides an analysis of the various concepts for improving the restoration solutions of the network restoration model for xWSN, Section 5 presents some important results from the improved solution model for network restoration in the xWSN, and Section 6 gives concluding remarks.

2. Review of related literature

Even though it is still an evolving technology, there are already a few researchers who have studied xWSN and discussed some relevant use of the technology in modern applications. An example of the application of xWSN in modern technologies is in cognitive radio sensor networks, as recently studied in [8]. Moreover, some works have investigated and developed network restoration solutions for xWSN and other emerging xG wireless networks. A good review of the application of network restoration for xG networks was carried out in [9]. The work explored network failure and restoration for xG networks, and gave specific examples of network restoration models and applications in 5G, IoT, xWSN, etc.

In [10], the authors developed the xWSN to be deployed for environmental monitoring, such as in border control or during forest fire emergencies. The SNs in the xWSN design were empowered to be able to remotely reprogramme their software. The SNs could also reconfigure their hardware, making it possible to remotely modify their design, long after it has been deployed. In the design, each SN was equipped with a particular unique and adaptable feature that the SNs use to adjust to their immediate environment, even after the deployment process has been completed.

The authors in [11] developed a new adaptive sleep-efficient hybrid medium access control protocol for the xWSN. The protocol was argued to achieve improved energy efficiency by allowing nodes to adjust their sleep time in a dynamic manner, mainly dependent on the amount of traffic load that is available in that time. In the model, whenever there was an increase in the traffic load of the network, the sleep time of the nodes was shortened to reduce the amount of energy that goes to waste as a result of their switching operations. Conversely, whenever the network's traffic load was low, the sleep time of the nodes was increased to save energy that would have gone to waste because of idle listening. As the network shared scheduling information and utilised system resources in an efficient manner, it was shown that the medium access protocol developed did help in reducing control overheads in the xWSN.

The models developed and studied in [12] are important examples of the development and analysis of network restoration models for xWSN. The network restoration models developed in [12] leveraged the peculiarities of WSN, as well as the promising prospects of xG communications, in achieving network restoration solutions that optimised resource usage, while also providing sufficient protection for the network. In the work, the pre-configured or pre-planned cycle (also called p-cycle) restoration scheme was employed to develop the network restoration models that were used to achieve timeous recovery of the xWSN from network failures.

Apart from the work in [12], more recent works on network failure and restoration for xG networks such as xWSN are now employing p-cycles to carry out restoration and recovery of their networks, and to protect them from network failures. Indeed, p-cycle restoration schemes have been shown to have some significant advantages over most other network restoration schemes. The first advantage of p-cycles over other schemes is that p-cycles achieve network recovery from network failures at speeds that are near to the achievable speed of ring-based restoration, while still attaining restoration capacities that are close to the achievable capacity of mesh-based restoration [13]. The next advantage is that p-cycles achieve good recovery and protection of communication networks against both link and node failures [14]. Another benefit is that p-cycles usually carry out network restoration using only the spare capacities of the links in the network, making the network highly capacity-efficient [9]. A final advantage is that network restoration through p-cycles is quite effective in protecting both spanning (or on-cycle) and straddling links in a network [12]. These important advantages make p-cycle restoration particularly ideal for xWSN and most other emerging xG networks.

In this paper, the p-cycle-based restoration scheme is further explored and advanced to achieve better protection and restoration for the xWSN, especially against link failures. Specifically, we first establish an appropriate and efficient p-cycle-based restoration model for xWSN. Thereafter, three different schemes – p-cycle selectivity, load redistribution and the use of a single p-cycle for double failure restoration – are employed in achieving significant improvement in the network restoration solutions for the xWSN. The improvement in the restoration solutions realised is significant in that it helps in providing efficient and sufficient protection against link failures for most practical xG applications, especially the xWSN.

3. System model

A simple, generic system model for xWSN is presented in Fig. 1. The xWSN consist of a large number of SNs dispersed within a geographical area. At any given time, some of the SNs are active, while others are inactive. The active SNs drive the sensing activities for the xWSN. The inactive SNs are inactive because they are either dead nodes or because they have been made inactive (that is, they have been temporarily put out of service in order to conserve network resources). The SNs are connected via the connecting links. The links are either wired links or wireless links. The network could be designed as either a distributed network or a centralised network. The generalised system model in Fig. 1 can be adapted to study most emerging xG communication networks. In this paper, the xWSN model is adapted for D2D communications.

