2013

Interference Aware Resource Allocation in Relay Enhanced Broadband Wireless Access Networks

Thulasiraman, Preetha

IGI Global

Thulasiraman, Preetha. "Interference Aware Resource Allocation in Relay Enhanced Broadband Wireless Access Networks." Distributed Computing Innovations for Business, Engineering, and Science. IGI Global, 2013. 18-46.

http://hdl.handle.net/10945/66241

Chapter 2

Interference Aware Resource Allocation in Relay Enhanced Broadband Wireless Access Networks

Preetha Thulasiraman
Naval Postgraduate School, USA

ABSTRACT

The use of relay nodes to improve the performance of broadband wireless access (BWA) networks has been the subject of intense research activities in recent years. Relay enhanced BWA networks are anticipated to support diverse multimedia traffic (i.e., voice, video, and data traffic). In order to guarantee service to users, efficient network resource distribution is imperative. Wireless multihop networks are distinguished primarily from their wired counterparts through the presence of interference. Wireless interference greatly influences the ability of users to obtain the necessary resources for service. This chapter provides a comprehensive study on the topic of interference aware resource allocation by investigating the impact of interference on various aspects of resource allocation, ranging from fairness to spectrum utilization. In this regard, the focus of this chapter is to investigate the problem of traffic flow routing and fair bandwidth allocation under interference constraints for multihop BWA networks.

First, a novel interference aware routing metric for multipath routing considering both interflow and intraflow interference will be discussed. Second, in order to ensure quality of service (QoS), an interference aware max-min fair bandwidth allocation algorithm is addressed using lexicographic ordering and optimization. A comparison among various interference based routing metrics and interference aware bandwidth allocation algorithms established in the literature is shown through simulation results derived from NS-2 and CPLEX. It is shown that the proposed interference aware resource allocation framework improves network performance in terms of delay, packet loss ratio, and bandwidth usage. Lastly, future challenges and emerging research topics and opportunities are outlined.

DOI: 10.4018/978-1-4666-2533-4.ch002

INTRODUCTION

The communications landscape has been changing dramatically in recent years under the increasing pressure of rapid technological development and intense competition. Thus, wireless networks are becoming more pervasive, accelerated by new wireless communication technologies, inexpensive wireless equipment and broader Internet access availability. Broadband wireless access (BWA) networks are one such technology that is fast becoming a viable solution to provide ubiquitous communications.

BWA networks are designed to support fixed and mobile users with heterogeneous and high traffic rate requirements. In such networks, a single base station is deployed to cover a cellular area. In such a large area, users at the cell edge often experience bad channel conditions. Moreover, in urban regions, shadowing by various obstacles can degrade the signal quality in some areas. Emerging broadband wireless applications require increasingly high throughput and more stringent quality of service (QoS) requirements. As real-time applications (i.e., voice over IP and video streaming) rapidly grow, BWA networks are expected to achieve efficient communications. Increasing capacity along with coverage in conventional networks dictates the dense deployment of base stations. Increasing the number of base stations is an expensive solution and increasing the base station power only increases the intercell interference. To meet the goal of low cost network deployment for both short range and long range coverage, the use of relay nodes has been shown to be a promising solution (Pabst et al., 2004; Soldani & Dixit, 2008). Broadband cellular multihop networks consist of fixed infrastructure relay nodes whose sole priority is to forward data to and from the users to the base station. Deploying relays is a feasible solution since typical relays are cheaper than base stations and they do not need their own wired backhaul.

The use of relays to improve the performance of BWA networks has been the subject of intense research in recent years because of their several performance benefits. First, a relay works on behalf of the base station to increase the network coverage. While conventional cellular systems normally cover a diameter of 2-5km, a relay normally covers a region (subcell) with diameter 200-500m. If the density of relay stations is somewhat high, most user-terminals will be close to one or more relays than to a base station. This has two primary advantages: the radio propagation paths are shortened so that the pathloss is lowered, and the path essentially can be routed around obstacles to mitigate effects of shadowing (Pabst et al., 2004). This results in higher data rates on the links between relays and users, thereby increasing throughput. Also, from the point of view of the user, the relay acts like a base station and so by having intermediate points of traffic aggregation, the capacity per area element can be balanced (Walke, Mangold, & Berlemann, 2006). Second, because relay stations are closer to the individual user terminals, the transmit power required for a relay to transmit to a user and vice versa is significantly lower than for a base station, thereby allowing for energy saving. Thus, the practical rationale for the deployment of relay enhanced BWA networks is to ensure that the QoS of a user, in terms of data rate, delay, outage probability, etc. does not wholly depend on its location and distance from the base station.

Resource Allocation in the Presence of Interference

Interference is the major limiting factor in the performance of wireless multihop networks. Sources of interference include simultaneous transmissions within a certain range as well as concurrent use of the same frequency channel for transmission. Interference is severe in urban areas due to the large number of base stations and mobile users. Interference has been recognized as a major bottleneck in increasing network capacity and throughput and is often responsible for dropped transmissions (Rappaport, 2002). Interference experienced at individual nodes (relays and users) is impacted by variations in network size (number of nodes), network density (relative positions of nodes) and traffic per node. There are two widely used models to characterize interference in a wireless network, namely, the protocol model and the physical model (Gupta & Kumar, 2000). The protocol model, also known as the unified disk graph model, has been widely used by researchers in the wireless networking community as a way to simplify the mathematical characterization of the physical layer. Under the protocol model, a successful transmission occurs when a node falls inside the transmission range of its intended transmitter and falls outside the interference ranges of other non-intended transmitters. The setting of the transmission range is based on a signal-to-noise-ratio (SNR) threshold. The setting of the interference range is a heuristic approximation and remains an open problem (Shi, Hou, Liu, & Kompella, 2009). Under the protocol model, the impact of interference from a transmitting node is binary and is solely determined by whether or not a receiver falls within the interference range of this transmitting node. That is, if a node falls in the interference range of a non-intended transmitter, then this node is considered to be interfered and thus cannot receive correctly from its intended transmitter; otherwise, the interference is assumed to be negligible (Iyer, Rosenberg, & Karnik, 2009). Various graph based approaches have been developed for modeling interference using the protocol model. The most common and widely used model is the conflict graph model (Jain, Padhye, & Padmanabhan, 2003). The nodes in the conflict graph, G_c, represent edges in the original connectivity graph G. An edge is placed between two nodes in the conflict graph if the corresponding links in the connectivity graph interfere. Due to such simplification, the protocol model has been widely used in developing algorithms and protocols in wireless networks (Alicherry, Bhatia, & Li, 2006; Ramachandran, Belding, Almeroth, & Buddhikot, 2006; Tang, Xue, Chandler, & Zhang, 2005).

The physical model, also known as the SINR model, is based on considerations arising from practical transceiver designs of communication systems that treat interference as noise. Under the physical model, a transmission is successful if and only if signal-to-interference-and-noise-ratio (SINR) at the intended receiver exceeds a threshold so that the transmitted signal can be decoded with an acceptable bit error probability. Furthermore, capacity calculation is based on SINR (via Shannon's formula), which takes into account interference due to simultaneous transmissions by other nodes. This model is less restrictive than the protocol interference model as it may occur that a message from node u to node v is correctly received even if there is a simultaneous transmitting node w close to v (for instance, because node u is using a much larger transmit power than node w). As a result, higher network capacity can be achieved by applying the physical interference model. However, the use of the SINR model is computationally more complex and requires various optimization and heuristic techniques to be used to obtain a solution. Nonetheless, it has been shown that despite the computational complexity, the SINR model provides a more practical and realistic assessment of wireless interference (Iyer et al., 2009; Brar, Blough, & Santi, 2006).

