A Framework for Connectivity in Inter-working Multi-hop Wireless Networks

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Abstract. Establishing connectivity between node pairs in inter-working multi-hop wireless networks is a challenge. Although connectivity in multi-hop wireless networks has been studied yet these analyses focused mainly on 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 between any node pair in an inter-working multi-hop wireless network should be estimated with the availability of links and the level of interference on the available links that form the communication route between the nodes. Interference is a major factor that inhibits connectivity as it can cause wasteful transmissions over low quality links. Therefore this paper presents a framework for connectivity in inter-working multi-hop wireless networks. In addition a connectivity aware routing technique is proposed. Simulation results of the performance of the proposed routing technique in comparison with other routing scheme are presented.

Keywords: Connectivity, Interference, Inter-working, Multi-hop Wireless networks.

1 Introduction

The emergence of different types of services (IPTV, video on demand etc), an increase in demand for these services and most especially the desire for a “more” convenient way to access these services are causing new networking standards to emerge. Networks (fixed/ mobile networks, single hop/ multi-hop networks, infrastructure-based/ infrastructure-less networks) are emerging with more sophisticated standards than their predecessor in order to satisfy the demand cravings. These networks are emerging in a networking world with limited radio resources. Therefore, the issue of how to optimize resources in order to satisfy demands will continue to arise.

Inter-working multi-hop wireless networks are evolving out of the demand for ubiquitous connectivity. Inter-working is a term which refers to the seamless integration of several networks. Apart from the benefit of spatial re-use with route diversity, interworking multi-hop wireless networks enables an increase in service area coverage and thus ubiquitous Internet connectivity [1]. Different multi-hop wireless networks can be inter-worked to conveniently enable the ubiquity of network ser-

S. Balandin et al. (Eds.): ruSMART/NEW2AN 2010, LNCS 6294, pp. 335–352, 2010.

vices. A resource optimization issue that arises in this case is how to route traffic through optimal paths for end-to-end sustained connectivity. This issue is complicated with the wireless medium being prone to impairment at anytime. Consider an inter-working multi-hop wireless network consisting of three heterogeneous multi-hop wireless networks which are integrated through an inter-domain co-ordination. Nodes have the opportunity to remain connected and have access to their on-going service even if they move out of their parent network's coverage area. At times, a node within the network may not have direct link to its intended destination node, so its transmission will have to be relayed through other nodes in the network. However, due to link's instability it is difficult to guarantee that all the links on a route will be connected throughout the transmission duration. Though there is an advantage of route diversity in multi-hop wireless networks, yet it is pertinent to identify optimal routes so as to prevent wasteful transmissions over low quality links.

Traffic engineering (TE) is an aspect in networking that deals with the optimization of resources. It involves how the traffic within the network are distributed (by network layer routing), and how resources (e.g. time and frequency) are allocated (through MAC layer scheduling). However all these cannot be effectively done without understanding the properties of the wireless link. A link is the physical layer resource that provides bandwidth and ensures connectivity. For inter-working multi-hop wireless networks, the capabilities and limitations that the physical layer imposes on the network performance should be taken into consideration [2]. The routing of traffic through optimal paths is dependent mainly on the connectivity provided by the links between the communication nodes. Connectivity is mutually dependent on the availability of the link and the interference on the link. However, a link must first be available before interference can be evaluated.

Considering the stochastic nature of the wireless link, this paper revisits the problem of connectivity by presenting a framework where connectivity is taken as the probability that a wireless link is available and interference resilient enough to guarantee successful transmission over it. Thus the connectivity model presented in this paper is a function of link availability and link interference. In our framework, link availability is the probability that two nodes are within at most the maximum transmission range that is sufficient for a communication link to be established between them. Building upon the work done in [3], we now consider the potential for the radio attributes of a link to satisfy the minimum requirement for successful communication, which is expressed in terms of a link's resilience to interference. When fine-tuned, resilience to interference is measured by the attributes of the physical layer which ensure proper functioning of the wireless links.

The works most related to our framework include [2-10]. Until recently, a lot of research works on multi-hop wireless networks have focused on the higher layers (Network and MAC layers). These works have designed protocols with simplistic assumptions about the physical layer. Also, the developments on connectivity theory for wireless networks in research works such as [4-10], have focused on ad-hoc/sensor networks. Some of these research works assume that transmission is successful between two nodes once they are within each other's range. In contrast to our framework, their models do not include metrics that actually determine the success of a transmission based on the network's resources and the capability of the network in terms of Signal to Interference and Noise Ratio (SINR) and probability of bit error.

For example, a link may exist between two nodes but the conditions surrounding the link may affect the throughput and delay of the traffic. Hence the quality of the transmission that a link can provide needs to be considered. Moreover, to the best of our knowledge, existing research works have not jointly considered availability and interference as a connectivity measure for traffic moving between networks in inter-working multi-hop wireless networks.

The main contributions of this paper are threefold. Firstly, as connectivity is vital to the ubiquity of network services given to the network users in an inter-working multi-hop wireless network, our connectivity framework ensures ubiquitous roaming features by allowing connectivity to be maintained in an optimized manner as traffic moves between networks. Particularly in a heterogeneous inter-working multi-hop wireless network, the challenge is that the inter-worked networks may be operating with different protocols. Therefore, it is desirable to have a unifying connectivity framework for inter-working multi-hop wireless networks. In order to come up with this framework, it is important to understand that: *The physical layer imposes certain bounds on the network. These bounds are dictated by the metrics that ensure proper functioning of the physical layer.*

Secondly, this paper provides a study of the relationship between the metrics and presents protocol independent models of the relationships. For example, in any network, based on the scheme in use on the physical layer, there are different models for evaluating the relationship between the SINR and probability of bit error on a link. However, in this paper protocol independent models are presented. These models have been incorporated in the connectivity framework. Finally, a link quality based routing technique is proposed as an adaptive routing scheme. The proposed scheme is evaluated through simulation to assess the advantage of using our scheme compared to myopic schemes which discount connectivity on wireless links. The proposed scheme employs connectivity as a routing metric which provides information about link quality. The routing scheme selects the best routes based on the level of connectivity that can be assured on the link. The next section explains the network models used in this paper. Section 3 presents the link availability and link interference models while section 4 presents the connectivity framework, the connectivity aware routing technique and simulation results. Section 5 concludes the paper.