3.1. Network architecture

In this subsection, we present a realistic consideration of the architectural description of the xWSN being set up for D2D communications. In practical xWSN to be employed for D2D communications, the network devices are the SNs in the network. Communication between the SNs can either be single-hop or multi-hop. Single-hop communication means that communication is simply from one SN to another neighbouring SN. Multi-hop communication implies that communication is from one (source) SN to another likely non-neighbour (destination) SN, via other SNs that act as relays between the source SN and the destination SN. For the D2D communications network under consideration, the SNs in close proximity communicate with one another using a direct link, therefore their radio signals do not travel through a base station or a core network. Furthermore, each SN has at least one sensing

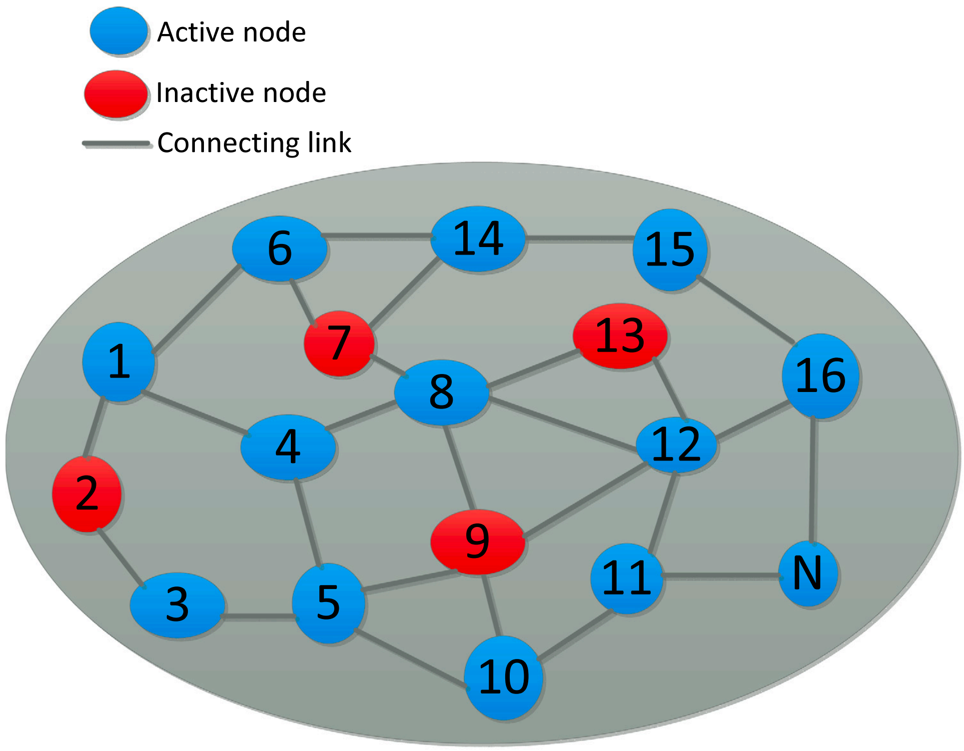

Fig. 1. A simplified system model for xWSN.

device through which it gathers information and communicates with other neighbouring SN(s). Then, each SN is allowed to carry out its transmission on more than one channel in and around the sufficiently wide area of communication.

Similar to most other xG technologies, in D2D communications, it is common to find heterogeneous traffic load demands and fluctuating wireless link conditions. Despite this, the xWSN for D2D communications under consideration should be capable of providing autonomous network services under such different conditions to various kinds of users, and for different kinds of user demands. The xWSN for D2D communications are able to achieve all these expectations by simply setting up the network using the distributed architecture. With this architecture, data transmission via the SNs is carried out in a distributed manner. The distributed network architecture for D2D communications offers some important advantages over other types of architecture, especially the centralised network topology. The most significant advantages of the distributed architecture are cost-effectiveness, ease of network recovery from failure and better scalability of the network [15].

3.2. Network model

In the xWSN for D2D communications being investigated, the set of nodes in the network (which are the SNs within the coverage area) is represented by N, and the set of all connecting links is represented by L. The link ij is the connection between the two SNs i and j. w_{ij} represents the working capacity on link ij, s_{ij} represents the spare capacity on link ij and t_{ij} represents the total capacity on link ij, ($\forall ij \in L$). We assume that the network's time frames are very short. Therefore, the network conditions do not change within each time frame but may only change from one time frame to another. Thus, the capacities do not change with time in each time frame.

In the network set up, the set of source nodes N_s and destination nodes N_d ($N_s, N_d \in N$) make up the end-nodes. The working paths (WPs) refer to original paths of communication between the source s and the destination d. The restoration paths (RPs) are the paths designed to help protect or restore traffic from s to d in case of a failure along its WPs. The total traffic flow f_{ij} on the link ij is the addition of all the traffic flows between s and d that have passed through link ij. Usually, $f_{ij} \leq t_{ij}$.

As discussed earlier, the p-cycle-based restoration has some peculiar advantages over other types of restoration that makes it an ideal restoration model for xWSN applications. As a result, the p-cycle restoration model is employed in this paper for achieving network protection and recovery in the xWSN being employed for D2D communications. The fundamental description of the network model for network restoration using p-cycles in xWSN has been established in the authors' previous work in [12], therefore, it is not necessary to repeat it in this paper. Rather, we focus our attention on improving the restoration solutions that can be realised by using p-cycle restoration for xWSN. A simple pictorial representation of p-cycles being employed for link failure restoration in xWSN is shown in Fig. 2.