In wireless communications, resource management is vital in controlling how scarce resources can be allocated, distributed, and utilized among all nodes in a system. Unlike wired links which have a constant link capacity, wireless links are relatively vulnerable due to fading over frequency and interference over time. Interference aware resource allocation involves striking a good balance between fair and efficient distribution of spectral resources throughout the network while concurrently mitigating the resulting interference. One of the major difficulties associated with interference mitigation is the lack of predictability of interference coming from other links that have simultaneous transmissions combined with channel variability.

In order to develop efficient resource allocation algorithms that are cognizant of interference, certain potential issues must be addressed, outlined as follows:

1. Interference and Fairness in Routing and Bandwidth Allocation: Efficient routing between pairs of nodes in communication networks is a basic problem of network optimization. Achieving high throughput and fair allocation of resources among competing users (or flows) in wireless networks is one of the most important problems in data communications and is directly coupled with routing between nodes. Throughput enhancement and fairness can not be simultaneously achieved, but rather must be balanced (Cheng & Zhuang, 2008). Max-min fairness (MMF) is considered to be an efficient approach that balances these two conflicting objectives by preventing starvation of any flow, and at the same time, increases the bandwidth of a flow as much as possible. In the wireless environment, allocation of bandwidth to paths sharing a set of links is further complicated by the inherent interference that is generated by simultaneous transmissions. Interference can be divided into two categories: interflow and intraflow. Interflow interference is generated when two links belonging to different flows are active on the same channel at the same time. Intraflow interference is when two links belonging to the same flow are active on the same channel at the same time. The effects of interference using the MMF approach have been quantified using graph theoretic approaches (i.e., conflict/contention graph) which ultimately exploits the protocol interference model (i.e., transmissions interfere only within a specific range) (Tang et al., 2005; Wang, Jiang, Zhuang, & Poor, 2008). Although, (Tang et al., 2005; Wang et al., 2008) have provided a theoretical foundation for fairness in wireless networks, the reliance on such graph based models induces binary conflicts which means any two links either interfere with each other or they are active simultaneously regardless of other ongoing transmissions, which is not true in practice (Brar et al., 2006). The use of the SINR model in determining MMF bandwidth allocation and fair routing would provide a less restrictive and more realistic allocation of bandwidth to the various network paths. Therefore, a SINR based MMF routing and bandwidth allocation optimization formulation would serve to fairly distribute resources and reduce competition between simultaneous flows.
2. Multipath Routing Using SINR Constraints: Discovering available relaying paths (routes) between a source and base station is a critical prerequisite for the success of multihop wireless networks. Multipath routing (MPR) has long been recognized as an effective strategy to achieve load balancing and increase reliability (Huang & Fang, 2008). To improve the transmission reliability and avoid shared-link (or node) failures, the multiple paths can be selected to be link or node disjoint. In this case, the MPR approach is referred to as disjoint multipath routing (DMPR). DMPR provides better robustness and a greater degree of fault tolerance than compared to the generic MPR. Due to these advantages, DMPR schemes have been researched in the context of wireless networks in order to enhance network survivability (Thulasiraman, Ramasubramanian, & Krunz, 2006; Thulasiraman, Ramasubramanian, & Krunz, 2007). Several routing metrics to capture interference on routing paths have been introduced in the literature. However,

the metrics developed have either 1) been based on extending existing routing metrics (i.e., expected transmission count (ETX)) or existing routing algorithms (Subramanian, Buddhikot, & Miller, 2006; Langar, Bouabdallah, & Boutaba, 2009) or 2) have integrated interference into variations of the shortest path routing scheme (Kar, Kodialam, & Lakshman, 2000; Qi, Biaz, Wu, & Ji, 2007). In the above mentioned works, the interference that is quantified does not refer to the interference received from the physical layer (i.e., signal strength). Rather, there has been a consistent focus on the level of interference in terms of distance using the protocol interference model because of ease of implementation. Limited research on SINR based routing schemes exist. Furthermore, in terms of interference based multipath routing, research has focused on the use of straightforward methods to quantify interference. Specifically, in (Teo, Ha, & Tham, 2008), the authors use an extension of the correlation factor (correlation factor is defined as the number of links connecting two paths) which captures interpath interference but provides little information about the level of interference between simultaneous transmissions. In addition to interference based routing, guaranteeing QoS provisions has also been investigated within this context (Wen & Lin, 2007; Xu, Huang, & Cheng, 2008). Providing fault tolerance and QoS provisioning in the presence of interference are major issues that must be studied jointly in wireless systems in order to gauge a realistic sense of network performance, particularly in terms of throughput.

Chapter Objectives

The purpose of this chapter is to provide a framework for interference aware resource allocation by studying multipath routing and fairness as discussed above. The objectives of this chapter are twofold and can be summarized as flows: First, an isotonic loop free routing metric is designed which is cognizant of interference and provides reliable multipath routing. The routing metric is used to quantify the interference on the network links such that least interfering paths can be obtained. The Routing with Interflow and Intraflow Interference Metric (RI^3M) captures both interflow and intraflow interference while balancing link loads. The isotonicity of the RI^3M routing metric is proven through virtual network decomposition and is used to find disjoint paths from each user to the base station. Second, an MMF optimization formulation to find the largest (lexicographically largest) bandwidth allocation vector for user traffic demands is discussed. This algorithm is referred to as the Lexicographic MMF Multipath Flow ($LMX{:}M^3F$) algorithm and explicitly considers the constraints of the wireless interference on the individual flows.

This chapter will show that the proposed routing metric and bandwidth allocation formulation improves bandwidth usage, throughput, and delay in comparison to existing interference aware fair bandwidth allocation algorithms[1].

BACKGROUND

Interference and Fairness in Routing

With the use of multihop relaying, increasing number of users, and limited spectrum, wireless multihop BWA networks are limited by two main resources: bandwidth and network capacity. While bandwidth refers to the achievable data rate, capacity refers to the data transport capacity available for each link in the network. Achieving high throughput and fair allocation of resources among competing users (or flows) in wireless networks is one of the most important problems in data communications. However, these two objectives may conflict with each other (Cheng

& Zhuang, 2008). In resource allocation, two situations must be avoided: 1) a flow must not be starved because of inefficient resources for transmission (i.e., bandwidth); and 2) a flow must not be provided more resources than necessary since only some of the resources may be used and the remaining will be wasted. Resources can be utilized efficiently if only the terminal with the best channel condition transmits, whereby the maximum throughput can be acquired. Such an opportunistic transmission, however, gives rise to unfairness and possibly violates the QoS requirements of some wireless nodes. The concept of fairness in wireless networks is a QoS policy and can be applied to various design issues such as scheduling and routing (Tassiulas & Sarkar, 2005; Maatta & Braysy, 2009).

