Link and Route Availability for Inter-working Multi-hop Wireless Networks.

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Abstract— **In inter-working multi-hop wireless networks, establishing resilient connectivity between source-destination node pairs is a major issue. The issues of connectivity in multi-hop wireless networks have been studied. However these analyses focused on network connectivity in ad-hoc networks. Since the next generation of wireless networks will be inter-working, an understanding of connectivity as it applies to such networks is needed. Specifically, this research emphasizes that the connectivity of node pairs in inter-working multi-hop wireless networks can be evaluated based on the availability and reliability of radio links that form the communication path linking the nodes. This paper presents an analytical study of the link and route availability in inter-working multi-hop wireless networks.**

Keywords-Availability, Connectivity, Inter-working, Multi-hop, Wireless Network.

I. INTRODUCTION

Inter-working is a term which refers to the seamless integration of several networks. A lot of benefits can be gained from the inter-working of wireless networks. Firstly, inter-working increases the service area coverage and network capacity, thereby enabling last mile broadband Internet access. Inter-working also enables seamless fusion and inter-operability between wireless networks. Secondly, though the competition between wireless networks and broadband technologies such as the cable, xDSL, and broadband wireless local loop is stiff, yet inter-working several wireless networks provides a viable alternative [1]. Thirdly, inter-working provides ubiquitous and low cost Internet access to users. It also eases the provisioning of Internet access in areas with no initial wire-line network coverage e.g. rural areas. Lastly, through inter-working, network users can have access to any service any time and any where using any network.

Different wireless access networks offer different data rates and cover different distance ranges [2]. Therefore, in order to guarantee a truly seamless inter-working, a strong connectivity must be ensured between these networks.

Connectivity is a fundamental property of any wireless network. Normally, in all networks, links are the basic element that ensures connectivity. In wired networks, links are readily provided by the communication cable and these links are stable and predictable. However, in wireless networks, links are provided by the air interface (wireless channel).

Generally, in wireless networks, nodes have to be within appreciable distance of each other before a communication link can be established between them. Any node that is not within the recommended range is said to be out of the network. In single hop wireless networks, it is sufficient for each node to be in the transmission range of at least one of the centralized base station to communicate with another node. On the other hand, in multi-hop wireless networks, if source-destination pairs are not within each other's transmission range, packets reach their destination nodes after some hops on nodes in between the source and destination. An advantage of multi-hop communications is that it ensures efficient spatial re-use.

In multi-hop wireless networks, the choice of the next hop depends on the availability of a link between intermediate node pairs. Most importantly, an available link must also be reliable for a good quality communication to be established between node pairs. One major characteristic of the wireless channel that affects the quality of communication is the variation in its strength over time and frequency. As a result of the variation, communication links in wireless networks tend to be unpredictable. Moreover, this variation affects the connectivity between two communicating nodes.

Another factor that affects connectivity between two communicating nodes is mobility. Since mobility may cause radio links to be broken frequently, a critical issue is for nodes in the network to be able to communicate on links that can last as long as the required packet transmission duration. Therefore the link between node-pairs has to be strong enough to ensure a lasting connectivity.

The developments of the theory of connectivity in wireless networks have been done in recent research works. However, most of the theoretical and analytical investigations have been developed with ad-hoc and sensor networks in mind [3-8].

In these research works, the issue of connectivity in wireless multi-hop networks has been studied by characterizing the wireless channel with simple models. These models state that node pairs can only be linked together if the distance between them is not greater than their transmission range. Such models are only sufficient as long as deterministic distance-dependent channel models are considered [9]. Unfortunately, wireless channels are not deterministic in nature, so these models are not realistic.

A wireless channel should be modeled in a more practical manner by considering the characteristics that induces randomness into the channel. Such characteristics include the attenuation, interference, bit error etc. [10] [11] showed that accurate modeling of the physical layer is indeed important in network-level research on wireless multi-hop networks. Furthermore, in order to ensure optimal resource allocation and quality of service for packet transmission in multi-hop wireless networks, an understanding of connectivity as it relates to the QoS metrics in networks is needed. Therefore, connectivity between two nodes in wireless networks does not only depend on the transmission range between node pairs as evaluated in previous research works.

