The Economy of Redundancy in Wireless Multi-Hop Networks

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***Abstract*—Due to frequent link failures in multi-hop wireless networks, redundancy can be an important feature. For example, when planning the structure of a backhaul mesh network for public access, it is common to introduce redundant nodes in the mesh network. These are called redundant, because they do not increase the network capacity under normal operation, due to the shortest-path metric of the routing protocol. Instead, their sole purpose is to increase the network reliability by providing failover links when a link in the shortest-path fails. This paper shows how to estimate the optimal number of redundant nodes for a given topology. In order to do so, a method to calculate the additional network reliability that results from introducing a redundant node to a given topology is also proposed.**

I. Introduction

A wireless multi-hop network (often referred to as an *ad hoc network*) is a network composed of a group of nodes interconnected via wireless links. The network implements a routing protocol so that nodes can communicate with each other over multiple link hops. The nodes in such networks are normally self-configured and self-organised. Examples of such networks include wireless mesh networks [1], mobile ad hoc networks (MANETs) [2] and wireless sensor networks (WSNs) [3].

A wireless mesh network (hereafter referred to as a *mesh network* or a *mesh*) is often thought of as a wireless multi-hop network of static nodes intended to form a backhaul network that ensures connectivity between some nodes in the mesh and a fixed infrastructure. The nodes of a MANET, on the other hand, are often assumed to be mobile. Unlike meshes and MANETs, WSNs are composed of sensor nodes. Although the methods presented in this paper are generally applicable to any of these networks, they fit best to static wireless multi-hop backhaul networks. Our analysis therefore uses examples from mesh networks when the proposed methods are presented.

The most popular mesh technology nowadays is based on the IEEE 802.11 standard [4], and its specification can be found in the IEEE 802.11s draft extension to 802.11 standard. However, there are also several other solutions for mesh networking, e.g. based on other technologies, such as IEEE 802.16 (WiMax) [5], and the presented methods are also applicable to these technologies.

According to the terminology of the IEEE 802.11s specification, a node in the mesh is referred to as a *mesh point* (MP). An MP is referred to as a mesh access point (MAP) if it includes the functionality of an 802.11 access point allowing regular 802.11 stations (STAs) to connect to the mesh infrastructure as clients. Furthermore, an MP is referred to as a *Mesh Portal* (MPP) if it has additional functionality for connecting the mesh network to other network infrastructures.

There are many promising applications of mesh technology. A large group of applications appears as a consequence of the high costs associated with interconnecting the MPs (i.e. routers) with wired links. With mesh technology it is possible to extend the reach of the wired backbone through a wireless backhaul mesh of MPs in a cost-efficient manner. Currently, there are a large number of commercial deployments of such solutions for public access in urban areas, where the nodes are often placed on roof-tops.

Such backhaul mesh networks are normally not formed in an ad hoc manner. Instead, the location and placement of each MP, MPP and MAP is carefully planned (*network planning*). Since the reliability of such mesh networks often is poor and a considerable barrier for wide deployment, it is common to introduce redundant MPs in the network in order to improve network reliability.

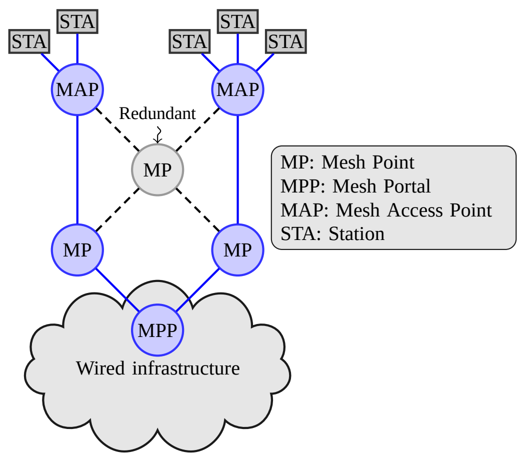


Figure 1. A backhaul mesh network with a redundant node.