The classic MMF problem was originally defined for wired networks in order to allocate bandwidth to a set of given routes (Bertsekas & Gallagher, 1992). Research on MMF routing in the wired environment can be split into two categories: nonsplittable and splittable (multipath). In the nonsplittable case (Bertsekas & Gallagher, 1992; Kleinberg, Rabani, & Tardos, 2001), a MMF distribution of resources (bandwidth) to connections is done for fixed single path routing. In the splittable (multipath) MMF routing case, the traffic demands are allowed to be split among multiple flows (paths) (Nace, 2002; Nace, Doan, Gourdin, & Liau, 2006; Allalouf & Shavitt, 2008; Nace, Doan, Klopfenstein, & Bashlari, 2008). It has been shown in (Nace & Pioro, 2008) that multipath (splittable) demand routing is a linear relaxation of the nonsplittable case, thus rendering the problem computationally tractable. To improve the transmission reliability and increase the probability of network survivability, the multiple paths can be selected to be link or node disjoint.

An important feature of multipath routing is the ability to provide QoS in terms of fair bandwidth allocation. Fairness based routing protocols that use the max-min model have been recently proposed in the literature (Pal, 2008; Huang, Feng, & Zhuang, 2009; Mansouri, Mohsenian-Rad, & Wong; Tang, Hincapie, Xue, Zhang, & Bustamente, 2010; Chou & Lin, 2009). All these works focus on the lexicographic (node ordering) optimization of routing for fair bandwidth allocation. These solutions can lead to high throughput solutions with guaranteed max-min bandwidth allocation value. However, they are formulated for ideal scenarios. Specifically, the inherent influence of interference has not been taken into account.

Interference Based Routing Metrics

Providing fault tolerance and QoS provisioning in the presence of interference are major issues that must be studied jointly in wireless networks in order to get a realistic sense of network performance. Developing routing metrics has long been the central focus of network layer protocol design. To compute paths using an interference aware routing metric is essentially equivalent to computing minimum weight (shortest) paths where the link weight is generated by the routing metric. In order to efficiently compute minimum weight paths using algorithms such as Dijkstra's shortest path or Bellman-Ford, the routing metric must be isotonic. The isotonic property essentially means that a routing metric should ensure that the order of the weights of two paths are preserved if they are appended by a common third path. In addition, isotonicity ensures loop free routing. If a routing metric is not isotonic, only algorithms with exponential complexity can calculate minimum weight paths, which is not tractable for networks of even moderate size (Yang, Wang & Kravets, 2005). The two most prominent metrics are Expected Transmission Count (ETX) (De Couto, Aguaya, Bicket, & Morris, 2003) and Expected Transmission Time (ETT) (Draves, Padhye & Zill, 2004). ETX is defined as the expected number of MAC layer transmissions needed to successfully deliver a packet through a wireless link. ETT improves upon ETX by considering the differences in transmission rates. Although both metrics are isotonic, neither considers interference. The earliest metric to consider interference is Weighted Cumulative ETT (WCETT) (Draves et al., 2004). This metric essentially captures intra-flow interference by reducing the number of nodes on a path of a flow that transmit on the same channel; it gives low weight to paths that have more diversified channel assignments. However, WCETT does not capture interflow interference and is not isotonic which prevents the use of an efficient loop free routing algorithm to compute minimum weight paths. The Metric for Interference and Channel switching (MIC) (Yang et al., 2005) improves WCETT by capturing interflow interference and overcomes the non-isotonicity problem. However, MIC does not measure interference dynamically, meaning that changes to interference level over time due to signal strength and traffic load may not be captured accurately. The Interference AWARE (iAWARE) routing metric (Subramanian et al., 2006) computes paths with lower interflow and intraflow interference than MIC and WCETT. It uses SNR and SINR to continuously monitor neighboring interference variations. Yet, iAWARE is not isotonic. Recently, improvements to the ETX and ETT metrics such as Interferer Neighbor Count (INX) were proposed in (Langar et al., 2009). Similar to MIC, INX takes into account interference through the number of links that can interfere on a link *l*. This metric performs better only in low traffic load conditions, and therefore load balancing is not completely resolved.

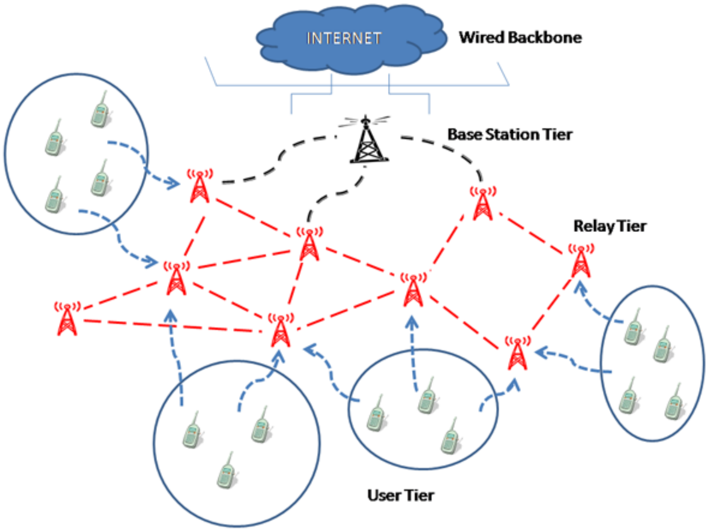
According to the main requirements of interference, load awareness and isotonicity, existing routing metrics address only some specific requirements. For this reason, in this chapter, a new routing metric is proposed in order to simultaneously address all of these aspects.

SYSTEM MODEL

The work presented in this chapter considers a multihop cellular network (MCN) consisting of a base station, *R* fixed relay stations and *N* users. The network topology is based on the MCN model used in emerging BWA networks (Park & Bakh, 2009). As shown in Figure 1, the proposed network architecture is based on three tiers of wireless devices: 1) set *N* of user nodes which are the lowest tier have limited functionality (i.e., do not communicate with one another and have no routing capability); 2) set *R* of relay nodes that route packets between the user and the base station is the second tier. They also communicate with one another; and 3) the base station is the highest tier and is connected to the wired infrastructure. In order to avoid single points of failure (i.e., failure of a relay node which will disrupt traffic flow), the relays are connected in a mesh manner so that multiple paths are available between the user and the base station, thereby increasing service availability and fault tolerance. Mesh networking is a promising technology for numerous applications (i.e., broadband networking) and has garnered significant attention as a cost effective way of deploying wireless broadband networks (Thulasiraman, Chen, & Shen, 2010). The combination of wireless mesh networks and relay networks has been discussed in the literature where the general structure of a mesh network has been incorporated with relaying aspects (Thulasiraman & Shen, 2010). The defined network architecture uses a wireless relay network structure that is enhanced with mesh networking capabilities.

This topology setup ensures that the network is at least 2-link connected (i.e., each node has at least two link connections to other nodes). In DMPR schemes, the disjointedness property ensures that when *k* multiple paths are constructed, no set of *k-1* link failures can disconnect all the paths. Through Menger's Theorem (Bagchi, Chaudhary, & Kolman, 2005), it has been shown that for two distinct nodes *x* and *y*, the minimum number of edges whose removal disconnects *x* and *y* is equal to the maximum number of pairwise link disjoint paths from *x* to *y*. Thus, in this case, 2-connectivity is a necessary and sufficient con-

Figure 1. Network architecture



dition to find a solution for two disjoint paths for each user node to the base station. Two-connectivity in wireless networks has been studied in (Thulasiraman et al., 2006; Thulasiraman et al., 2007)[2].