This research studies the theory of connectivity in inter-working multi-hop wireless networks. The main contribution of this research is to provide a further development of the analysis of connectivity between any node pair by including the quality of wireless links between them. The quality of the wireless links is determined by the physical layer QoS metrics. Specifically, this research emphasizes that the connectivity of node pairs in inter-working multi-hop wireless networks can be evaluated based on the availability and reliability of radio links that form the communication path linking the nodes. The first part of this research is based on the analysis of link and route availability while the second part of the research is based on the analysis of the link and route reliability.

In a wireless network, a link's availability depends on the distance between two node pairs and a link's reliability depends on the link's quality. These measures are based on probability since the wireless network is stochastic network. So, the probability of connectivity between node pairs in a network depends on the probability that a link is available and reliable. In addition, the probability of connectivity on a route with specific number of hops depends on the availability and reliability of links on that route. Availability means that two node pairs are within at most the maximum transmission range that is sufficient for a communication link to be established. Reliability means that the radio attributes of a link satisfies the minimum requirement for successful communication in a wireless network.

In particular, this paper presents only the first part of the research, which is the analysis of the inter-dependency that exists between link availability and route availability in multi-hop wireless networks. Note that in this paper, a link refers to the connection between any node pair in the network, while a route refers to the last mile connection path between a source and destination pair.

For this investigation, the fundamental models needed to represent the inter-working multi-hop wireless network are:

1) A model for the spatial distribution of nodes- this represents and gives a notion of how nodes are distributed in the network.

- Nodes are independently located and the average density of the nodes is uniform throughout the network.

2) A model for the transmission range between nodes- this shows if a link exists between any two nodes in the network.

- The maximum transmission range of any node is R. An independent communication link is available for any two nodes within a distance less than or equal to R. The model gives the probability that a node in the neighborhood of any other node is at a distance less than or equal to R. If β is the distance between any two nodes, a link is available between the nodes as long as β is less than or equal to R.

3) A model for the characteristics of the wireless channel between any two nodes- this shows whether the link that exists between the nodes can transmit packet reliably or not.

In section II, the node distribution and the node degree models are described. The analysis of the link distance distribution model and the link and route availability models are presented in Section III, while section IV concludes the paper.

II. NETWORK MODEL

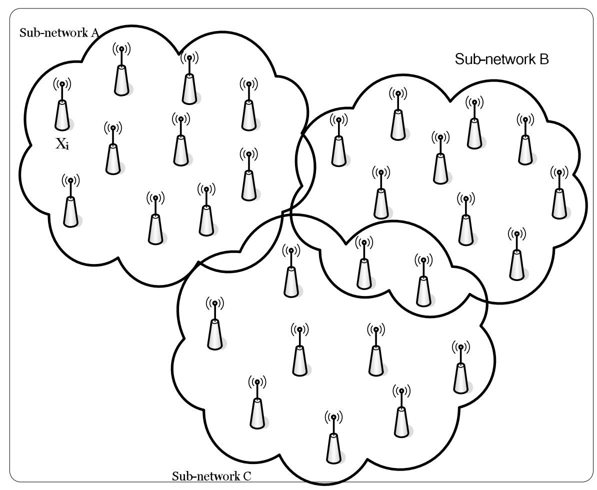

Figure 1. Network Ω

The network (Ω) in fig 1 represents a set of inter-working wireless networks. Network Ω contain three subset networks (sub-networks) A, B, C. The total number of nodes in Ω is denoted N_{Ω}, while the number of nodes in each of these sub-networks A, B, C are N_a, N_b and N_c respectively, where $N_a + N_b + N_c = N_{\Omega}$ and $N_a = N_b = N_c = N$ (i.e. the sub-networks contain the same number of nodes). Each of the nodes have the same transmission capability and packets are transmitted from the source node towards the destination node via a multi-hop path.