2 Network Models

Since nodes' locations are completely unknown a priori in wireless networks, they can be treated as completely random. The irregular location of nodes, which is influenced by factors like mobility or unplanned placement of the nodes may be considered as a realization of a spatial point pattern (or process) [11]. A spatial point pattern is a set of location, irregularly distributed within a designated region and presumed to have been generated by some form of stochastic mechanism. In most applications, the designation is essentially on planar $\mathbb{R}^d$ (e.g. d=2 for two-dimensional) Euclidean space [12]. The lack of independence between the points is called complete spatial randomness (CSR) [3]. According to the theory of CSR for a spatial point pattern, the number of points inside a planar region $\mathbb{P}$ follows a Poisson distribution [12]. It follows that the probability of p points being inside region $\mathbb{P}$, (Pr (p in $\mathbb{P}$)) depends on the area of

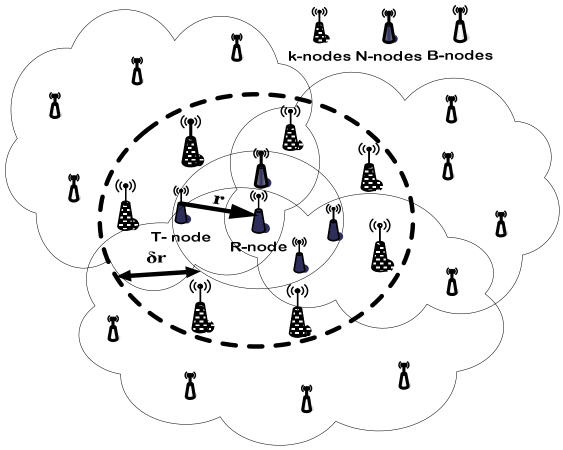

Fig. 1. Inter-working network model: Representation of the transmission from a T-node to a R-node on link *l*, with interfering nodes (k-nodes), non-interfering nodes (N-nodes), and nodes beyond δr (B-nodes). *r* is the transmission range of the T-node.

the region (A_p) and not on the shape or location of the plane. Pr (p in P) is given by (1), where μ is the mean number (spatial density) of the points.

$$\Pr(\, p \text{ in P}) = \frac{(\mu A_{\mathrm{P}})^{p}}{p!} e^{-\mu Ap}, \, p > 0. \tag{1}$$

This is a reasonable model for networks with random node placement such as the inter-working multi-hop wireless networks. Moreover the most popular choice for modelling nodes' spatial distribution is the Poisson point process as in [3] [13] [14] [15]. Fig. 1 represents network Ω, which is a set of inter-working multi-hop wireless networks (sub-networks A, B, and C). Each network is considered as a collection of random and independently positioned nodes. The nodes in the network are contained in a Euclidean space of 2-dimensions ($\mathbb{R}^2$). The total number of nodes in Ω is denoted by N_Ω, while the number of nodes in sub-networks A, B, C are N_a, N_b and N_c respectively, where $N_a + N_b + N_c = N_\Omega$. The mean number of nodes (spatial density) of each sub-network is given by μ_A, μ_B, μ_C ($\mu = N/a$, N is the number of nodes in a sub-network, a is the sub-network's coverage area and μ is given in nodes /unit square).

Theorem 1: The superposition of N independent Poisson processes with intensities λ_i is a Poisson process with intensity $\lambda = \sum_i \lambda_i$

Using theorem 1, the entire inter-working network can be considered as a merging Poisson process with spatial density: $\mu_{Net} = \mu_A + \mu_B + \mu_C$. In the network, nodes may communicate in a multi-hop manner and transmit at a data rate of Ψ bps. In this paper, *source-nodes* are referred to as *transmitter-nodes* (T-nodes) while *destination-nodes* are referred to as *receiver-nodes* (R-nodes). l represents the links between nodes and $\beta_{T,R}$ represents the link distance (length of a communication link) between aT-node and an R-node.

The degree of a node is defined as the number of neighbor nodes within its transmission range. A node is a neighbor of another node if the distance between the two nodes is less than or equal to their transmission range. This means that both nodes have a bi-directional link to each other. If the distance between them is greater than their transmission range, then the nodes are not neighbors. The degree of a node X_i is denoted by $D(X_i)$. A node is termed a "lone node" if $D(.)=0$. The desirable condition for connectivity in a multi-hop wireless network is for all nodes to have $D(.) > 0$. The probability that $D(.) > 0$ for any node pair is the same as the probability that a link is available for the node and it is given by equation 2. R_a is the transmission range of the node and $f(x)$ is the density function of the distance between any two nodes in the network.

$$\Pr(D(\,.\,) > 0\,) = Pr(link\ \ availabili\ ty) = \int_{o}^{Ra} f(x)dx\,. \tag{2}$$

From our work in [4], Pr(link availability) is as expressed as P_{link} in equation 3.

$$P_{l\,ink} = \begin{cases} 1 - e^{-\mu_{net}\pi R_a^{\ 2}} & for \quad 0 < \beta_{T,R} \le \mathrm{R}_{\mathrm{a}} \\ 0 & for \quad \beta_{T,R} > R_a \end{cases}. \tag{3}$$