It is assumed that each relay node is equipped with omnidirectional transceivers and that relays are used purely for packet forwarding (i.e., relays do not inject traffic into the network). It is also assumed that each user and relay node has a maximum power level, P_{max}, where the P_{max} value is different for the user and relay node. It is also assumed that channels have been assigned to the links in the network using a generic link coloring approach. In addition, each node knows the geographic location of all the other nodes in the cell via location discovery schemes (Mauve, Widmer, & Hartenstein, 2001). This information is necessary for the receivers to feedback SINR measurements to their respective transmitters.

Interference Model

The network architecture is represented by a communication graph, $G = (V, E)$, where V is the set of nodes (relays, users and base station) and E is the set of edges. The physical interference model states that a communication between nodes u and v is successful if the SINR at v (the receiver) is above a certain threshold. The SINR for transmission between u and v is given as follows

$$SINR_{uv} = \frac{P_v(u)}{N + \sum_{w \in V'} P_v(w)} \geq \beta \qquad (1)$$

where $P_v(u)$ is the received power at node v due to node u, N is the noise power, V' is the subset of nodes in the network that are transmitting simultaneously and β is the SINR threshold.

In this chapter, both the protocol and physical interference models are considered, similar to the approach given in (Brar et al., 2006). To be specific, the following variation of the protocol model is used to accurately mimic the behavior of carrier sense multiple access/collision avoidance (CSMA/CA) relay based cellular networks (Park & Bakh, 2009). Let R_T^{max} (r_T^{max}) and $R_I^{max}(r_I^{max})$ represent the maximum transmission and interference ranges of each relay (user) node, respectively. All relay nodes use the same maximum transmission range (R_T^{max}) as do all the user nodes (r_T^{max}). Each wireless node i (either relay or user node) has a transmission range which is a circle in a 2D plane, centered at i with radius R_T^{max} (r_T^{max}). The transmission range represents the maximum distance up to which a packet can be received, while the interference range represents the maximum distance up to which simultaneous transmissions interfere. In the literature, the interference range is usually chosen to be twice as large as the transmission range which is not necessarily a practical assumption (Iyer et al., 2009). The actual values of the transmission and interference ranges depend on the transmission power used by the nodes. To provide realistic limits for R_T^{max} (r_T^{max}) and $R_I^{max}(r_I^{max})$, a method called a "reality check" is used. The reality check method, introduced in (Shi et al., 2009), essentially sets a realistic interference range in which links are assumed to interfere. For the protocol model, R_T^{max} (r_T^{max}) and $R_I^{max}(r_I^{max})$ are the only two parameters used. Since the underlying physical layer is the same, the parameter R_T^{max} (r_T^{max}) should be consistent with the β parameter in the physical model, as shown in Equation (1). Two nodes with distance R_T^{max} (r_T^{max}) should be able to communicate with each other under the maximum transmission power P_{max} and the SINR should be β. As a result, according to (Shi et al., 2009), R_T^{max} (r_T^{max}) is $\frac{P_{\max}}{\beta}$.

Note that the maximum interference range, R_T^{max} (r_T^{max}), is a parameter introduced by the protocol model and there is no corresponding parameter in the physical model. The only requirement on $R_I^{max}(r_I^{max})$ is $R_I^{max}(r_I^{max}) > R_T^{max}$ (r_T^{max}) i.e., a lower bound for $R_I^{max}(r_I^{max})$ is R_T^{max} (r_T^{max}). Thus, if the interference range is set to be slightly higher than the transmission range, $R_T^{\max}(r_T^{\max}) = \frac{P_{\max}}{\beta}$, then the solution is more realistic.

Since link layer availability is required for CSMA/CA, an acknowledgement (ACK) packet is generated by each receiver for every data packet it receives. Due to carrier sensing and RTS/CTS/ACK exchanges, a transmission along link $e = (u, v)$ (in either direction) blocks all simultaneous transmissions within the interference ranges of u and v. In the physical interference model, successful reception of a packet sent by node u to node v depends on the SINR at v. To be coherent with the link-layer availability, the physical interference model is extended as follows. It is assumed that a packet sent by node u is correctly received by node v if and only if the packet is successfully received by v, and the ACK sent by node v is correctly received by node u. Furthermore, for a transmission from node x to node y that is concurrent with the packet on (u,v), the interference from both node x's data packet and from node y's ACK is accounted for. Although only one of x and y transmits at a time, their data and ACK packets could both overlap with either the data packet or the ACK along (u, v). Thus, the maximum of the interferences from x and y is chosen when calculating the total interferences at u and v. Note that which of the two (x or y) contributes the maximum interference could be different at u and v. Thus, a packet sent along link (u, v) (in either direction) is correctly received if and only if:

$$SINR_{uv} = \frac{P_v(u)}{N + \sum_{(x,y)\in E'} \max(P_v(x), P_v(y))} \geq \beta \tag{2}$$

and

$$SINR_{vu} = \frac{P_u(v)}{N + \sum_{(x,y)\in E'} \max(P_u(x), P_u(y))} \geq \beta \tag{3}$$

where E' contains all the links that have simultaneous transmissions concurrent with the one on *(u,v)*.

It must be noted that optimization techniques to find an efficient algorithm that determines the collision domain and backoff times for each node based on the interference range have been studied in (Zhou & Mitchell, 2010). The authors propose closed-form expressions for the mean backoff time in terms of path flow variables, making it possible to optimize the network based on multipath routing. However, their approach is analytically complex. In addition, since the focus of this chapter is to incorporate the physical-layer interference into the protocol model, determining the optimal collision domain and wait periods is not relevant.

Isotonocity

As mentioned earlier, isotonicity reflects the ability of a routing metric to compute minimum weight and loop-free paths. Assume that for any path *a*, its weight is defined by a routing metric, which is a function of *a*, denoted as *W(a)*. Denoting the concatenation of two paths *a* and *b* by $a \oplus b$, isotonicity can be defined as follows:

Definition 3.1: isotonicity: A routing metric, *W(·)*, is isotonic if $W(a) \leq W(b)$ implies that both

$$W(a \oplus c) \leq W(b \oplus c)$$

and

$$W(c' \oplus a) \leq W(c' \oplus b),$$

for all *a, b, c, and c'*.

In (Yang et al., 2005) it was shown that isotonicity is a sufficient and necessary condition for both the Bellman-Ford and Dijkstra's algorithms to find minimum weight paths that are loop free. Therefore if a routing metric can be proven to be isotonic, any variation of a shortest path algorithm can be used to route packets in a wireless network.