A. Node Distribution Model

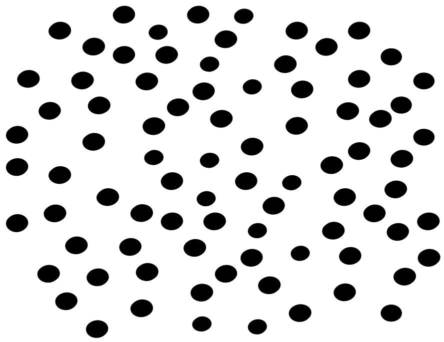

Figure 2. Spatial Point Pattern.(try to redraw in visio)

Consider each sub-network in fig.1 as a collection of random points (nodes or data or events) whose realization is called a spatial point pattern as shown in fig.2. These nodes are contained in a Euclidean space of 2-dimensions (R^2), and their positions in the network are independent of each other. The lack of dependence between these nodes is called *complete spatial randomness (csr)* [12]. From theory, these nodes can be said to form a realization of a Planar Homogeneous Poisson Point Process. With regards to the analysis of spatial point pattern, the distribution theory of such points (nodes in this case) under complete spatial randomness is well known under the theory of the Nearest Neighbor Distance (NND). These theories are used to analyze point patterns in biological sciences and are also applicable to wireless networks [4]. Note that the distance between a node and its closest neighboring node is the nearest neighbor distance.

In any of the sub-networks in fig. 1, nodes are independently and randomly placed on this 2-dimensional space with area A. Therefore, for each sub-network, the node density ρ=N/A (number of nodes per unit area). These nodes are distributed randomly within the area A of each sub-network.

The maximum transmission range of each of the nodes is R and the distance between any two nodes, Xi and Xj ($\forall i, j \in Z \text{ and } i \neq j$) in the network is represented by d(Xi,Xj) = $|x_i-x_j|$. x_i and x_j represent the location of nodes Xi and Xj respectively. In a multi-hop wireless network, two nodes are able to communicate with each other if $|x_i-x_j| \leq R$ [4]. However, the probability of connectivity between two nodes is not only dependent on the distance between them, but also on the physical attributes of the link.

1) Node Degree

As a prelude to the link distribution model in the next section, this sub-section gives an overview of the node degree concept as applicable to wireless networks.

The degree of any node in a wireless multi-hop network is defined as the number of neighboring nodes that it is able to set up a link with directly [13]. A node is said to have neighbor nodes if the distance between the node and each of its neighbor nodes is less than or equal to its maximum transmission range. Therefore, node degree can also be the number of neighbor nodes within a node's transmission range.

The node degree of a node Xi is denoted by D (Xi). In an instance where for a node, D (.) = 0, the node is termed a "lone node". The existence of a "lone node" in a multi-hop wireless network is an undesirable condition. For a static multi-hop wireless network, this type of node is totally useless to the whole network in terms of connectivity. However in a mobile scenario, a lone node becomes useful as it moves into the transmission range of another node or when another node moves into the node's transmission range. The desirable condition for any multi-hop wireless network is to have D (.) for all nodes greater than zero i.e D (.) > 0. The probability that D (.) > 0 for any node pair is the same as the probability that a link is available for the node, and the probability density function is given by equation 1.

$$P(D(.) > 0) = P(link\ availability) = \int_{o}^{R} f(x)dx \qquad (1)$$

where R is the transmission range of the node. The function in equation 1 depends on the distribution of the nodes in the network.

III. AVAILABILITY

A. Link Distance Distribution Model

In multi-hop wireless networks, the probability that a multi-hop communication path is available is related to the availability of the individual links that make up the path. Therefore, it is important to analyze the distribution of the link distances between nodes in multi-hop wireless networks [14].

Let β denote the NND of a randomly chosen node. For any two nodes, Xi and Xj, $\beta=|x_i-x_j|$, $\forall i, j \in Z^+, i \neq j$. With theorem 1 given below, the probability that β is greater than R can be evaluated.

Theorem 1: *For a Homogeneous Poisson Point Process in* $\Re^2$ *(two dimensional plane), the probability that there are no point within a distance y of an arbitrary point (p) is* $e^{-\lambda \pi y^2}$, *where the parameter* λ *is the expected number of points per unit area [12, pg 636].*

The above theorem applies to any of the three sub-networks in fig. 1 in the following ways:

1) For an arbitrary node in any of the three sub-networks, the probability that there are no nodes within a distance β ≤ R, (probability that a node has no neighbor/probability that a node is a lone node) is:

$$P(D(.) = 0) = P(\beta > R) = e^{-\rho \pi R^2} \text{ for } R > 0 \qquad (2)$$

where ρ is the number of nodes per unit area of each of the sub-network.