3 Link Interference

3.1 Propagation Model

The length of a communication link between a T-node and a R-node is represented by $\beta_{T,R}$. To account for path-loss, the channel attenuation for link l is given by $A_l = (\beta_{T,R})^{-\alpha}$. It is typically given that the received power from a T-node at distance $\beta_{T,R}$ from the R-node decays exponentially (i.e. $(\beta_{T,R})^{-\alpha}$). The path loss exponent, α, is a constant that can take on values between 2 and 6[1]. However, in this paper, α is taken as =2. Other link parameters are: 1) $P_l^{\,t}$: the transmitting power of the T-node on link l. 2) P_o: the thermal noise power level at the R-node on link l. $P_o = FkT_oB$ where k is the Boltzman constant (1.38×10^{-23} J/°K/Hz). T_o is the ambient temperature, B is the transmission bandwidth and F is the noise figure [18]. 3) $P_l^{\,r}$: the power received by the R-node on link l. The free space propagation model is used to predict the received signal strength. For a packet transmitted by the T-node on link l and received by the R-node, the actual received power at the R-node can be expressed by the Friis equation given as:

$$P_{l^r} = cP_{l^t} A_l = cP_{l^t} (\beta_{T,R}\,)^{-\alpha}\,. \tag{4}$$

$$\left[\mathrm{c} = \frac{G_t G_r \lambda_g^{\ 2}}{(4\pi)^2 L_f} \right]$$

[1] The model in this paper can make use of any path-loss exponent value.

G_t and G_r are the transmitter and receiver gain respectively. λ_g is the wavelength, λ_g=g/f_g, g is the speed of light and f_g is the carrier frequency. $L_f \geq 1$ is the system loss factor.

3.2 Interference on a Link

The SINR model in [19] has been adopted to evaluate a link's SINR denoted by $\theta^{(l)}$ in this paper. $\theta^{(l)}$ is given by equation (5). A transmitted signal (packet) at a data rate Ψbps can only be correctly decoded by the R-node on link *l* if $\theta^{(l)}$ is not less than a threshold value ($\theta^{(th)}$) throughout the duration of packet transmission [20] [21]. P_{int} is the total interference power experienced by the R-node at the end of link *l*. P_{int} is the sum of the thermal noise power (P_o) and the inter-node interference power (P_{ini}). For link *l*, P_{ini} is the cumulative of the interfering power that the R-node experiences from nodes concurrently transmitting with the T-node. All k-nodes (for k= 1, 2, 3…..∞) are potential interfering nodes while *S* is the total number of simultaneously transmitting nodes that contributes to the effective interference power. $P^{t(k)}$ is the transmitting power of a k-node and $\beta_{k,R}$ is the distance between a k-node and the R-node. As illustrated in fig. 1, for a particular link between a T-node and an R-node, an interference region (δr) is defined for the R-node on that link.

$$\theta^{(l)} = \frac{P_l^r}{P_{\text{int}}} = \frac{P_l^r}{P_{ini} + P_o} = \frac{cP_l^t (\beta_{T,R})^{-2}}{\sum_{k=1}^{S} cP^{t(k)} (\beta_{k,R})^{-2} + P_o} \tag{5}$$

A potential k node will interfere with the reception of the R-node if the distance of the node to the R-node fulfills the constraint in equation (6).

$$r < \left|\beta_{k,R}\right| \leq r + \delta r \,. \tag{6}$$

Nodes within the region δr effectively contribute to the value of P_{ini} irrespective of the network topology or multiple-access technique. Usually, whenever a link is established between a T-node and an R-node, the MAC technique will prohibit nearby nodes in the network from simultaneous transmission. The portion of the network occupied by these nearby nodes is directly related to the size of *r* around the R- node [22].

Theorem 2: If each random point of a Poisson process in $\mathbb{R}^d$ with density λ are of *x* different types and each point, independent of the others, is of type *N* with probability P_i for i = 1· ·N, such that, $P_1 + P_2 + P_{3...} + Px = 1$, then the points are mutually independent Poisson processes with $\lambda_i = P_i\lambda$ and $\lambda = \lambda_1 + \lambda_2 + \lambda_{3...} + \lambda_x$ [23].

Using the splitting property of the Poisson process in theorem 2, all the nodes in the inter-working network (with spatial density μ_{Net}) are sorted independently into 3 types (k-nodes, N-nodes, and B-nodes). Note that all the nodes in the inter-working network have been classified into three types (k, N and B) according to the effect they have on the R-node of interest. These nodes are still the same set of nodes in the network. If the probability of a node being a k-node, N-node or a B-node is P_I, P_N, or P_B respectively such that P_I+P_N+P_B=1, then these 3 classification of nodes are mutually independent Poisson processes with spatial densities: $\mu_I=P_I\mu_{Net}$, $\mu_N=P_N\mu_{Net}$, $\mu_B=P_B\mu_{Net}$ where $\mu_{Net}=\mu_A+\mu_B+\mu_C$. μ_I represents the spatial density of k-nodes, μ_N is the spatial density of the N-nodes and μ_B is the spatial density of nodes beyond δr.

If $\beta_{j,R}$ represents the link distance between the R-node and an arbitrary node *j* in the network, then:

$$\Pr(\ j \in N - nodes\ ) = \Pr(\ \left|\beta_{j,R}\right| \leq r). \tag{7a}$$

$$\Pr(\ j \in k - nodes\ ) = \Pr(\ r < \left|\beta_{j,R}\right| \leq r + \delta r). \tag{7b}$$

$$\Pr(\ j \in B - nodes\ ) = \Pr(\ \left|\beta_{j,R}\right| > r + \delta r). \tag{7c}$$

Note that if node *j* is a k-node, the $\beta_{j,\,R}$ becomes $\beta_{k,\,R}$.. Due to the random geographic dispersion of nodes, P_{ini} also has a stochastic nature. Since several nodes can simultaneously transmit in the δr region and they altogether influence the value of P_{ini}, then $\theta^{(l)}$ (the SINR on a link) can be estimated using the expected value of P_{ini}.

$$E[P_{ini}] = cP^{t(k)}E\left[\sum_{k=1}^{S}(\beta_{k,R})^{-2}\right]. \tag{8}$$

In order to solve equation (8), the distribution function of the distance between the R-node and the k-nodes ($\beta_{k,R}$), given by $f_{\beta_{k,R}}(r)$, is of particular interest.