Figure 1 illustrates the introduction of a redundant node in a backhaul mesh network. In normal operation, each STA is connected to a MAP, and the STA's traffic is forwarded along the shortest path between the MAP and the MPP. However, if a link in the shortest path becomes unavailable, the routing protocol ensures that a new path between the MAP and the

MPP is formed via the redundant node.

Note that due to the shortest-path feature of the routing protocol, there is no load-sharing on the network. This means that the introduction of the redundant node does not increase the overall throughput of the network. Its main function is to improve the network reliability. Thus, in our study, we are solely concerned with the connectivity measures of a wireless mesh network, while other network performance metrics, such as throughput and delay, are not relevant here.

For many mesh networks, including commercial backhaul mesh networks in urban areas (e.g. roof-top mesh networks), there is a high site-acquisition cost associated with each node, and it is not economically feasible to introduce too many redundant nodes. Instead, one needs careful network planning in order to estimate the optimal number of redundant nodes.

The network planning should include a cost-benefit analysis, where the value of the additional network reliability of adding a redundant MP is weighted against the additional costs (including equipment cost, installation cost, site-acquisition cost and operational cost) of adding the node. The paper demonstrates how the optimal number of redundant nodes can be found.

While the cost of adding a redundant node is normally easy to forecast, it is more difficult to forecast the additional reliability of adding the node. The main reason is that little have been published about network reliability for mesh networks. Thus, the benefit in terms of improved reliability of adding a redundant node is unknown for the network planner. In order to estimate the optimal number of node, a method to determine the additional availability of adding redundant nodes is also presented.

Another component of network planning is to also find good locations for nodes, including the redundant nodes. Applying common sense, it is clear that there are certain mesh topologies that are less favourable than others with regards to reliability and availability. This problem is out of scope in this paper. Instead, it is assumed that the locations to place the nodes are limited, so that all nodes of the mesh network (i.e. both core nodes and redundant nodes) should be placed in some predefined possible locations.

The rest of the paper is organised as follows: Section II argues that the economy of redundancy depends on the type of traffic that the network is carrying. Reliability and availability metrics for a mesh network are presented in Section III. In Section IV the effect of redundant MPs in a backhaul mesh network is evaluated for a given topology. Based on the evaluation of this topology, the optimal number of redundant nodes is found in Section V. Finally, the related work is summarised in Section VI before the paper is concluded in Section VII.

II. Background

A. The Economy of Redundancy

While *reliability* normally refers to the full time-dependent connectivity behaviour of a network, i.e. both the transient behaviour and the steady-state behavour, *availability* normally refers only to the time-independent (steady-state) part of the reliability behaviour. The availability gives the share of time the network is up (i.e. the ”uptime” of the network), but it does not provide insight into the mean time to failure (MTTF) given that the network is connected at time t = 0 or the mean time between failures (MTBF).

For simplicity, this paper studies the economy of redundancy only in the context of the time-independent availability measure. The economy of redundancy also depends on a number of other factors. For example, it might depend on the time-dependent reliability, user perception and so forth. Extending the analysis also to take the time-dependent reliability or other factors into account, is left for further work.

The MTBF depends on the rate, λ, of the occurrence of link failures on connected links, as well as the rate, μ, of link repairs on disconnected links. In wireless radio networks with static nodes, link failures and repairs may occur at a high rate, due to the swift variation in the radio conditions, resulting from transmission collisions, interference, fast fading, etc. Thus, both λ and μ are often relatively high in these networks, compared to links in fixed networks

A fundamental basis of the analysis presented in this paper is the observation that different kind of traffic has different capability of accepting short-term link failures. To exemplify this point, this paper makes a distinction between *voice* and *data* traffic. The former is typically real-time, synchronous and delay sensitive communication, while the latter is often the opposite.