4. Improving p-cycle-based network restoration solutions

We have established that p-cycle restoration has peculiar advantages over other schemes that make it an ideal restoration scheme for D2D communications, particularly xWSN. Furthermore, xWSN and most other D2D communication designs support both single-hop and multi-hop communication possibilities, making p-cycle restoration even more suitable for them. However, in designing p-cycle-based network restoration models to protect the xWSN for D2D communications against link failures, the candidate p-cycles must be such that they do not require too many hops, otherwise the protection or restoration provided may be suboptimal and inadequate for the network [12].

Therefore, to achieve optimal or near-optimal restoration of the network against link failures, the p-cycle-based restoration models to be used for D2D communications must be well designed such that the number of hops in the RPs of the p-cycles is always at the barest minimum. Moreover, apart from using a minimum number of hops, there are other very useful ideas that, when incorporated into the p-cycle restoration model, can help improve the overall performance of

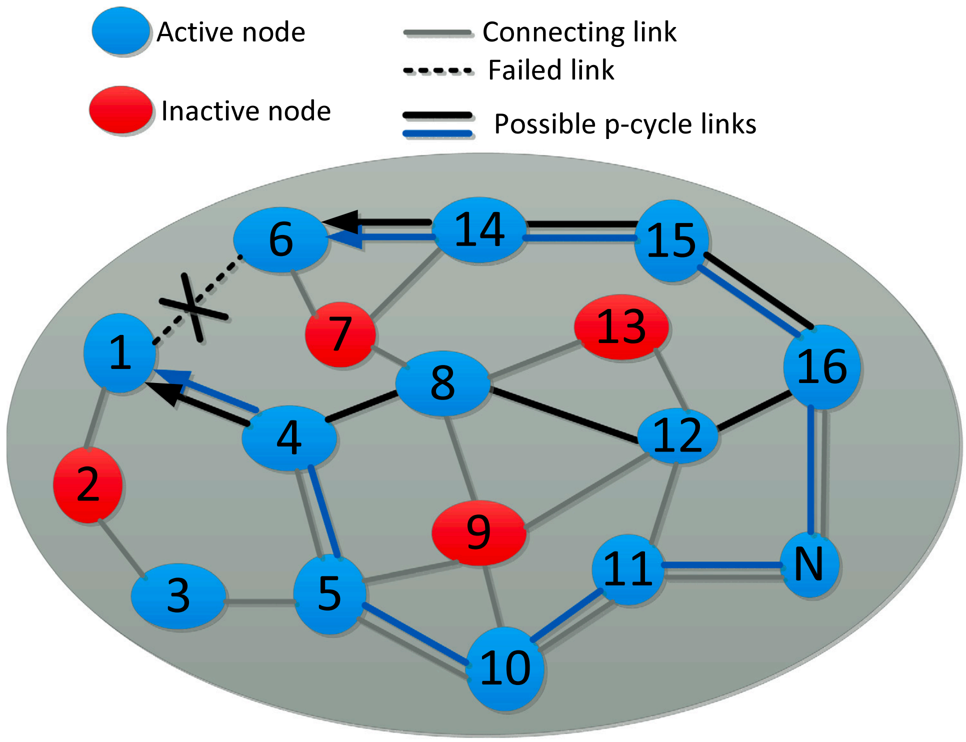

Fig. 2. A pictorial representation of p-cycles used for link failure restoration in xWSN.

the restoration model. In this section, we investigate some of the most useful concepts that can help improve the network restoration solutions of p-cycles in order to meet the specifications and demands of emerging xG networks, particularly xWSN.

4.1. p-Cycle selectivity

The first concept that we advance for improving the network restoration solutions of the p-cycles being used for protecting and restoring xWSN is the concept of p-cycle selectivity. To ensure that the number of hops in the RPs of the p-cycles is always at a minimum, it is possible to select one or more candidate p-cycles from all the available p-cycles in the network that achieve a desired hop count requirement, especially when the number of potential p-cycles is quite high. The idea of selecting a candidate p-cycle(s) from among all the p-cycles that are available for achieving network restoration against link failures was first developed in [16]. More recently, the concept was explored in [12] for achieving network restoration in xG communications. In this subsection, the important concept of p-cycle selectivity is employed for achieving improved link failure restoration in xWSN. One important benefit of employing the selection-based p-cycle restoration solution explored in this subsection is that it is possible to achieve complete protection and recovery of the network against failures at minimal costs for the xWSN in consideration.