3.2.1 Distribution Function of $\beta_{k,R}$ and the Probability of Interference

As illustrated in fig. 1, nodes that can potentially interfere with the R-node's reception lie in the region outside the range *r*. However, nodes beyond the region (r+δr) cause negligible interference. The region within δr consists of the effective k-nodes. In order to find the probability that the distance between the R-node and all k-nodes fulfill the condition in (4), two events are defined: a) ξ_1= {no k-node exists within distance *r*} and b) ξ_2= {at least one k-node exists within δr}. Similar to the nearest neighbor analysis in [24], the probability that concurrently transmitting nodes fulfill the condition in (6) is given by:

$$\left(\Pr[(\ \xi_1) \cap (\xi_2)]\right) = \left(\Pr(\ \xi_1)\right)\left(\Pr(\ \xi_2)\right) \tag{9}$$

$$\Pr(\ \xi_1) = e^{-\mu_I \pi r^2} \tag{10}$$

To evaluate $\Pr(\xi_2)$, the interference cluster is laid as a strip with length $2\pi r$ and width δr as shown in fig. 2.

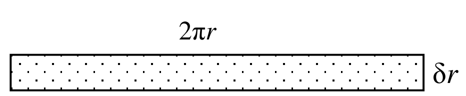

Fig. 2. An approximation of the ring created by the interference cluster

As δr approaches zero, the area of the annulus can be approximated by $2\pi r\delta r$. It follows from Poisson distribution that the probability of at least one node in the annulus is:

$$\Pr(\ \xi_2) = 1 - e^{-\mu_I 2\pi r \delta r} \tag{11}$$

From the first and second term of the Taylor's series $1-e^{-\mu_I 2\pi r\delta r} = \mu_I 2\pi r\delta r$ .Therefore, the probability of having at least a k-node within δr is:

$$\left(\Pr(\xi_1)\right)\left(\Pr(\xi_2)\right) = \left(2\mu_I \pi r\delta r\right)\left(e^{-\mu_I \pi r^2}\right) \tag{12}$$

Since all k-nodes have been considered to fulfill equation (7b), equation (12) can also be expressed as the probability of at least a nodes with link distance $\beta_{k,R}$ to the R-node, this is given as:

$$\Pr(r < \left|\beta_{k,R}\right| \leq r + \delta r) = \left(2\mu_I \pi r\delta r\right)\left(e^{-\mu_I \pi r^2}\right) = f_{\beta_{K,,R}}(r)\delta r$$

$$\therefore\ f_{\beta_{k,R}}(r) = 2\mu_I \pi r e^{-\mu_I \pi r^2} \tag{13}$$

Page 179 of [25] provides the detailed proof to substantiate (13). Now that the distribution of $\beta_{k,R}$ has been evaluated, the expected value of the summation of the negative-second moment of ($\beta_{k,R}$), can be solved. So from equation (8):

$$E[\sum_{k=1}^{S} (\beta_{k,R})^{-2}] = \sum_{k=1}^{S} E[(\beta_{k,R})^{-2}] = \sum_{k=1}^{s} \varpi \tag{14}$$

ω is an approximate solution for the negative moment of $\beta_{k,\,R}$ which is a Poisson R.V. The Tiku's solution [26] has been adopted to find ω.

$$\varpi \approx \frac{1}{(\mu_I - 1)(\mu_I - 2)........\ ...(\mu_I - \tau)}. \tag{15}$$

For the τ^{th} negative moment of $\beta_{k,R}$ (τ represents the positive value of the power of $\beta_{k,R}$)[2]. The distribution of the distance between the R-node and k-nodes is $f_{\beta_{k,R}}(r)$ in (13). $\mu_I = P_I \mu_{Net}$ where P_I is the probability of interference. As long as the transmission range of the T-node on a link overlaps with the transmission range of an I-node, the receiver node on the link on which T-node transmits experiences interference. In practice, not all nodes within δ*r* will transmit at the same time, with the T-node on link *l*, therefore P_I is defined by two events:

ξ_3=at least a node exist within δ*r* and ξ4 = the node is transmitting. For an interworking multi-hop wireless network with density μ_{Net}, Pr(ξ_3) is the probability that > 0 nodes exist within δ*r* of the R-node and it is given by: $1 - e^{-\mu_{Net} A_I}$. A_I is the area of δ*r* for the R-node. Using μ_{net} will allow the evaluation of μ_I.

$$\Pr(\xi_4) = \begin{cases} 1, & \text{if } P^{t(k)} > 0 \\ 0, & \text{if } P^{t(k)} = 0 \end{cases} \quad \forall P^{t(k)} \geq 0.$$

Thus: $P_I = \Pr(\xi_3)\Pr(\xi_4) = 1 - e^{-\mu_{Net} A_I} \quad \forall P^{t(k)} > 0$. Now, the expected value of P_{ini} in equation (8) can be solved and the $\theta^{(l)}$ on a link can be evaluated.

[2] τ can take on any value depending on the path-loss exponent value.