Voice traffic is typically nearly useless when the share of the packet loss is high or when a high share of the packets or a packet trains gets significantly delayed due to temporary link failures. Data traffic, on the other hand, is able to handle lost and delayed packets or packet trains much better. An UDP-based asynchronous instant messaging service, for example, would allow for quite high delay and jitter, and could implement retransmission strategies to allow for a significant share of packets being lost. TCP-based data communications are also quite tolerant to temporary loss, delay and jitter.

In summary, the usability of a network - or in economical terms *the value of the networking service* - depends on the type of traffic that is primarily sent over the network. This is illustrated in Figure 2. If the mesh network is installed as a backhaul link for mobile/cellular networks, the network is expected to carry primarily voice traffic, and the *voice* curve is relevant. The curve illustrates that the backhaul network is nearly useless until the short-term availability approaches 100%. Otherwise, the codecs can fail, and the user experience will be poor. If the mesh network is installed for data traffic, on the other hand, a low short-term availability will not make the services useless; it is only the average data rate that will be perceived as low. For many services, having a low data rate is certainly better than having none. The *data* curve illustrates that the usability increases steeply from zero availability to some availability, and ends up at full usability at a 100% short-term availability.

The term *normalised value* in Figure 2 is deliberately quite

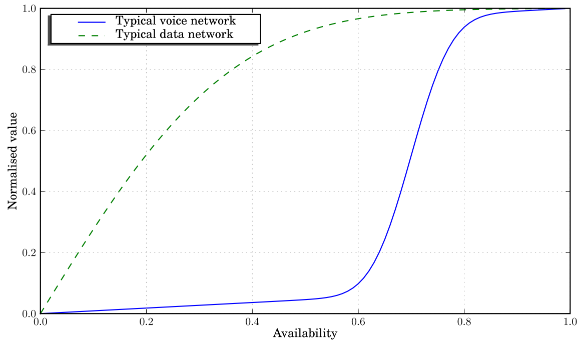


Figure 2. How the usability (value) of different types of networks varies with the network availability.

vague, and might have many meanings. By using the term *value*, it is assumed that the usability of the network - or the lack of usability due to a low availability - can be estimated in monetary terms. In Figure 2, *value* might mean the revenue that the networking service is generating on a periodic (e.g. daily, monthly or yearly) basis or the accumulated *net present value* found by using discontinuation of the revenue over a number of years [6]. Later in the paper, *value* is not only referring to the revenue but also to the costs, e.g. the negative periodic (e.g. daily, weekly or yearly) costs or the accumulated costs in terms of the negative net present value. The analysis is independent of how the term *value* is defined, however, the *revenue* and *costs* must be defined consistently over the same periodic time span.

The *normalised* value of the revenue, means that the value is normalised relative to the full revenue that would be generated at an availability of 100% (i.e. the normalised value is 1 at an availability of 1). Later in the paper, the term *normalised value of the costs* will also be used. Since fixed costs and other node-independent costs do not influence the results of the analysis (i.e. these costs do not affect the optimal number of nodes - they only affects whether the network investment is economically profitable or not), the costs can be *normalised* in a number of ways.

Before the economy of redundancy with respect to the short-term availability can be analysed, a method to calculate the reliability and availability of a network must be found. This will be presented in the following sections and in the subsequent chapters. Then, at the end of the paper, these results are used to estimate the economy of redundancy for a given network topology.

III. The Reliability and Availability of Backhaul Mesh Networks

A. The reliability of a mesh network

Due to the routing protocol's ability to deal with dynamic link failures, the mesh network does not fail to provide connectivity between two nodes, before the mesh network is considered as disconnected.

When analysing the degree of connectivity of a wireless mesh, the network is modelled as an undirected graph *G*. The graph is composed of the nodes $v_j \in S$, where the nodes v_j serve as vertices. Any of two distinct nodes v_j and v_i create an edge $e_{i,j}$ if there is a link between them.