ROUTING WITH INTERFLOW AND INTRAFLOW INTERFERENCE METRIC (*RI³M*)

Problem Formulation

The *RI³M* interference routing metric takes into consideration the following three factors: interflow interference, intraflow interference, and traffic load. Interflow interference generally results in bandwidth starvation for some nodes since a flow contends for bandwidth along its own path and its neighboring area. To prevent such starvation, the routing metric must balance the traffic load along the path of the flow and reduce the interflow interference imposed in the neighboring area. *RI³M* consists of two components. The first component, *IL*, deals with interflow interference and load awareness. The second component, channel switching cost *CSC*, captures intraflow interference. The interference aware routing metric can be formalized as follows. Let *G(V,E)* be an undirected, two-connected network, where *V* is the set of nodes and *E* is the set of links. Let *p* be a path from a user node to the base station. *RI³M* is defined as follows:

$$\sum_{\forall(i,j)\in p} IL_{ij} + \sum_{\forall i\in p} CSC_i \tag{4}$$

where node *i* represents a node on path *p* and link *(i,j)* represents a link on the path *p*.

IL_{ij} Component

The IL_{ij} component is intended to depict information about the interflow interference and traffic load simultaneously. It consists of two separate subcomponents. To capture the interflow interference, the concept of the interference ratio (*IR*) (Subramanian et al., 2006), which is based on the physical interference model, is used. The *IR* depicts the interference based on the ratio between SNR and SINR. The *IR* captures interference by monitoring the signal strength values. When there is no interference (i.e., no interfering neighbors or no traffic generated by interfering neighbors), the SINR of link *(i,j)* is independent of the interflow interference and the quality of the link is determined by the intraflow interference component. Equation (5) shows the *IR* ratio:

$$IR_{ij} = \frac{SINR_{ij} + SINR_{ji}}{SINR_{ij}} \tag{5}$$

where SNR is given by $\frac{P_j(i)}{N}$ and the SINR in the numerator is the sum of the SINR values given in Equations (2) and (3).

To estimate the traffic load on a wireless relay node, a typical approach is to measure the traffic volume going through the corresponding node in terms of byte rate or packet rate. Unfortunately, this approach is unable to give an accurate estimate of the usage of the radio channel at which the node operates because the total capacity of the network is not fixed and depends on many factors, such as the physical transmission rate of each relay node, frame size, number of retransmissions, interference, etc. Simply counting the bytes or even packets going through a relay node fails to take into account these factors. In light of these limitations, the authors of (Athanasiou, Korakis, Ercetin, & Tassiulas, 2009) adopt an alternative approach to estimate the traffic load, which is based on the percentage of channel time of the relay node that is consumed for frame transmission.

To measure the traffic load, the concept of Channel Busy Time (*CBT*) is used. A radio channel's time consists of a series of interleaved busy periods and idle periods. A busy period is a time period in which one node attempts to transmit frames, while other nodes hold off their transmission. An idle period is a time period in which every node considers the radio medium available for access. Using the *CBT*, it is possible to estimate the traffic load (channel utilization) on each link. The *CBT* calculation is the percentage of time that a channel is busy (transmitting). In order to compute this time, the different states that a node can be assigned must be defined first:

- **Success:** This state refers to the case where a node has successfully received the acknowledgment of the packet it has sent.
- **Backoff:** Even though a node has some data to transmit and the medium is free, there is a random waiting period (during which the wireless medium has to remain idle) before it starts sending its data.
- **Wait:** If there are ongoing transmissions within the interference range of the node which causes the SINR threshold to drop below β, it has to wait until the ongoing communications are completed before starting its own.
- **Collision:** In this state, a node which has sent a packet never receives an acknowledgment for this packet.

Let $T_{success}$, $T_{backoff}$, T_{wait}, and $T_{collision}$ be the time spent in the states Success, Backoff, Wait, and Collision, respectively. The idle time (i.e., time where there is no data to keep the channel busy), T_{idle}, considers backoff times, collision times, and the waiting times. Thus, the percentage of time the channel spends idle is defined as

$$T_{idle} = \frac{T_{backoff} + T_{collision} + T_{wait}}{T_{backoff} + T_{collision} + T_{wait} + T_{success}} \tag{6}$$

Let us denote the denominator of Equation (6) as the total time T_{total}. Then, the *CBT* for a link *(i,j)* is defined as

$$CBT_{ij} = \frac{T_{total} - T_{idle}}{T_{total}} \tag{7}$$

The *CBT* is used as a smoothing function, weighted over IR_{ij}. Using the IR_{ij} and CBT_{ij} subcomponents, IL_{ij} is defined as follows:

$$IL_{ij} = (1 - IR_{ij}) * CBT_{ij} \tag{8}$$

where $0 \leq IR \leq 1$ and $0 \leq CBT \leq 1$.

CSC Component

To reduce the intraflow interference, the RI^3M routing metric uses the *CSC* component. *CSC*, originally defined in (Yang et al., 2005), designates paths with consecutive links using the same channel with higher weight than paths that alternate their channel assignments. This allows paths with more diversified channel assignments to be favored in the routing process. Intraflow interference can occur between successive nodes on a path, however, depending on the interference range, it can also occur between nodes further away along the path. In this case, it is necessary to consider the channel assignments at more hops in order to choose an effective path that reduces intraflow interference. To eliminate the intraflow interference between node *i* and its previous hop, *prev(i)*, node *i* must transmit to the next hop, *next(i)*, using a different channel from the one it uses to receive from *prev(i)*. *CSC* denotes *CH(i)* as the channel that node *i* transmits on to *next(i)*. The *CSC* of node *i* for intraflow interference reduction of successive nodes is given as

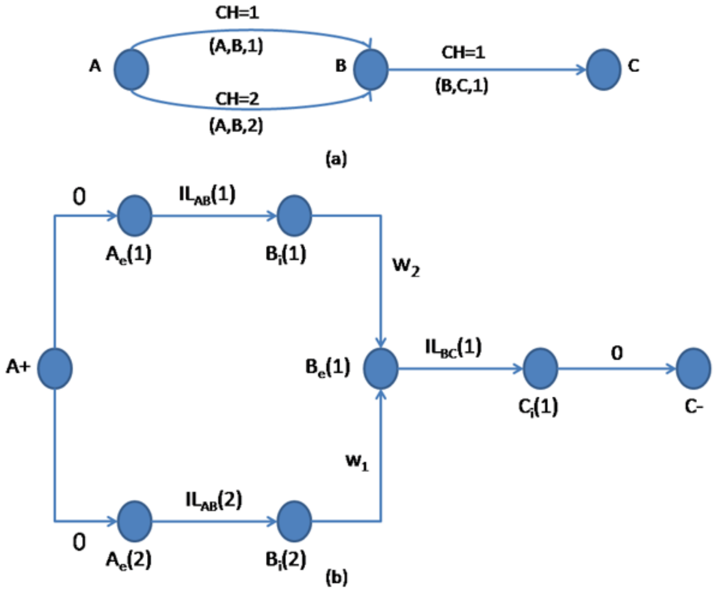
$$CSC_i = \begin{Bmatrix} w_1, & \text{if } CH(prev(i)) \neq CH(i) \\ w_2, & \text{if } CH(prev(i)) = CH(i) \end{Bmatrix} \tag{9}$$

where $w_2 \geq w_1 \geq 0$ to ensure that a higher cost is imposed for those nodes that transmit on the same channel consecutively. In order to capture intraflow interference between two nodes that are two hops away, node *i* interferes with both nodes *prev(i)* and $prev^2(i)$, where $prev^2(i)$ is the node that is the two hop precedent of *i*. According to (Yang et al., 2005), the multihop extension of the *CSC* equation of Equation (9) is Equation (10) where w_3 captures the intraflow interference between nodes $prev^2(i)$ and *i* and w_2 captures the intraflow interference between nodes *prev(i)* and *i*. The weight w_3 must be strictly less than the weight w_2 because since the further away that two nodes are, the less interference exists between them. The intraflow interference is considered to be up to the limit of a node's interference range which is typically within a three hop range.