3.3 Probability of Bit Error

This section explains the relationship between the probability of bit error on a link l denoted by ($\mathbf{\Phi}^{(l)}$) and the link's SINR, denoted by ($\theta^{(l)}$). The value of $\mathbf{\Phi}^{(l)}$ on a link is dependent on the value of $\theta^{(l)}$. The decoding performed at the R-node on a link is a probabilistic process which determines the success or failure of any transmission. Due to potential interference, communication may not be totally error-free; hence success is specified in terms of an acceptable value for $\mathbf{\Phi}^{(l)}$. $\mathbf{\Phi}^{(l)}$ expresses the success or failure of a transmitted signal (packet) in terms of probability. For the correct decoding of a transmission, the value of $\theta^{(l)}$ must be greater than or equal to a SINR threshold value (θ^{th}) as expressed in (16). The threshold value is a pre-set value that is used to ensure successful transmission in a network.

$$E(\theta^{(l)}) \geq \theta^{th} \tag{16}$$

$E(\theta^{(l)})$ is the expected value of $\theta^{(l)}$. According to [27], the mean signal strength over the separation distance between a T-node and an R-node is appropriate for estimating the transmission strength of the link. Measures of signal variability are only appropriate in system design issues such as antenna diversity and signal coding. Hence, the mean value of $\theta^{(l)}$ will be used for the estimation of $\mathbf{\Phi}^{(l)}$. Since θ^{th} is the minimum SINR that is required for successful packet reception at the R-node, then a transmission error can be declared once there is a probability that $E(\theta^{(l)})$ is below θ^{th}. Therefore:

$$\Phi^{(l)} = \Pr(E(\theta^{(l)}) < \theta^{th}) = 1 - \Pr(E(\theta^{(l)}) \geq \theta^{th}) \tag{17}$$

In evaluating $E(\theta^{(l)})$, the transmit power, received power and noise power level on link l are kept constant. This is because $E(\theta^{(l)})$ is mostly influenced by the value of P_{ini}. As long as nodes operate in the same transmission frequency band, inter-node interference is bound to occur. However, the transmission from nodes simultaneously transmitting with the T-node will not interfere with the reception at the R-node if the distance between these nodes and the R-node exceeds the upper bound for $\beta_{k,R}$ given by:

$$r + \delta r = \sqrt{\frac{SP^{t(k)}\theta^{th}}{P_l^t}}(\beta_{T,R}) \tag{18}$$

In deriving (18) the thermal noise power has been considered negligible compared to interference power (P_{ini}). Therefore, (6) now becomes:

$$r < \left|\beta_{k,R}\right| \leq \sqrt{\frac{SP^{t(k)}\theta^{th}}{P_l^t}}(\beta_{T,R}) \tag{19}$$

However, not all of the nodes within δr will interfere since some of them will not even transmit when the T-node is transmitting. Now, what is the threshold of the number of interfering nodes that can be in this interference region, beyond which, a transmission error can be declared? Note that in order to maintain a target SINR threshold, there is a maximum number of interfering users that can be supported [28].

Let S_{th} represent the threshold of interfering nodes which has their distance to the R-node ($\beta_{k.R}$) fulfilling equation (19). For analytical tractability, let the interfering nodes' power be constant. Since unsuccessful transmission is declared when $E(\theta^{(l)}) < \theta^{th}$, then there is a probability of bit error at the receiver node if:

$$S > S_{th} \tag{20}$$

S is the number of interfering nodes. In order words, $E(\theta^{(l)})$ becomes less that θ^{th} as S increases beyond S_{th} and there is a probability of bit error when $E(\theta^{(l)}) < \theta^{th}$. Therefore,

$$\Phi^{(l)} \approx \Pr(S > S_{th}) = 1 - \Pr(S \leq S_{th}) \tag{21}$$

$\mathbf{\Phi}^{(l)}$ can be estimated as:

$$\Phi^{(l)} \approx 1 - \sum_{k=0}^{S_{th}} \frac{(\mu_I A_I)^k}{k!} e^{-\mu_I A_I} \tag{22}$$

μ_I is the density of interfering nodes in the interfering region of area A_I. Equation (22) approximates the $\mathbf{\Phi}^{(l)}$ as a function of the number of interfering nodes. Thus irrespective of the network's topology or the multiple access technique, only the effective density of interfering nodes is considered. Considering that noise power (P_o) is very weak (negligible) relative to the interference power (P_{ini}) then (23) can be used to evaluate the value of S_{th}.

$$S_{th} = \left\lceil \frac{1}{\varpi} \left(\frac{P_l^t (\beta_{T,R})^{-2}}{P^{t(k)} \theta_{th}} \right) \right\rceil \tag{23}$$

There is a minimum (threshold) for $\mathbf{\Phi}^{(l)}$ that should to be maintained on a link for the link to be termed interference resilient enough to maintain a successful transmission [28]. The maximum number of interfering nodes (nodes in the δr region) that can be supported to maintain this threshold is S_{th}. Once the threshold is exceeded, unsuccessful transmission is likely to occur. The probability that a link is interference resilient is represented by $\mathbf{\Phi}^{(l)'}$ and estimated as the compliment of equation (22). Thus if the probability of bit error is high, then the interference resilience on that link is low and vice-versa.

The network scenario shown in fig. 1 is a case where the link considered is at the centre of the inter-working multi-hop wireless network. Three wireless multi-hop networks with 10 nodes, 15 nodes and 25 nodes respectively have been inter-worked and the network coverage area is 1000unit square. The separation distance between the T-node and the R-node is 10units. Nodes in the network transmit with the power level of 10mW. G_t and G_r, the transmitter and receiver gains respectively are assumed to be equal to 1. L_f=1, θ^{th} is given as 6dB. The interference region is 100unit square.