A minimal set of edges in the graph whose removal disconnects the graph is an *edge cutset*. The minimum cardinality of an edge cutset is the *edge connectivity* or *cohesion* $\beta(G)$. A (minimal) set of nodes that has the same property is a *node cutset*, and the minimum cardinality of this is the *node connectivity* $\chi(G)$.

To provide an adequate measure of network reliability, one has to use probabilistic reliability metrics and a *probabilistic graph*. This is an undirectional graph where each node has an associated probability of being in an operational state, and likewise for each edge. For our analysis of mesh networks we assume that the nodes $v_j \in S$ in the topology are invulnerable to failure. Furthermore, we assume that a link $e_{s,d}$ connecting two nodes v_s and v_d fail independent from $e_{i,j} \in S \backslash \{v_s, v_d\}$.

B. Using the k-terminal reliability as a connectivity metric

Consider a mesh network, G, that works as a backhaul mesh network and includes $k-1$ different distribution nodes d_i in D, $D = (d_1, d_2, ..., d_{k-1})$, and one root node r. According to our previous terminology of IEEE 802.11s, a distribution node corresponds to a MAP in an IEEE 802.11s network, while the root node corresponds to an MPP (Figure 1).

Under normal network operation, transit traffic in the network is directed along the shortest path between the root node r and each distribution node, d_i in D. If any distribution node is disconnected from the root node, the network has failed, as it is not operating as intended. Thus, the network planner should consider the network as fully operational only if there is an operational path between the root node and each of the distribution nodes. This is true if, and only if, k nodes, consisting of the root node r and the $k-1$ distribution nodes are all connected. The *k*-terminal reliability is exactly the metric addressing this. It is defined as the probability that a path exists and connects *k* nodes in a network:

$$P_c^{r,d_1,\cdot\cdot,d_{k-1}}(G) = 1 - \sum_{i=\beta}^{\epsilon} C_i^{r,d_1,\cdot\cdot,d_{k-1}} (p)^i (1-p)^{\epsilon - i} \quad (1)$$

where $C_i^{r,d_1,\cdot\cdot,d_{k-1}}$ denotes the number of edge cutsets of cardinality i and p denotes the probability of a link being down. *In summary, the network planner should analyse the reliability of the network using the k-terminal reliability in Eq.(1).*

C. The network availability

The network reliability [7] is defined as the probability that a network G is disconnected at a time $t = t_a$, given that it was not disconnected at the time $t = 0$, and incorporates the transient behaviour of the network. The network availability, on the other hand, is the steady-state probability that the network is not disconnected as $t \to \infty$. For a network planner, the network availability is an important reliability measure because it says how big share of the time the network is operational.

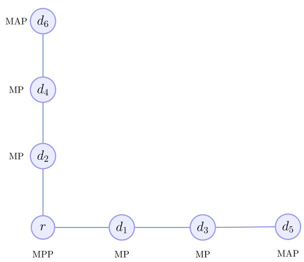
Let us assume that link failures on operational links and link repairs on failed links are both exponentially distributed with a failure rate parameter λ and a repair rate parameter μ, respectively. Then, at steady-state, the probability of a link being down, p, is:

$$p = \frac{\lambda}{\mu + \lambda} \tag{2}$$

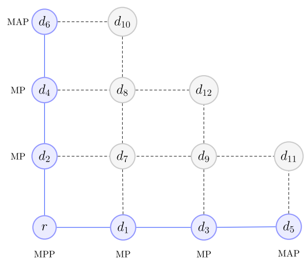
Thus, the k-terminal availability can now be found by inserting the steady state link failure probability p in Eq.(2) into the expression for the k-terminal reliability in Eq. (1).

IV. Example of an Availability Analysis

This section considers an example topology where two MAPs are distributed and connected to a MPP over a mesh network (Figure 3(a)). A network planner would normally be mostly interested in finding the availability for the service provided by the MAPs. The availability is found as the steady-state condition of the three-terminal reliability P_c^{r,d_5,d_6}.