2) Also, for an arbitrary node in any of the three sub-networks, the probability that the distance between a randomly chosen node and its nearest neighbor node is less than the

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node's transmission range R (the probability that a node has at least one neighbor) is:

$$P(D(.) > 0) = 1 - e^{-\rho\pi R^2} \quad \forall \text{ R} > 0 \tag{3a}$$

$$P(\beta \leq R) = \begin{cases} 1 - e^{-\rho\pi R^2} & \forall \text{R} > 0, \\ zow & \end{cases} \tag{3b}$$

Equations 3a and 3b only hold as long as beta is less than or equal to R. R is the maximum distance for which communication can occur between any two nodes.

Equation 3b represents the cumulative distribution function (CDF); (F_β(R)) of the distance between any two randomly positioned nodes in any of the sub-networks in fig. 1. It also represents the probability that a link is good. Assuming that links fail independently, this quantity can be taken as the probability of success in a binomial trial. If the trial is repeated N times, then an estimate of the number of good links is given is N × F_β(R) [14]

B. Link Availability

As long as β≤ R, a link is available between any two arbitrary nodes [15][16]. Therefore, the CDF (F_β(R)) of the link distance β can be taken as the probability that at least a link is available for transmission. Thus, the availability of a link in a network is a function of the transmission range and the number of nodes in the network. P_{link} is the availability of a 1-hop link for any arbitrarily chosen node.

A node becomes a lone node (no link is available) once β>R

$$\therefore P_{link} = \begin{cases} 1 - e^{-\rho\pi R^2} \; for & 0 < \beta \leq \text{R} \\ 0 \qquad for & \beta > R \end{cases} \tag{4}$$

Fig. 3 gives a plot of the availability of a link as the value R takes on increases. The case of a network of N=20 nodes in an area of 10 square unit has been considered. At R=0.2, only 22.2% of the total nodes are available for a 1- hop link to any chosen node and 99.8% of nodes are available if R=1. All (100%) of the links are available once R is greater than or equal to 1.6, which means that every node has a link to all other nodes in the network, This phenomenon indicates that the network is fully connected. Certainly, for a network with N nodes in area A, as R increases, the number of available 1-hop link in the network increases.

From Poisson distribution, equation 3a is analogous to equation 5b, which is the probability of finding > 0 nodes in the radio range area pi*R^2, for any value of R. The probability that the degree of a node is equal to n nodes is expressed as:

$$P(D(.) = n) = \frac{(\rho\pi R^2)^n}{n!} e^{-\rho\pi R^2} \; for \text{ R} > 0 \tag{5a}$$

$$P(D(.) > 0) = \sum_{n=1}^{N-1} \frac{(\rho\pi R^2)^n}{n!} e^{-\rho\pi R^2} \; for \text{ R} > 0 \tag{5b}$$

Therefore, the number of available 1-hop link within the transmission radius of an arbitrary node can be expressed as: $P_{link}(N-1)$ for N nodes in the network. Note that a maximum of N-1 links are available to any node in a network of N nodes.

The CDF of the link distance between two nodes, (F_β(R)), given in figure 3 is a monotonically increasing function. Consequently, in a network with area A and N nodes, the availability of a link for a node increases as the node's transmission range increases.