To carry out the p-cycle selectivity, an appropriate cost is assigned to each p-cycle being considered for possible selection. This cost is determined by summing the costs of all the links that make up the p-cycle. For the selection process, the set of p-cycles selected comprises the p-cycles that minimise the total costs associated with selecting them. Determining the particular p-cycle(s) to be selected for achieving network restoration by using the cost implications of each potential p-cycle as a criterion is a crucial aspect of the selection process. This is because selection based on cost implications helps to achieve the needed cost-effectiveness in the network restoration design for the xWSN.

Therefore, in the optimisation problem set up, the appropriate objective would be to determine (and select) the p-cycles that minimise the total cost of achieving the network restoration, with the guarantee that every link is protected from failure. This objective must be subject to the constraint that the total traffic flowing on any link to be restored (that is, the failed link) must be less than or equal to the total spare capacity that is made available through the p-cycles that are selected for restoring that link. In other words, the total spare capacity of the p-cycles that are selected for network restoration must be large enough to restore the original traffic flowing through the failed link, otherwise the selected p-cycles would not be able to restore the network sufficiently.

Let

P be the set of all possible p-cycles from which the RPs are to be selected; $P(ij)$ is the set of distinct cycles that are selected for restoring link ij.

c_p be the cost accrued by using the p-cycle p for achieving network restoration. The value of c_p is obtained by adding the costs of using the spare capacities of all the links that make up p; c_{ij} is 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 when link ij fails.

$X_p \in \{0,1\}$ be the parameter that encodes whether a p-cycle is selected or not. $X_p = 1$ if p-cycle p is selected and $X_p = 0$ otherwise.

The optimisation problem for selecting the candidate p-cycle(s) from the total number of p-cycles that are available for achieving network restoration in the xWSN for D2D communications can now be formulated as follows:

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

subject to

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

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

The optimisation problem given in Eqs. (1)–(3) is a convex problem. Therefore, any of the well-defined classical optimisation approaches for solving convex programming problems may be employed to solve the problem and to obtain optimal solutions [17]. In this paper, the well-known branch-and-bound (BnB) optimisation approach is employed to solve the optimisation problem. The BnB approach is known to be computationally demanding, because it checks each possible branch in the network problem before determining the best branch to use to arrive at an optimal solution. To keep the computational demand of the optimisation solution within the acceptable limits for the xWSN, therefore, the implicit enumeration tool is used alongside the BnB optimisation approach. The implicit enumeration tool, employed with the BnB optimisation approach, achieves an advantage in that it is able to identify the most viable branch for optimal solutions in a reasonably shorter time [18].

Furthermore, to ensure that the additional traffic on the links that are being used to carry out the restoration does not affect the original traffic flowing in those links, in the network design the concept of network restoration without interference is employed. This implies that the restoration is carried out using only the spare capacities on the links that make up the p-cycles. As a result, the spare capacities on the links that would otherwise have remained unused are now well employed in the network. With this design plan, capacity gain is achieved on individual links in the network, which translates into improvement in the overall restoration capacity of the network.

4.2. Load redistribution

The second important concept for improving the restoration solutions of the p-cycles being used for restoring xWSN is the concept of load distribution. Even though p-cycle selectivity helps in improving the capacity that the network restoration achieves, the total amount of traffic that the selected p-cycle p realises may still be limited. This is because the traffic that the selected p-cycle can successfully restore without interference depends on the link that has the minimum spare capacity on that p-cycle [12]. The link with the minimum spare capacity in a p-cycle is referred to as the limiting link. The limiting link of a p-cycle poses a serious bottleneck to the amount of traffic that the selected p-cycle can restore.

Therefore, to realise even better restoration capabilities for the p-cycle(s) that are selected for network restoration in the xWSN design, the capacity limitation imposed on the p-cycle(s) by the limiting link has to be overcome. Overcoming the capacity limitation of the limiting link in a p-cycle can be achieved by seeking means to improve the capacity of that limiting link. Improving the capacity of the limiting link of the p-cycles that are selected for network restoration will then result in an improvement in the overall capacity of the p-cycles being used for carrying out network restoration in the xWSN.

To improve the capacity of the limiting link in the p-cycles that are selected for network restoration, in this subsection, we employ the concept of load redistribution. Simply, load redistribution means shifting some of the load on a link to other neighbouring links in order to free up more space (capacity) on that particularly link. Specifically for the model developed in this paper, we target the limiting link of the p-cycles that are selected for network restoration as the link to carry out the load redistribution in the xWSN design. In other words, the load redistribution incorporated helps to achieve an improved value for the amount of spare capacity of the limiting link ij of the p-cycle p being used in restoring the network. This implies that, by employing load redistribution, the value of $s_{ij,p}$ becomes a value $s'_{ij,p} > s_{ij,p}$. The improvement in the capacity of the limiting link results in a higher value for the total restoration capacity of the p-cycle(s) selected for restoring the network.