For the inter-working network, if the $\mathbf{\Phi}^{(l)}$ increases beyond the threshold, it means that there is a high probability that the transmission on the link of interest will be unsuccessful. Fig. 3 shows the trend of $\mathbf{\Phi}^{(l)}$ for the scenario illustrated. The value of S_{th}=12. The interfering node density (μ_I) was increased by increasing the probability of interference (P_I). In this network scenario, the value of $\Phi^{(l)}$ increased continually as the density of interfering nodes increased beyond the threshold value for which link l

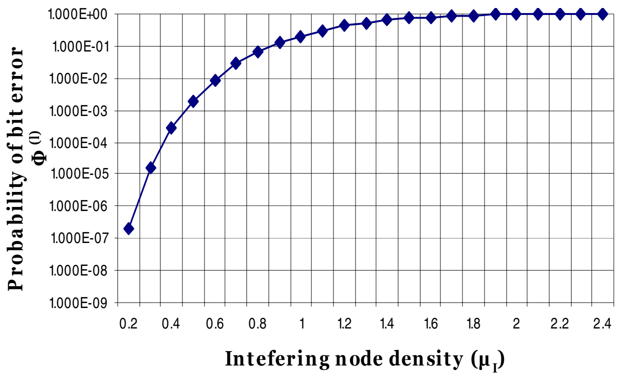

Fig. 3. Probability of Bit Error vs. Interfering node density

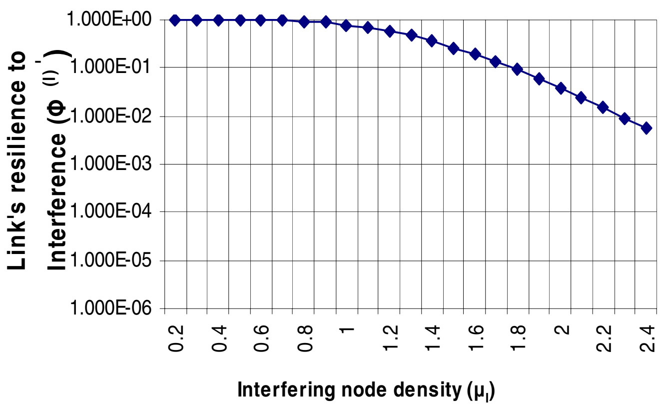

Fig. 4. Link Reliability vs. number of interfering nodes

is termed interference resilient enough to maintain a successful transmission. The link is highly resilient for all values of $S \leq S_{th}$ and the threshold for $\boldsymbol{\Phi}^{(l)}$ =1.15727E-06 (when $S=S_{th}$). Consequently, unsuccessful transmission can be declared for values greater than this threshold value. This gives an inclination that successful transmission on the link of interest in the inter-working network cannot be guaranteed any longer when $\Phi^{(l)}$ becomes greater than the acceptable threshold probability. With the pre-set θ^{th} for the network, the upper bound for the acceptable $\boldsymbol{\Phi}^{(l)}$ on a link can be determined. If the $\boldsymbol{\Phi}^{(l)}$ evaluated for a link in the network is higher than the acceptable value, then that link's interference resilience level will not guarantee a successful transmission. In this way, unreliable links can be identified and optimized traffic routing decisions can be made in inter-working multi-hop wireless networks irrespective of the link/MAC layer technologies of the inter-working networks. Fig. 4 illustrates the interference resilience of the link considered in the inter-working multi-hop wireless network scenario as the density of interfering nodes increases.

4 Link Connectivity Framework

The link connectivity framework presented in this section gives an indication of how successful the communication between any two nodes will be. The quality of a transmission is specified by metrics, which define the state of a link. These metrics include probability of interference, SINR, and probability of bit error. Evaluating the connectivity of links in inter-working multi-hop wireless networks is quite challenging because different wireless networks use different physical layer protocols to specify these metrics. However, in this section, we present a unifying connectivity framework for inter-working multi-hop wireless networks. In accordance with [29], the framework only considers the effective density of interfering nodes irrespective of the topology or the multiple access technique.

Connectivity in inter-working multi-hop wireless networks is defined as the probability that a link is available and interference resilient enough to guarantee a successful transmission over it. The model for connectivity has been developed based on the link availability and link interference models presented in previous sections. Firstly, for any T-node (source node) in the network, the probability that a link is available for it to transmit its packet is given by equation (3). The link may be a direct link to the intended destination node or it may be a link to intermediate nodes between the T-node and the intended destination node. It is only after confirming the availability (existence) of a link that the reliability metrics (e.g. probability of interference, interference power, SINR, and probability of bit error) on the link can be evaluated. Secondly, after the confirmation of the existence of a link, an interference region is defined for the R-node (intended destination or intermediate node) on the link of interest as stated in section 3.2. All nodes present within this region are potential interfering nodes. However, only the nodes that happen to be transmitting concurrently with the T-node will contribute to the interference power. The probability that a node in the inter-working network will contribute to the interference power is given in section 3.2.1. Thirdly, using the probability of interference, the density of interfering nodes can be evaluated and also the total interference power, which is used to evaluate $E(\theta^{(l)})$ on the link of interest. If the $E(\theta^{(l)})$ on the link is less that the threshold SINR value (θ^{th}) in the network, then there is a likelihood that transmission errors will occur on that link. The set value for θ^{th} in the network is also used to estimate the threshold of the number of interfering nodes (S_{th}) and the threshold value for $\mathbf{\Phi}^{(l)}$ that can be tolerated in order to able to guarantee a successful transmission. The compliment of equation (22) is used to evaluate the interference resilience of the link. Finally, the probability that a link is available and interference resilient, which is termed connectivity in this paper, is given by:

$$P_{con} = e^{-\mu_I A_I} - e^{-(\mu_{Net}\pi R^2 + \mu_I A_I)} \tag{24}$$

Fig. 5 shows the probability of connectivity on link l as μ_{Net} increases. In the first part of this figure, it can be observed that an increase in μ_{Net} increases the interfering node density (μ_I). However, the increase in μ_I does not yet affect connectivity on the link because $S \le S_{th}$. In this case, the $\mathbf{\Phi}^{(l)}$ is still less that the threshold value for the probability of bit error. In the second part of fig. 5, after S_{th} is exceeded, it can be observed that connectivity begins to decline. At low values of μ_{Net} link availability is low, but any link that is available has high reliability due to low probability of interference, so connectivity is sustainable. At high values of μ_{Net}, even though availability is high, the link's interference resilience and connectivity begins to decline as a result of a high density of interfering nodes. There is a certain number of nodes that the inter-working network can sustain in order to maintain a high connectivity that can guarantee successful transmission between nodes. Once the network exceeds this number of nodes the likelihood of strong connectivity decreases. This model can be used to ensure that QoS is guaranteed to traffic and also for admission control policies for inter-working multi-hop wireless networks.

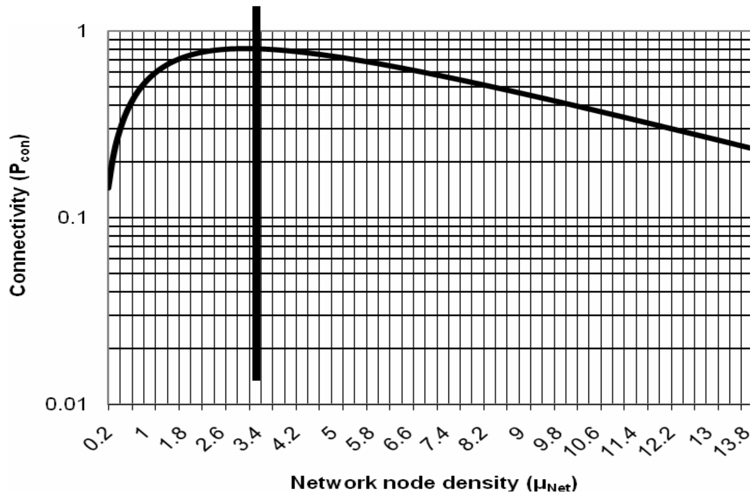

Fig. 5. Connectivity vs Network node density

4.1 Connectivity Aware Routing Technique

A dynamic reaction to the changes in the wireless channel is required for traffic routing within an inter-working multi-hop wireless network. The routing technique presented is based on the pre-calculation of the connectivity from a T-node to the R-nodes on the links en route to the final destination node.

Step 1: The link availability is calculated in order to identify potential links for routing.
Step 2: For each link that is available, the instantaneous parameters for the probability of interference at the R-node on the link, the SINR and the bit error probability are obtained.
Step 3: The interference resilience level on each potential link is evaluated.
Step 4: With the knowledge of the interference resilience level and availability, the connectivity on each link is obtained.
Step 5: The link with the highest P_{con} is chosen as the next link for routing the transmission. In a case of equal values of P_{con}, the link closest to the final destination node is chosen.

With this technique, connectivity can be used as a routing metric for determining how traffic are routed within the network. The routing technique is well-suited for inter-working multi-hop wireless networks where the wireless channel is unstable. The routing technique not only estimates the quality of wireless links in terms of a quantitative measure, such as the probability of interference, probability of bit error and SINR, but also adapt to temporal dynamics of the links and prevents wasteful transmissions over low quality links. For a network, the lower bound on connectivity can be obtained and QoS can be guaranteed based on this lower bound.

4.2 An Application of the Connectivity Framework to a 23-Node Test Network

We conducted experiments with a 23-node 45-link model to simulate an inter-working wireless MPLS network in order to evaluate the performance achieved by the connectivity-aware routing scheme when setting up connection-oriented tunnels in the network under different routing scenarios. These include the routing of tunnels for different applications. The paths carrying the traffic offered to the wireless MPLS network were computed using three different routing metrics: two myopic metrics referred to as OSPF (Open Shortest Path First) and CSPF (Constrained Shortest Path First) that discounts connectivity and our proposed connectivity aware metric referred to as Connectivity Aware Routing (CART).

We developed a simulation model where each tunnel setup requests $d_{i,e}$ bandwidth units, where the $d_{i,e}$ are uniformly distributed in the range [1,M] in wireless MPLS routing. This allows different types of applications depending on the value of M. Higher values of M represent high bandwidth demanding applications while lower values represent low bandwidth demanding applications. The simulation model is based on the following features:

- Long-lived tunnels of capacity $d_{i,e}$ are set up in random order among the ingress-egress pairs.
- Requests to set up short-lived tunnels of capacity $d_{i,e}$ bandwidth units arrive to the ingress-egress pair (i, e) according to a Poisson process with parameter $L_{i,e}$.
- Requests to tear down short-lived tunnels arrive to the ingress-egress pair (i, e) according to a Poisson process with parameter $L_{i,e}$.
- One of the three routing algorithms (OSPF, CSPF or CART) is used to find a path between (i, e) to route the requested tunnel.
- If a path can be found, the routing request is accepted. If a path cannot be found due to insufficient band-width, the routing request is rejected.