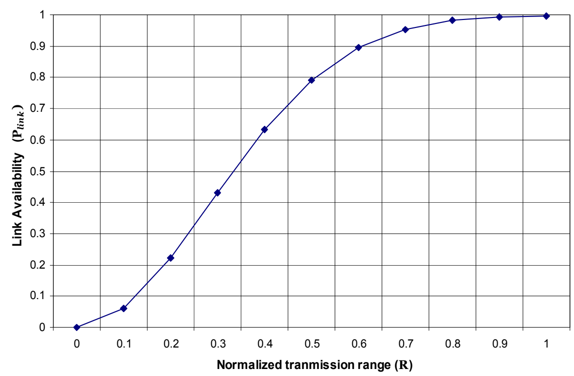

Figure 3. Link Availability vs Normalized transmission range

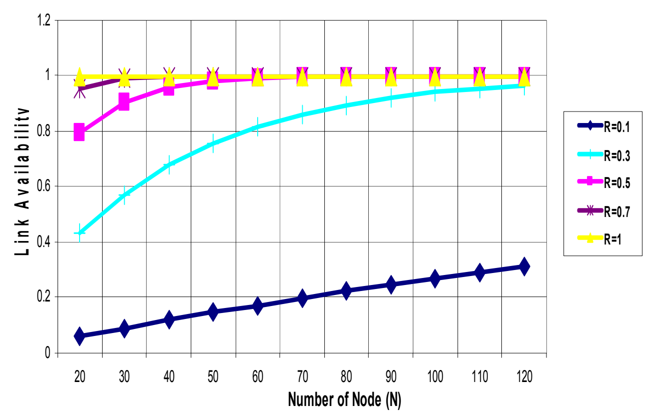

Figure 4. Link Availability vs Number of Nodes (N) for different values of R

Fig. 4 gives a plot of the link availability at fixed transmission range (R) as the number of nodes in the network increases. The same area of 10 square units has been considered, but the number of nodes was increased from 20 nodes to 120 nodes at fixed node transmission range values of 0.1, 0.3, 0.5, 0.7 and 1. From figure 4, generally, link availability increases as the number of nodes increases, indicating that in multi-hop wireless networks, the probability of having a node-pair linked up is higher in a dense network. For high values of R, the link availability is at very high values for a large number of nodes in the network.

As stated in section II, assuming that the transmission range R is the same for all nodes in the network. Then the probabilistic upper bound for link availability between any node pair is given as:

$$P_{link-upper} = 1 - e^{-\rho\pi R^2} \; for \; \mathrm{R} > 0 \tag{6a}$$

While the probabilistic lower bound for the unavailability of a link is

$$P_{no-link-lower} = e^{-\rho\pi R^2} \; for \; \mathrm{R} > 0 \tag{6b}$$

The availability of a link is a sufficient condition for connectivity, but it is not sufficient enough to ensure a reliable transmission of packets between node pairs. For optimal resource dimensioning and quality of service in multi-hop wireless networks, it is desirable to also consider the randomness in the wireless environment. The second part of this research work includes the factors that affect the availability of a link in the evaluation of P_{link}. However, for simplicity, let's assume that the availability of a link between node-pairs is dependent only on the distance between the nodes, and that links in the network are identical.

C. Route Availability

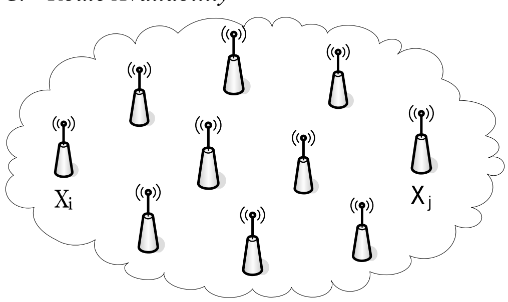

Figure 5. A Subnetwork

If the distance between a source and destination (β) is greater than R, then P_{link}=0, therefore a multi-hop route has to be utilized for packet transmission. In this case, a multiple hop routes in the direction of the destination node are used. [17] explains the different routing mechanisms, which can be used to achieve this. To ensure end to end route availability, each intermediate node on the route must have at least two neighbour nodes. These two neighbours are for the purpose of packet reception and transmission.

Let ℓ represent the link between any two nodes in the network, where $l \in L$ and L is the set of all links that exits in the network. If a transmitted packet from a node have to hop on a total of ℓ links to arrive at the destination node, then, ℓ-1 intermediate nodes will be required on this route.

Consider the sub-network in fig. 5 with N nodes. If a route is to be established between nodes Xi and Xj, where Xj is the specific target destination, then there are N-2 possible intermediate nodes between Xi and Xj. Depending on the source to destination distance (β), the maximum number of hops that can be utilized for packet transmission from Xi to Xj is N-1and the minimum number of hop is 1.

The number of hops depends on β, and the transmission range (R) of the source node and the intermediate nodes. Note that in this paper, the transmission ranges of all nodes in the network are equal. Fig. 6 shows a plot of the number of hops versus transmission range. As in section 3b, a 20 node network with an area of 10 square units has been considered. The value of β is 3.58 and R varies from 0.2 to 4.0. From the results, as R increases, the number of hops (ℓ) that will be utilized to transmit packets from source to destination decreases towards a threshold. For this network, a route can not be established between the source and destination if β=3.58 and R=0.1 unit. This because is due at R=0.1 unit for all nodes, each node has only one neighbor node, hence a route from source to destination cannot be established.