Actually, the improvement in the link capacity of the limiting link of the selected p-cycle is achieved by improving the channel occupancy ratio (COR) of the limiting link of the p-cycle. The COR of a link gives information on the available or free channel airtime on that link. It is important to understand how the local traffic load redistribution of the load on the limiting link of the p-cycle(s) is carried out to achieve capacity improvement (that is, an improvement in the COR value) of the limiting link. This is because it is an integral part of the process of improving the overall capacity of the p-cycle(s) being used for restoring the network. The local traffic distribution process is explained in the remaining part of this subsection.

First, we define the COR of links in a network. The COR (represented by μ) of any link in a network is defined as the ratio of its working capacity (or aggregate load) to its total capacity. Particularly, for the limiting link ij in the xWSN of interest, μ_{ij} is given as:

$$\mu_{ij} = \frac{w_{ij}}{t_{ij}}. \tag{4}$$

From the μ_{ij} value that is obtained, the spare capacity (or achievable link capacity) s_{ij} of the limiting link ij for the particular p-cycle of interest can be calculated. The value of the spare capacity s_{ij} is obtained as:

$$s_{ij} = (1 - \mu_{ij})t_{ij}. \tag{5}$$

After obtaining the value of the spare capacity s_{ij} of the limiting link for the p-cycle that is being used for restoring the network, we now seek to achieve a better value of s_{ij} that can improve the overall capacity of the p-cycle. As already established, the improvement in the value of s_{ij} can be realised by carrying out a local redistribution of some of the original load on the limiting link ij, when required. To decide whether a local traffic load redistribution of the original load on the limiting link is required or not, the p-cycle that is selected for restoring the network must first establish if it has sufficient capacity for the requested backup or restoration needed. If the spare capacity s_{ij} of the limiting link ij for the selected p-cycle is sufficient for the requested restoration or backup stream, the p-cycle accepts the backup without any need for local load redistribution. However, if the spare capacity s_{ij} of the limiting link ij of the p-cycle is insufficient for the requested restoration or backup, it immediately triggers the local traffic redistribution process to redistribute some of the original load on that limiting link ij.

In the local redistribution process, part of the traffic or load on the limiting link ij is simply moved to its neighbouring, one-hop nodes with sufficient spare capacities to accommodate the extra incoming load. Importantly, the neighbouring nodes to be used for the local load redistribution must be nodes that are not part of the p-cycle. By moving some part of the original traffic of the link, new spare capacity s'_{ij} on the limiting link ij is achieved. As a result of the load redistribution, the newly obtained spare capacity s'_{ij} of the limiting link ij is now an improved value of the initial spare capacity s_{ij}. We write the new spare capacity s'_{ij} of the limiting link as:

$$s'_{ij} = s_{ij} + m_{ij}, \tag{6}$$

where m_{ij} is the amount of capacity that is freed up by the redistribution of some of the original load on the link ij to its neighbouring nodes through the local redistribution process. The value of m_{ij} is usually a fraction of the working capacity or original aggregate load on the limiting link ij. With the load redistribution achieved, and depending on how much load has been redistributed, the network is able to realise significant improvement in the amount of the restoration solutions for the xWSN. The new optimisation problem for link restoration with load redistribution on the limiting link of the p-cycle(s) selected for restoring the network is now given as:

$$\min_{X_p} \sum_{\forall p \in P} c_p.X_p, \tag{7}$$

subject to

$$f_{ij} \leq \sum_{\forall p \in P(ij)} s'_{ij,p}.X_p \quad \forall ij \in L, \tag{8}$$

$$X_p \in \{0, 1\} \quad \forall p \in P. \tag{9}$$

By solving the optimisation problem in Eqs. (7)–(9), an improvement in the total capacity per cost is achieved for the p-cycles that are selected for restoring the xWSN. Since the new optimisation problem in Eqs. (7)–(9) is still a convex problem, any of the well-defined classical optimisation approaches may be employed to solve the problem, and to obtain optimal solutions. Again, the BnB approach with implicit enumeration is employed for solving the optimisation problem because of its advantage of obtaining optimal solutions timeously.

4.3. Single p-cycle for double link failure restoration

Further to the concepts of p-cycle selectivity and load redistribution already incorporated, in this subsection we present a third useful concept for achieving significant improvement in the capacity of the p-cycles being selected for restoring xWSN from link failures. The concept is that of employing individual p-cycles to achieve network restoration from double link failures. Indeed, if two links are in close proximity and they do have overlapping protection, the probability of simultaneous failure on the two links can be quite high. Thus, providing sufficient but also resource-efficient protection from such double link failures is quite essential for the xWSN.

The possibility of using a single p-cycle to protect a network from double link failures depends on the simple fact that all the straddling links of a p-cycle can be protected from any two simultaneous link failures, provided the p-cycle protection has as many copies as the working capacity plus one additional unit of the straddling link with the highest capacity on the p-cycle [19]. The number of copies is the number of p-cycles that are available on each link for achieving network protection or recovery from failure. Usually, a copy of a p-cycle protects two units capacity on a straddling link but only a unit capacity on an on-cycle link. This is because on a p-cycle, each straddling link has two alternative paths it can follow to achieve network restoration.