(a) Initial core topology



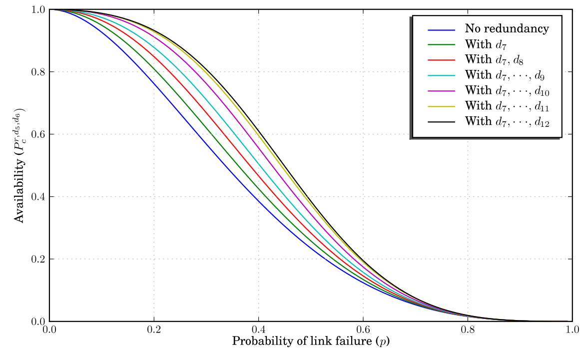
(b) Topology with redundant MPs

Figure 3. Topology with or without redundant MPs

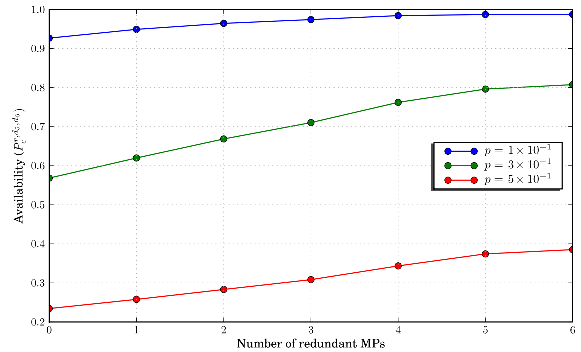
In the network planning phase, a cost-benefit analysis needs to be performed in order to compare the additional cost against the improved reliability introduced by a redundant MP. Ignoring the cost factor of adding redundant MPs, Figure 4(a) shows the calculated availability and the effect when an extra MP is added to the network. The redundant MPs are added in a particular order, $d_7, \cdots, d_{12}$ (Figure 3(b)).

Figure 4(a) illustrates how the availability is dependent on the probability of a link failure, and how the availability is increasing as redundant nodes are added. We observe that adding MP d_{12} results only in a negligible improvement to the availability at any value of p, since at this point, all the nodes in the backhaul have at least two links on which their service can be reached. Adding d_{12} does not change the number of links connecting the backhaul, and d_{12} can therefore be removed from the network without any noticeable loss of availability.

Figure 4(a) indicates that the effect of adding redundant MPs is greatest for a probability of link failures in the approximate range $p \in [0.1, 0.5]$. Figure 4(b) considers this probability range and show the availability increases as redundant MPs are added, providing a clearer picture of how redundant nodes improve the availability.



(a)



(b)

Figure 4. The availability depends on (a) the link failure probability p, and (b) the number of redundant nodes.

V. Analysis of the Economy of Redundancy

A. Value analysis

In this chapter the economy of redundancy is analysed by estimating the optimal number of redundant nodes in the topology in Figure 3(b) from an economical perspective. It is assumed that the network planner is able to forecast how the revenue of the network will be affected as the network availability is degrading from the ideal revenue of a 100% network availability. Furthermore, the *voice* and *data* curves of Figure 2 in section II-A are used to exemplify how a network planner would estimates the relationship between usability and availability of a voice network and a data network, respectively. The definitions of *value*, *revenue* and *costs* are as explained in section II-A.

Combining the curves in Figure 2 with the availability results for $p = 0.3$ in Figure 4(b), illustrates how the revenue (or more specifically the normalised value of the revenue) of the network depends on the number of redundant nodes. The resulting *revenue of voice network* curve and *revenue of data network* curve are shown in Figure 5. For simplicity, the revenue value of the network is set to zero when the network has fewer than 7 nodes This is because with fewer than 7 nodes the network planner will not be able to realise the core network, i.e. the original network without any redundant nodes. However, setting the value to zero here does not affect the overall results of the analysis.