Equation 10.

$$CSC_i = \begin{Bmatrix} w_2, & \text{if } CH(prev^2(i)) \neq CH(i) = CH(prev(i)) \\ w_3, & \text{if } CH(prev^2(i)) = CH(i) \neq Ch(prev(i)) \\ w_2 + w_3, & \text{if } CH(prev^2(i)) = CH(i) = CH(prev(i)) \\ w_1, & \text{otherwise} \end{Bmatrix}$$

Figure 2. (a) Example to illustrate the non-isotonocity of the RI^3M routing metric; (b) Decomposition of the network in (a) into a virtual network to show that RI^3M is isotonic



Virtual Network Decomposition to Illustrate Isotonicity

The RI^3M routing metric is not isotonic if used directly. This can be seen in the example network given in Figure 2a. In the example, a link is represented by three parameters: starting node of the link, ending node of the link, and the channel the link transmits on. If it is assumed that link $(A,B,1)$ has a smaller RI3M value than link $(A,B,2)$, the weights of paths $(A,B,1)$ and $(A,B,2)$ satisfy: $RI^3M(A,B,1) < RI^3M(A,B,2)$. However, adding path $(B,C,1)$ to path $(A,B,1)$ introduces a higher cost than adding $(B,C,1)$ to $(A,B,2)$ because of the reuse of channel 1 on path $(A,B,1) \oplus (B,C,1)$. Thus

$$RI^3M((A,B,1) \oplus (B,C,1)) \\ > RI^3M((A,B,2) \oplus (B,C,1)),$$

which does not satisfy the definition of isotonicity.

To make RI^3M into an isotonic routing metric, a decomposition technique is used that creates a virtual network from the real network and decomposes RI^3M into isotonic link weight assignments on the virtual network. First introduced in (Yang et al., 2005) to prove the isotonicity of the MIC routing metric, the decomposition of RI^3M is based on the fact that the non-isotonic behavior of RI^3M is caused by the different increments of path weights due to the addition of a link on a path. Whether a cost increment will be different by adding a link is only related to the channel assignment of the previous link on the path. Since the possible assignments of channels for the precedent link are limited, several virtual nodes are introduced to represent these possible channel assignments. Namely, for every channel *c* that a node *X*'s radios are configured to, two virtual nodes $X_i(c)$ and $X_e(c)$ are introduced. $X_i(c)$ indicates that node *prev(X)* transmits to *X* on channel *c*. $X_e(c)$ indicates that node *X* transmits to its next hop, *next(X),* on channel *c*. The subscript *i* stands for ingress and the subscript *e* stands for egress. In addition, two additional virtual nodes are introduced, *X*- and *X*+, which represent the start and end nodes of a flow (i.e., *X*- is used as the virtual destination node for flows destined to node *X* and *X*+ is used as the virtual source node for flows starting at node *X*. Hence, *X*+ has a link weight with 0 pointing to each egress virtual node and *X*- has a link weight 0 pointing away from each ingress virtual node of *X*.

Links from the ingress virtual nodes to the egress virtual nodes at node *X* are added and the weights of these links are assigned to capture different *CSC* costs. Link ($X_i(c), X_e(c)$) represents that node *X* does not change channels while forwarding packets, and hence, weight w_2 is assigned to this link. Similarly, weight w_1 is assigned to link, ($X_i(c), X_e(c1)$) where $c \neq c1$, to represent the low cost of changing channels while forwarding packets. Links between the virtual nodes belonging to different real nodes are used to capture the *IL* weight. Figure 2b shows the virtual decomposition of Figure 2a.

By building the virtual network from a real network, RI^3M is essentially decomposed in the real network into weight assignments to the links between virtual nodes. This is because the RI^3M weight of a real path in a real network can be reconstructed by aggregating all of the weights of the virtual links on the corresponding virtual path. The *IL* part of RI^3M is reflected in the weight of the links between virtual nodes in different real nodes. The *CSC* costs are captured by routing through different virtual links inside real nodes.

Multipath Routing Using RI^3M

Now that RI^3M has been shown to be isotonic using a virtual network decomposition, it can be used with any shortest path algorithm to find least interfering (minimum weight) paths. The problem of finding two link disjoint paths (primary and backup) of minimum total weight across a network has been dealt with efficiently by Suurballe's algorithm (Bhandari, 1999). The algorithm developed by Suurballe has become the reference algorithm for finding link disjoint paths in wireless networks. Suurballe's algorithm always finds two link disjoint paths from a source node to the destination, as long as the paths exist in the network, assuring the total weight of both paths is the minimum among all pairs of paths in the network. Suurballe's algorithm is run on the virtual network $G_v(V_v,E_v)$, where V_v and E_v are the nodes and links of the virtual network, respectively. The link weights are determined by the values of the RI^3M routing metric. Due to space constraints, the steps of Suurballe's routing algorithm are omitted in this chapter. For further details of Suurballe's algorithm, refer to (Bhandari, 1999).

LEXICOGRAPHIC MMF MULTIPATH FLOW (*LMX:M³F*) ROUTING ALGORITHM WITH INTERFERENCE CONSTRAINTS

Problem Formulation

In this chapter, the MMF bandwidth allocation problem is modeled as a multicommodity flow (MCF) problem. The MCF problem is a network flow problem where multiple commodities (demands) flow through the network (Shahrokhi & Matula, 1990). It is assumed that each demand has two candidate paths (where the paths are determined by using RI^3M). Thus, the flows realizing each demand volume are split among the allowable paths. In the remainder of this chapter, vectors will be denoted with an arrow overhead. Optimal vectors will be denoted as regular vectors except with an additional star (*).

Definition: multicommodity flow: Given *D* demands, let $\delta_{edp}x_{dp} \geq 0$ be the flow allocated to path *p* of commodity (demand) *d*, $d \in D$ in link $e \in E$, where δ_{edp} is a binary variable that denotes whether link *e* belongs to path *p* or not. Also, consider a vector $\vec{X}_d = (x_{dp} : \forall p, d \in D)$ as a single commodity flow of commodity *d*. A multicommodity flow is the union of flows for each commodity. Specifically, $\vec{X} = (\vec{X}_d : d \in D)$ is a feasible multicommodity flow if $\sum_{d \in D} \sum_{p \in P_d} \delta_{edp} x_{dp} \le C_e, \forall e \in E$.

The capacity of link $e \in E$ is denoted C_e and is mathematically expressed as

$$C_e = \log_2(1 + SINR_e) \ge \beta \tag{11}$$

where $SINR_e$ is given in Equation (1).

In this chapter, the objective is to attain the MMF bandwidth allocation vector under interference constraints where the allocation vector is lexicographically the largest possible.