The attribute of a p-cycle protecting two units of capacity on a straddling link but only a unit of capacity on a spanning link is what is leveraged to achieve the use of a single p-cycle in protecting the xWSN from two simultaneous link failures. Therefore, the p-cycles are used to provide protection only to straddling links and no on-cycle (or spanning) protection is carried out. Usually, when a p-cycle is shared among multiple straddling links, the number of copies of the p-cycle is taken to be equal to the straddling link with the highest capacity. The major advantage of using the concept of a single p-cycle for double restoration is that, since the scheme requires only one p-cycle to help protect the xWSN against two simultaneous link failures, a significant reduction in the computational time demand and the number of variables required for arriving at solutions is realised. Also, the spare capacity is more efficiently utilised, especially if the average nodal degree of the network is considerably high. Thus, the possible improvement in the restoration solution capabilities that can be realised when single p-cycles are employed for restoring double simultaneous link failures makes the use of the concept an important consideration in modern xWSN designs.

In practical applications, the most significant improvements in the network restoration solutions for xWSN can be realised by combining multiple concepts that work hand in hand to achieve the best restoration solutions for the network. For example, if the concepts of p-cycle selectivity, load redistribution and the use of single p-cycles for double link failure restoration are combined, the improvement in resource usability and restoration capability for the xWSN can be very substantial. Therefore, it is recommended that as many improvement concepts as possible be incorporated into the network restoration model for xWSN, as long as the concepts can complement one another, and as long as the resulting complexity of the network is still within acceptable limits, especially in practical xWSN designs.

5. Results and discussion

In this section, we present some results to demonstrate the performance of the restoration model and the various improvement concepts incorporated and investigated in this paper. The xWSN for D2D communications is simulated as a test network of 100 SNs (which represent the devices in the D2D communication network) and 250 links between the SNs. The SNs are randomly deployed in a sufficiently wide geographical location. The packet switched traffic model is used for modelling the data traffic in the network. The packet switched traffic model is employed because it supports most internet protocol-based transmissions, and because it is a well-developed standard for machine-to-machine communications, of which D2D communications are part. One other scenario that could impact the range of the parameters used is the possible large size of practical xWSN. However, the model and parameters employed in the paper are quite scalable. Therefore, they are sufficient to represent practical applications of xWSN.

In the xWSN developed for D2D communications, the demand for nodes and links to be used for data transmission and network restoration between the N_s and the N_d is distributed in an even manner among all the nodes in the network. The network topology is varied slightly at different simulation runs for each nodal degree used. This is to help guarantee the accuracy of the solutions, and to eliminate any possible bias in the results obtained for the network. The network topologies employed have a highest average nodal degree of 4.0. The average nodal degree of 4.0 was used in the paper because of the need to compare with the reference works to help validate the model and results provided. Furthermore, an average nodal degree of 4.0 is quite commonly used for wireless sensor networks, therefore, it is considered best to apply it in this paper. Still, results that compare the model at an average nodal degree of 4.0 with similar networks having higher nodal degrees (5.0 and 6.0) were considered. As expected, the results show a similar pattern in the performance of the network, irrespective of the average nodal degree being employed. Since the results are very similar to the ones presented, they are not repeated for the sake of brevity.

The MATLAB software is used for simulating the network. Since the resulting problems are classical optimisation problems, the YALMIP solver – a MATLAB-based tool developed in [20] for solving classical optimisation problems – is employed to solve the problems. The processor used for carrying out the simulation runs at a speed of 3.2 GHz and has a random access memory size of 8 GB. In all cases, restoration solutions are obtained at an average runtime of a minute.

To achieve optimal restoration solutions for the xWSN designed for D2D applications, the restoration model investigated in this paper takes into consideration the possible shortest route between the N_s and the N_d for each network demand. Furthermore, the capacity costs are normalised to the lowest cost of achieving the network design. All topologies in consideration use a maximum of the average nodal degree of 4.0 in achieving their normalised capacity cost. Therefore, the data points plotted in the results presented can be seen as the results of the normalised total capacity cost of the optimal solution for the network.

In evaluating the performance of the p-cycle-based restoration model and the improvement in the restoration solutions realised through the various schemes incorporated, we present the results of the average path length and the total capacity cost for the network. The average path length is given as the number of links in the p-cycle that is selected and used for restoring the network. Thus, the average path length indicates the hop count of the p-cycles being employed for achieving network restoration. The total capacity cost is the sum of the costs of using the WPs and the RPs. The cost of using the WPs is usually known in advance by the network. The cost of the RPs is the additional cost incurred by employing the p-cycle(s) that are selected for network restoration. This cost is evaluated as the sum of the costs of all links on the p-cycle(s) being used for restoring the network.