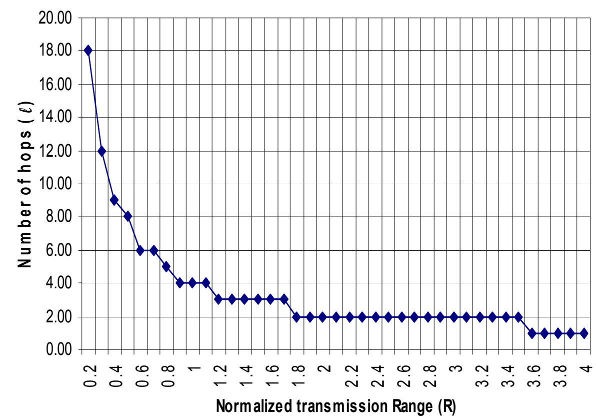

Figure 6. Average number of hops versus normalized tranmission range.

To establish a route with a definite number of hops (links) say ℓ hops between Xi and Xj in fig. 5, the transmission range for each node has to be at a certain maximum value as illustrated in fig.6. If R is lower than the maximum value, more hops will be utilized to set up such a route.

Also, depending on the number of nodes in the network, intermediate nodes can be linked up in several distinct ways. Since ℓ-1 nodes will be required on this route, as stated earlier, let G be the number of ways that these intermediate nodes can be linked up to set up distinct routes of only ℓ hops between Xi and Xj. Given that there are N-2 possible intermediate nodes for the connection and ℓ-1 nodes are required to establish an ℓ-hop route, then;

$$G = \frac{(N-2)!}{((N-2)-(l-1))!} \quad ,1 \le l \le N-1 \tag{7}$$

For a network of N nodes, the probability of an ℓ-hop route ($P_{\ell\text{-hop}}$) between any source-destination pair, e.g. Xi and Xj, is given below for $1< \ell \leq$ N-1,

$$P_{l-hop} = \frac{(N-2)!}{((N-2)-(l-1))!}(P_{link})^l \tag{8a}$$

$$P_{l-hop} = G(P_{link})^l \tag{8b}$$

Equations 8a and 8b are based on the assumption that for all nodes in the network P_{link} exists and it is the same for all nodes. It is also possible to find $P_{\ell\text{-hop}}$ if the P_{link} between any node pair in the network varies. For example, in the case where X_k (k takes values within $\mathbf{Z}^+$ such that $\forall i, j, k \in Z^+, i \neq j \neq k$) is a neighbor node to the destination node X_j and P^k_{link} is the link availability of node X_k to node X_j . $P_{\ell\text{-hop}}$ is given as in equation 8c, for $1 < \ell \leq$ N-1.

$$P_{l-hop} = G(P_{link})^{l-1} P^k{}_{link} \tag{8c}$$

Now, what is the probability that in a multi-hop network, a source destination pair will be connected anyhow irrespective of the number of hops from source to destination?

Let P_r denote the probability that a route is available.

$$P_r = \sum_{l=1}^{N-1} P_{l-hop} \tag{10}$$

Route availability (P_r), depends on the probability of establishing ℓ-hop route for $1\leq \ell \leq$ N-1. Now the probability of an ℓ-hops route between any pair of source-destination node in a sub-network is dependent on the link availability, node transmission range and the number of nodes in the network.

IV. CONCLUSION

In this paper an analysis of the link and route availability in wireless multi-hop networks has been presented. The research work focuses on route connectivity in inter-working multi-hop wireless networks. For multi-hop wireless networks such as mobile ad-hoc networks, a network connectivity analysis is needed. However, in multi-hop inter-working wireless networks, an analysis of the route connectivity is more desirable. For there to be connectivity between a source-destination node pair in an inter-working multi-hop wireless network, a route has to be available. Route availability is dependent on the availability of a link between the node pairs. A distance-dependent model of link availability has been assumed. However, this model does not accurately represent the stochastic nature of the wireless channel. Although, in mobile multi-hop network, β would be stochastic parameter, yet the channel model does not include the effect of attenuation, interference and fading on the wireless channel. In the second part of this research work, the parameters that induce randomness into the wireless channel are considered in the development of a link and reliability model for inter-working multi-hop wireless networks.

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