Definition: An n-vector $\vec{x} = (x_1, x_2, ..., x_n)$ sorted in non-decreasing order $(x_1 \le x_2 \le ... \le x_n)$ is *lexicographically greater* than another n-vector $\vec{y} = (y_1, y_2, ..., y_n)$ sorted in non-decreasing order $(y_1 \le y_2 \le ... \le y_n)$ if an index *k*, $0 \le k \le n$ exists, such that $x_i = y_i$ for $i = 1, 2, ..., k$ and $x_k > y_k$.

In the following section, the formulation of the lexicographic bandwidth allocation algorithm will be discussed using the interference-aware routing metric, *RI³M,* that was developed earlier in the chapter.

LMX:M³F Algorithm

Given the network *G*, paths for routing the traffic flow are found by using the routing metric, *RI³M,* and running Suurballe's multipath routing algorithm. Given these paths, the formulation of the lexicographically largest allocation vector using MMF considering interference constraints and the subsequent methodology used to solve it is provided. The *LMX:M³F* formulation is given in Equations (12)-(15) (referred to as Problem A in the remainder of the chapter) and follows a multicommodity flow approach.

LMX:M³F

Problem A

Objective: Find the total bandwidth allocation vector such that it is lexicographically maximal among all total bandwidth allocation vectors.

$$\text{lexicographically maximize } \vec{\text{X}} \tag{12}$$

subject to

$$\sum_{p \in P_d} x_{dp} = X_d, \qquad \forall d \in D \tag{13}$$

$$\sum_{d \in D} \sum_{p \in P_d} \delta_{edp} x_{dp} \le C_e, \qquad \forall e \in E \tag{14}$$

$$x_{dp} \ge 0 \tag{15}$$

where P_d are the paths for demand *d*, x_{dp} is the flow (bandwidth) allocated to demand path *p* of demand *d*, and X_d is the total flow (bandwidth) allocated to demand *d*, $\vec{X} = (X_1, X_2, ..., X_D)$.

In order to find the MMF allocation vector for the corresponding paths, the quantity known as the *demand satisfaction vector* $\vec{t}$ is defined. Let $\gamma_d \ge 0$ be the flow value of x_{dp}, and $\zeta^+(v)$ and $\zeta^-(v)$ be the outgoing and incoming links to node *v*, respectively. The law of flow conservation states that

$$\sum_{e \in \zeta^+(v)} x_{dp} - \sum_{e \in \zeta^-(v)} x_{dp} = \left\{ \begin{matrix} \gamma_d, & \text{if } v = \text{base station} \\ -\gamma_d, & \text{if } v = \text{ source} \\ 0, & \text{otherwise} \end{matrix} \right\} \tag{16}$$

A feasible multicommodity flow $\vec{X}$, with $\gamma_d \geq h_d,\ d \in D$ defines an admissible flow (bandwidth), where h_d is the amount of demand to be routed. Assume that $\vec{X}$ is feasible and also consider a vector $\vec{t} = (t_d \geq 0 : d \in D)$ such that $\gamma_d = t_d h_d$ in Equation (16). If $t_d \geq 1$ for all $d \in D$, then the flow is admissible (i.e., it fulfills the demand requirement $h_d, d \in D$). Thus, $\vec{t}$ is denoted as the demand satisfaction vector for routing vector $\vec{X}$. Specifically, the physical meaning of the value *t* is the amount that is added to saturate/satisfy x_{dp}. The optimization formulation given in Equations (17)-(21) (referred as Problem B in the remainder of the chapter) is used to solve for *t*.

Problem B

$$\text{maximize } t \tag{17}$$

subject to

$$X_d = \sum_{p \in P_d} x_{dp}, \qquad \forall d \in D \tag{18}$$

$$t - X_d \leq 0, \quad \forall d \in D \tag{19}$$

$$\sum_{d \in D} \sum_{p \in P_d} \delta_{edp} x_{dp} \leq C_e, \qquad \forall e \in E \tag{20}$$

$$x_{dp} \geq 0 \tag{21}$$

The objective function in Equation (17) and the constraint in Equation (19) are equivalent to the ultimate objective to be achieved given in Equation (22):

$$\max \min \ X_d : d \in D \tag{22}$$

Problem A can be solved by computing consecutively the value of the demand satisfaction vector of Problem B. Primarily, the idea is that first, the lowest value among the components of $\vec{t}$ has to be maximized before the second lowest value is maximized. In order to ensure that the demands are satisfied, it is necessary to check which total demand allocations, X_d, can be further increased. A demand *d* whose satisfaction value t_d cannot be further increased is called blocking (Nace & Pioro, 2008). To check the satisfaction of a demand, the following linear program (LP) (Equations (23)-(27)), referred to as Problem C, is solved for each demand *d*.

Problem C

$$\text{maximize } X_d \tag{23}$$

subject to

$$X'_d = \sum_{p \in P_{d'}} x_{d'p}, \qquad \forall d' \in D \tag{24}$$

$$t_{d'} - X_{d'} \leq 0, \qquad \forall d' \in D \tag{25}$$

$$\sum_{d' \in D} \sum_{p \in P_{d'}} \delta_{ed'p} x_{d'p} \leq C_e, \qquad \forall e \in E \tag{26}$$

$$x_{d'p} \geq 0 \tag{27}$$

where $t_{d'}$ are constants. To put Problem C in perspective, let *t** be the optimal solution of the LP. A demand is nonblocking (can be further increased) if the optimal X_d value, X^*_d, is strictly greater than *t** (i.e., $X_d^* > t^*$).

The components of Problem B and Problem C are used in conjunction to solve the original *LMX:M³F* (Problem A) problem. The algorithm for solving *LMX:M³F* is given as follows:

Step1: Solve Problem B. Let $(t^*, \vec{x}^*, \vec{X}^*)$ be the optimal solution of Problem A. Initialize: $k := 0$ (number of iterations), $Z_0 := \varnothing$ (set of demands that are blocking/saturated), $Z_1 = \{1, 2, ..., D\}$, and $t_d := t^*$ for each $d \in Z_1$.

Step2: $k := k + 1$. Consider each demand, $d \in Z_1$, one by one to check whether the total allocated bandwidth X_d^* can be increased more than t^* without decreasing the already found maximal allocations $t_d^{'}$ for all other demands, $d^{'}$. To check the demands, solve Problem C. If there are no blocking demands in Z_1, go to Step3. Otherwise for blocking demand d, add d to set Z_0 and delete it from set

$$Z_1, Z_0 := Z_0 \cup \{d\}, Z_1 := Z_1 \setminus \{d\}.$$

If $Z_1 = \varnothing$ STOP. Then,

$$\vec{X}^* = (X_1^*, X_2^*, ..., X_D^*) = (t_1, t_2, ..., t_d)$$

is the solution of Problem A.

Step3: To improve the current best bandwidth allocation, solve the following LP (Problem D).

$$\text{maximize } t$$

subject to

$$X_d = \sum_{p \in P_d} x_{dp}, \qquad \forall d \in Z_1$$

$$t - X_d \le 0, \qquad \forall d \in Z_0$$

$$\sum_{d \in D} \sum_{p \in P_d} \delta_{edp} x_{dp} \le C_e, \qquad \forall e \in E$$

$$x_{dp} \ge 0$$

Let $(t^*, \vec{x}^*, \vec{X}^*)$ be the optimal solution of Problem D. Put $t_d := t^*$ for each $d \in Z_1$. Go to Step2.