The results presented in Fig. 3 act as a validation for our restoration model. To help validate the p-cycle-based restoration model for

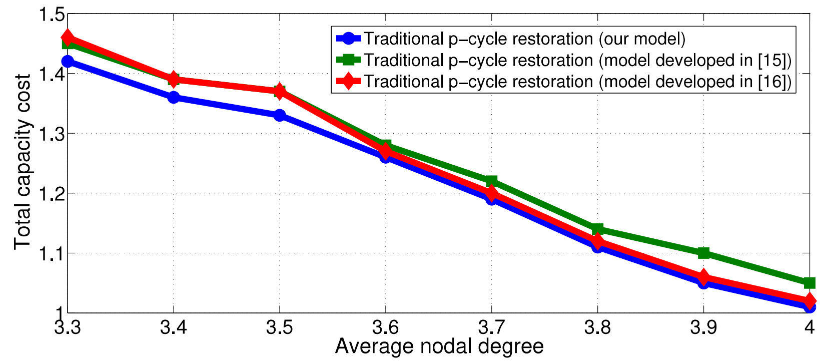

Fig. 3. Comparison of various traditional p-cycle restoration models.

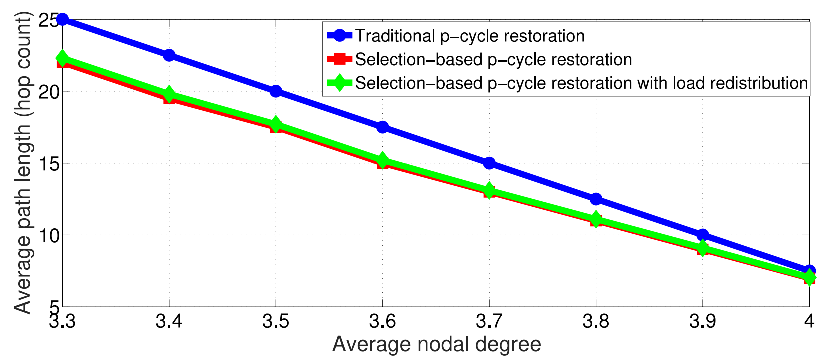

Fig. 4. Link failure restoration for xWSN using p-cycles. The average path lengths are compared for the different improvement schemes incorporated in the restoration model.

the xWSN developed in this paper, we compare the results of our restoration model with the possible closest p-cycle-based restoration models available in the literature. From an extensive search, the closest traditional p-cycle-based restoration models available are the models presented in [21,22], which developed viable p-cycle-based restoration solutions for wavelength division multiplexing networks. Comparative results in terms of capacity cost are thus presented in Fig. 3. We note that the results are very close for all the network restoration models compared. This establishes that the results from our p-cycle-based restoration model agree with traditional p-cycle restoration solutions, thereby validating our restoration model.

Fig. 4 presents the results of the average path lengths for the p-cycle restoration model for xWSN, as investigated in this paper. In terms of the average path length, the results for the traditional p-cycle restoration model obtained in this work are similar to the ones obtained in [23], which further validates the results. Furthermore, the plot in Fig. 4 compares the results of the average path lengths for some of the restoration concepts incorporated to improve the restoration solutions of the p-cycle restoration model for xWSN. Particularly, the results obtained from the introduction of the concepts of p-cycle selectivity and the load redistribution are compared with the results from the traditional p-cycle restoration.

From the results presented in Fig. 4, we note that the link failure restoration improvement concepts incorporated, alongside the traditional p-cycle-based link failure restoration, all achieve 100% link protection for the network. This means that any of the restoration concepts can indeed be successfully employed to provide the required p-cycle protection for each link in the network. More importantly, we observe that by incorporating any of the selection-based improvement concepts, that is, either the p-cycle selectivity concept or the load redistribution concept, the network achieves better results than by using just the traditional link restoration. The reason is that the selection-based schemes select the p-cycles that have a minimal number of hops from the set of possible p-cycles to achieve network restoration or protection against link failure. Therefore, by selecting the p-cycles that have a minimal number of hops, the time taken to complete data transmission is reduced, thereby improving the overall restoration performance for the network.

Fig. 5 presents the results of the total capacity costs for the restoration model developed in this paper. Furthermore, the plot compares the results of the total capacity costs for the various restoration concepts introduced to improve the restoration solutions of the p-cycle restoration model developed for xWSN. As the results show, the incorporation of the concepts of p-cycle selectivity, load redistribution, and the use of a single p-cycle for restoring double link failures all brought about a significant improvement in the capacity cost-efficiency of the p-cycles in comparison with the use of the traditional restoration scheme alone. This is because the selection-based schemes leverage their ability to select the most-appropriate p-cycles from the set of possible p-cycles in providing cost-effective protection for the network against link failures. Moreover, the selection-based scheme with load redistribution, because of the further improvement in the capacity realised through load redistribution, outperforms the ordinary selection-based restoration scheme in providing better efficiency in the capacity cost realisation for the network. Still, the highest improvement in the capacity cost is observed when the concept of a single p-cycle for double link failure restoration is used concurrently with the selection-based restoration concept and the load redistribution concept. The results prove that the combination of the right improvement concepts will always yield the best improvement in the restoration performance of the p-cycles being used for restoring xWSN from link failures.