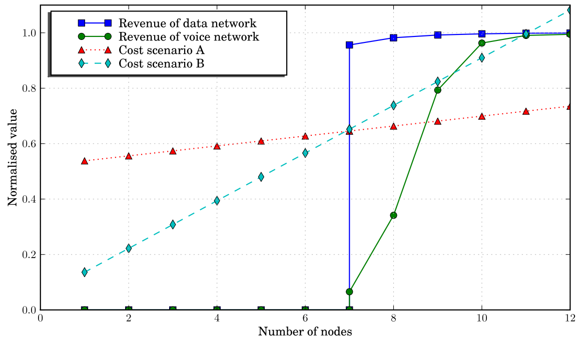


Figure 5. Both the revenue and the costs vary with the number of nodes.

Figure 5 also shows two cost curves. In terms of a varying number of nodes, the costs can be divided into two types, (i) costs directly associated with each node referred to as *node-dependent costs* and (ii) other costs referred to as *node-independent costs*. Examples of node-dependent costs include site acquisition costs, site operational and maintenance costs, site utility costs, capital costs associated with investment in the site equipment, and so forth. The node-independent costs are all other costs, including fixed costs and variable costs that vary as a function of other variables than the number of nodes.

The Figure 5 includes two cost scenarios, represented by the curves *Cost scenario A* and *Cost scenario B*. Cost scenario A is a scenario where the node-independent costs are dominant. This scenario might apply to a campus network without site acquisition costs and where the nodes are relatively inexpensive access points. Cost scenario B, on the other hand, is a scenario where the node dependent costs are dominant. This scenario might apply to a public access network where the node equipment often is expensive and/or where the site-related costs are significant. Both curves increase linearly with the number of nodes, which is quite natural. However, the method presented here might accommodate a non-linear dependency between the costs and the number of nodes.

B. Finding the optimal number of redundant nodes

Figure 6 shows the net value for Scenario A. This is derived by subtracting the cost curve in Figure 5 from the two revenue curves in the same figure. The figure shows that the optimal number of nodes for the topology in Figure 3(b) is eight nodes (i.e. one redundant node) for the data network example and 11 nodes (i.e. four redundant nodes) for the voice network detail.

The cost scenario B, which is illustrated in Figure 7, shows that it is not economically reasonable to deploy any redundant nodes at all for the data network, while the net value of the voice network is highest with three redundant nodes.

In summary, the economy of redundancy can be found using the methods presented in this paper, and it is economically sound to add a redundant node to a given topology as long as the marginal revenue of adding the node exceeds its marginal costs [6].

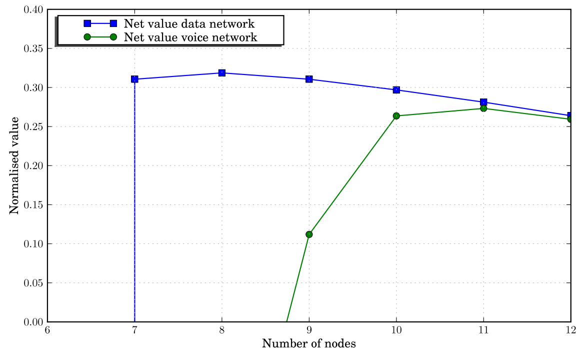


Figure 6. The net value of the network using the cost curve of Scenario A in Figure 5.

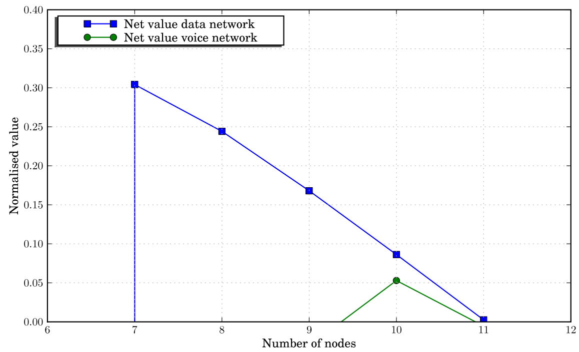


Figure 7. The net value of the network using the cost curve of Scenario B in Figure 5.