We conducted a number of simulation experiments under different traffic profiles using short- and long-lived tunnel requests to evaluate the performance of the proposed framework. Different traffic profiles were chosen by inflating the tunnel setup request rate $L_{+\,i,e} = \eta L_{i,e}$ to reflect light load conditions ($\eta = 1$) and heavier load conditions ($\eta > 1$). Different types of applications were modeled by varying the upper bound of the demand range M to represent different levels of bandwidth demand. The simulation model computes the following network performance metrics. The routing efficiency is given by the tunnel acceptance (ACC) and the average link utilization (UTIL). ACC is the percentage of flows which were successfully routed and UTIL defines how far the links are from the congestion region where the link load is close to its link capacity. UTIL also defines the potential for the network to support traffic growth: a lower utilized network offers a higher potential to support an increase of traffic load than a highly utilized network. The network reliability is given by the average link interference (AVL) and the maximum link interference (MAX) where AVL is the average number of tunnels carried by each network link. AVL determines the average number of tunnels which must be re-routed upon failure. A routing algorithm which achieves a lower average interference is more reliable since it leads to re-routing fewer flows upon failure. MAX defines the maximum number of tunnels that will be re-routed upon a failure of the link with the largest interference. The scalability of the routing process is given by the average node interference (AVN) which is the average number of tunnels traversing each node. This parameter indicates the size of the routing tables. A routing algorithm that achieves a lower AVN is more scalable than an algorithm which achieves a higher AVN.

Fig. 6 shows the effect of the traffic profiles on short-lived tunnels**.** The traffic profile is determined by the parameter η which scales the tunnel setup request rates. We conducted simulation experiments using short-lived tunnels (M = 4) to analyze the effect of the traffic profiles on the network efficiency. The results presented in fig. 6 reveal that the CART algorithm performs somewhat better than the other routing algorithms in terms of efficiency (highest ACC and lower UTIL), reliability (lower AVL and MAX) and scalability (lower AVN). In particular, CART achieves a lower MAX value. Fig. 7 shows the effect of the type of application on long-lived tunnels. The application type is determined by the value of the upper bound M on the tunnel size. We conducted simulation experiments using long-lived tunnels to analyze the effect of the type of application on the network efficiency. The results presented in fig. 7 are similar to the results for short-lived tunnels: the CART algorithm again performs better than the other routing algorithms in terms of efficiency (highest ACC and lower UTIL), reliability (lower AVL and MAX) and scalability (lower AVN).

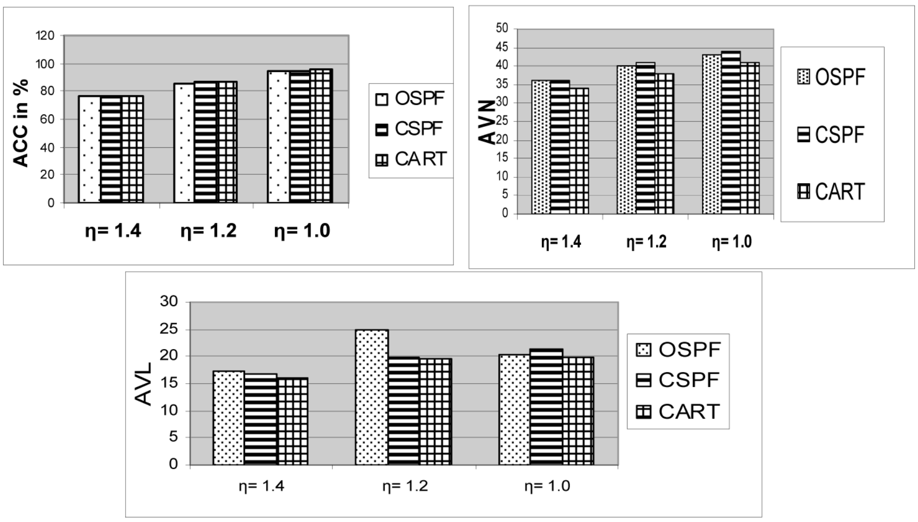

Fig. 6. Effect of the traffic profiles on short-lived tunnels

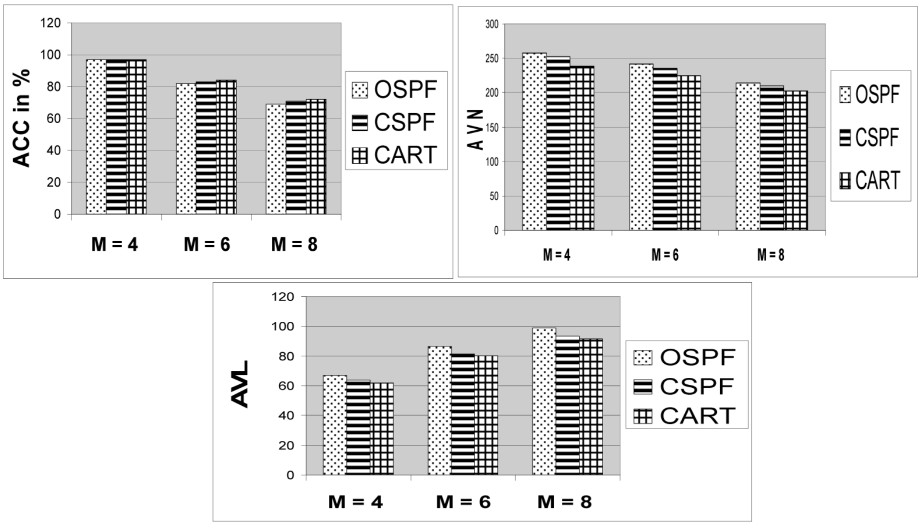

Fig. 7. Effect of the type of application on long-lived tunnels

5 Conclusion

Firstly, the paper presented an analysis of the relationship between the major physical layer metrics such as SINR and probability of bit error. Since different wireless networks have different models for evaluating the relationship between these metrics, and this will pose a challenge when analyzing such metrics for inter-working multi-hop wireless networks; we developed protocol independent models of these relationships. Secondly, these models were incorporated in the connectivity framework and results of the evaluation of the framework were presented. Connectivity is considered as the probability that a wireless link is available and interference resilient enough to guarantee successful transmission over it. Finally, the simulation performance of the proposed routing technique termed connectivity aware routing technique (CART) was compared with routing schemes such as the OSPF and the CSPF. In trems of efficiency and scalability CART performed better than OSPF and CSPF.

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