Fig. 6 presents the performance of the selection-based restoration scheme with load redistribution when more than one limiting link is considered for load redistribution. In the plot, the case for double load redistribution (that is, the redistribution of loads on the two most-limiting links of the p-cycle) and triple load redistribution (that is, the redistribution of loads on the three most-limiting links of the p-cycle) are presented. The plot shows that as load redistribution is

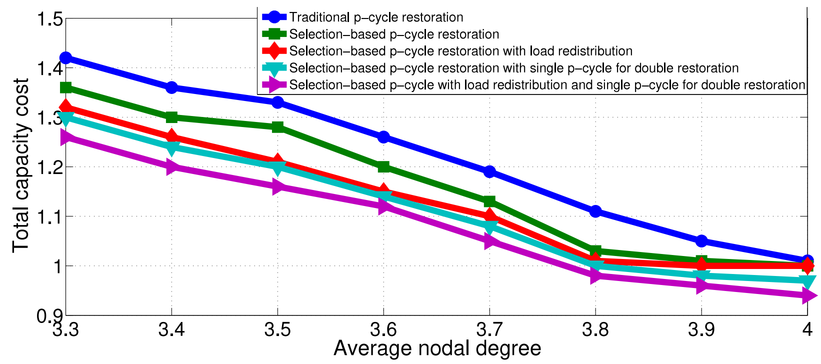

Fig. 5. Link failure restoration for xWSN using p-cycles. The total capacity costs are compared for the different improvement schemes incorporated in the restoration model.

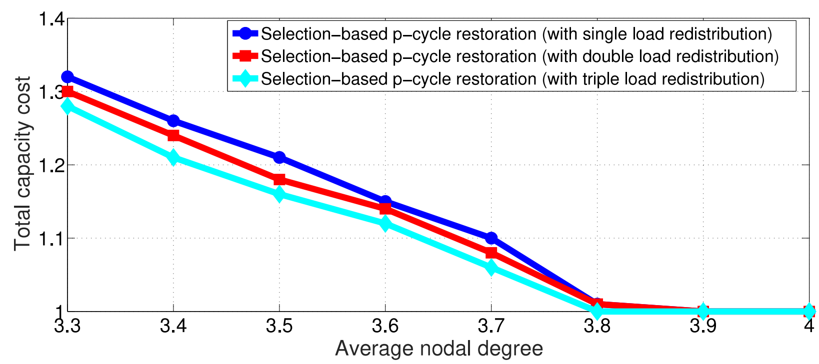

Fig. 6. The plot of the total capacity cost at different nodal degrees for the selection-based restoration scheme with load redistribution. The results for single, double and triple link load redistribution are presented.

carried out on more limiting links, further improvement in capacity cost solutions is realised. However, in practical terms, the feasibility of having the loads of more than one limiting link redistributed may not be guaranteed, as the xWSN may become too complex in design and analysis, given such considerations.

6. Conclusion

This paper has developed and investigated an appropriate p-cycle-based network restoration model for xWSN being employed for D2D communications. The p-cycle restoration model is employed because of the important advantages that p-cycles have over most other restoration mechanisms, especially because they provide adequate network restoration at very high speeds and optimal capacity. Further, a number of improvement concepts are advanced for the network restoration model for xWSN applications. The particular improvement concepts investigated are the concepts of p-cycle selectivity, load redistribution, and the use of a single p-cycle to achieve double failure restoration. The improvement in the capacity efficiency realised through the various concepts incorporated makes the restoration model an ideal model for protecting and restoring the xWSN against link failures in practical xWSN applications. It is noted that there could be several external parameters (such as an unexpected increase in network traffic demand) and external events (such as natural disasters) that may influence the probability of the occurrence of failures and the performance of the network restoration solutions that has been explored in this paper. The cases and impacts of such external factors have not been considered in this paper and would be explored in future works.

CRediT authorship contribution statement

Babatunde S. Awoyemi: Conceptualisation of ideas, Methodology development, System modelling, Visualisation, Investigation, Analysis, Simulation, Writing – original draft. **Bodhaswar T. Maharaj:** Conceptualisation of ideas, Methodology development, System modelling, Visualisation, Investigation, Analysis, Writing – reviewing and editing, Supervision, Validation.

Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to https://doi.org/10.1016/j.array.2022.100147.

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