VI. Related Work

To the best of our knowledge, there is no work published on methods to determine the optimal number of redundant nodes with respect to network availability in a wireless multi-hop network. However, the curves in Figure 2, which forms a basis for this analysis, resemble the curves presented by Scott Shenker in 1995 [8]. He argued that the usability of a network as a function of the data rate depends on the type of traffic - much in the same way as shown in the figure. At a low data rate, the voice traffic will be nearly useless, while the usability curve of the data traffic increases steeply as the data rate increases from zero. Using the same type of curves, he argued that the necessity of admission control depends on the type of traffic in the network. A network carrying primarily voice traffic will benefit from quality of service with admission control, while this there is few economical arguments for deploying admission control when the network carries primarily data traffic. Some researchers have claimed that Scott Shenker *"was the first to give a correct analysis of the economy of quality of service"* [9].

The method for finding the optimal number of redundant nodes depends on the method for finding the network availability for a given network topology. There is only a limited number of studies on network reliability of wireless networks.

The early work in [10] analyses radio broadcast networks showing that computing the two-terminal problem for these networks are computational difficult. The work in [11] deals with the problems of computing a measure for the reliability of distributed sensor network and for the expected and the maximum message delay between data sources. The two-terminal reliability of ad hoc networks is computed in [12]. This work focuses on the reliability of nodes and on the effects of node mobility, while the effects of link reliability in static topologies - which we investigate in this paper - are not considered.

For fixed networks, on the contrary, there have been several studies on two-terminal reliability for wired networks [13][14][15]. The results from most work on network reliability of fixed networks are not generally applicable to wireless networks. The main reason is that in fixed networks the probability of a link failure is so low compared to the probability of a node failure, that in the analysis it is common to consider the link as invulnerable to failure. In wireless networks, on the other hand, link failures occur frequently due to the inherent characteristics of the radio channel, such as radio fading, signal attenuation, radio interference and background noise. The link failure frequency is normally so much higher than the node failure frequency that it is natural to model the nodes as invulnerable to failure, and only focus only on the link failures in the analysis.

In [15], however, link failures in fixed ring or double ring network structures are analysed. The work focuses on the design of a physical network topology that meets a high level of reliability using unreliable network elements. It is shown that for independent link failures, network design should be optimised with respect to reliability under high stress, as reliability under low stress is less sensitive to network topology.

There are several other reasons why fixed network analyses are not applicable to wireless networks. For example, in fixed networks a link monitoring mechanism, or a *Link Integrity Test* operation is often used to identify if a link has failed, while there is no equivalent to this in wireless networks.

VII. Conclusions and Future Work

This paper presents a method to estimate the benefits of adding redundant nodes from a network planner's point of view, assuming that the network planner will have to take economy into considerations as part of the decision making. By example, it is demonstrated how the optimal number of redundant node for a given topology can be found. To the best of our knowledge, no previous work has been published on this issue.

Furthermore, the paper also investigates the reliability and availability of wireless multi-hop networks, since this is a prerequisite for doing the aforementioned *economy of redundancy* analysis. To the best of our knowledge, also this has not been studied in previous works.

Our results show how redundant nodes improve network reliability, and also how the introduction of a limited number of redundant nodes increase the net value of a network. Although analyses and results depend on the actual topology, the same analyses as presented here can be applied to any wireless multi-hop network topology of interest.

While the network availability is a useful reliability measure, it does not provide a full picture of the network reliability, since it is a steady-state measure. For example, it could be interesting to make a defined distinction between the short-term availability and the long-term availability of a mesh network, and conduct the same kind of analysis in this context. To estimate such time-dependent measures, one needs to first study the transient behaviour of the k-terminal reliability. We plan to address this in future work.

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