PERFORMANCE EVALUATION

Simulation Model and Performance Metrics

For the simulations, a two-connected cellular network *G* in a 900 x 900 m^2 region where all nodes are stationary is considered. Each user generates traffic and the flows are routed to and from the base station. NS-2 is used to simulate the networks and CPLEX is used to solve the optimization formulation for *LMX:M^{3}F*. The base station is located in the center of the network. Locations for the set of relay nodes that form the mesh network and the users are randomly generated. It is assumed that the base station and relays have an infinite buffer, thus eliminating complications due to buffer overflow. The simulation parameters used are as follows: system bandwidth (W) = 1MHz, additive white Gaussian noise (AWGN) = -90 dBW/Hz; transmission power: relay (35 dBm), user (24 dBm) (note that the power levels of the nodes are such that it is sufficient to allow nodes to connect to at least two of its neighbors, ensuring two-connectivity); physical layer specification: 802.11; number of channels per radio: 12; and antenna: omnidirectional. To evaluate the performance of *RI^{3}M*, the following performance metrics are studied: 1) end-to-end delay (amount of time it takes to deliver packets from the client node to the base station) and 2) flow throughput. Twenty simulations are run for each set of data and the average results are shown. To evaluate the performance of *LMX:M^{3}F*, the following performance metrics are adopted: 1) bandwidth blocking ratio (BBR): BBR represents the percentage of the amount of blocked traffic over the amount of bandwidth requirements of all traffic requests (connection requests) during the entire simulation period; 2) total bandwidth usage: this measurement helps examine whether the *LMX:M^{3}F* algorithm can save more network resources (use less) than other established MMF routing algorithms that incorporate interference; and 3) link load: measurement that indicates the traffic load on each link due to different routing approaches. Note that the performance evaluation of *LMX:M^{3}F* is based upon the paths determined from using the *RI^{3}M* routing metric.

As benchmarks for evaluating the effectiveness of the proposed routing metric, five other routing metrics in the literature are used for comparison. Specifically, ETX (De Couto et al., 2003), ETT (Draves et al., 2004), MIC (Yang et al., 2005), iAWARE (Subramanian et al., 2006), and INX (Langar et al., 2009). Each metric is used with Suurballe's disjoint multipath routing algorithm. The proposed routing metric is also used with two disjoint multipath routing algorithms. First, the algorithm developed in (Kortebi, Gourhant, & Agoulmine, 2007) introduces a routing metric where a node calculates the SINR to its neighboring links based on a 2-Hop interference estimation algorithm (2-HEAR). Second, the algorithm developed in (Teo et al., 2008) provides an interference minimized multipath routing (I2MR) algorithm that increases throughput by discovering zone disjoint paths using the concept of path correlation. As benchmarks for evaluating the effectiveness of the bandwidth allocation algorithm, *LMX:M^{3}F* is compared to two MMF bandwidth allocation algorithms that consider interference when allocating bandwidth. First, the algorithm developed in (Tang et al., 2005) is an interference-based routing and bandwidth algorithm, known as MICB. The protocol model is used to create an auxiliary graph such that the maximum interference level within the network does not exceed a maximum value. Second, the algorithm described in (Wang et al., 2008) quantifies interference through the creation of contention graphs where interfering flows are captured in multihop wireless networks. The implementations of these algorithms are modified so that multiple paths are considered.

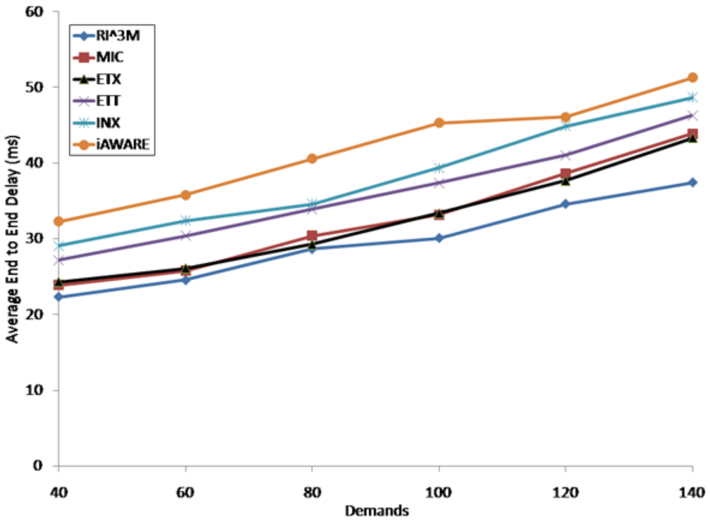
Simulation Results and Discussion

RI^{3}M is evaluated first in terms of end-to-end delay. The end-to-end user demand delivery delay is used as a metric to evaluate the impact of the interference quantification method of *RI^{3}M* in comparison to the existing routing metrics and the two established disjoint multipath routing algorithms. To measure the end-to-end delay, the transmitting rate of the user and relay nodes are set to 4.5 Mbps. All routing flows are CBR flows with 512 byte packets. To model the packet dropping error, for a given SINR value, the packet error ratio (PER) (Takai, Martin, & Bragodia, 2001) is used, which is readily available in NS-2.

Performance Evaluation of RI^{3}M

RI^{3}M is first compared with the existing routing metrics. Networks with 100 nodes (1 base station, 6 relays, and 93 user nodes) are simulated. Figure 3 shows the average end-to-end delay values of *RI^{3}M* versus the other routing metrics, measured against varying demands (traffic load). It can be seen that the proposed *RI^{3}M* routing metric achieves the lowest delay in comparison to the other metrics, particularly as demands increase. It can be said that *RI^{3}M* quantifies interference more accurately because it considers the influence of interflow and intraflow interference which thereby allows us to avoid paths with high interference, and reduce the time taken to deliver a packet. The remaining metrics behave somewhat similarly because most of them are derived from one another. Therefore, despite small implementation differences, there is no overarching performance improvement among the remaining metrics (i.e., ETT, ETX, MIC, and iAWARE). As can be seen from Figure 3, the delay values for all the metrics

Figure 3. Average end-to-end delay values for RI^3M compared to prominent routing metrics in the literature



(including *RI^3M*) increase as demands increase, which intuitively is true.

In Figure 4, the average end-to-end delay values for *RI^3M* with Suurballe's algorithm, referred to as SRA-*RI^3M* in the simulation graphs, is compared to the two aforementioned disjoint multipath routing algorithms. They are referred to as 2-HEAR and I2MR in the simulation graphs. The SRA-*RI^3M* achieves the lowest end-to-end delay compared to the other algorithms. The better performance of the SRA-*RI^3M* can be justified as follows: In both 2-HEAR and I2MR, the paths are formed using incomplete interference information. In 2-HEAR, the SINR calculated by each

Figure 4. Comparison of average end-to-end delay for Suurballe's disjoint multipath routing algorithm using RI^3M (SRA-RI^3M) and two established disjoint multipath routing algorithms: I2MR and 2-HEAR

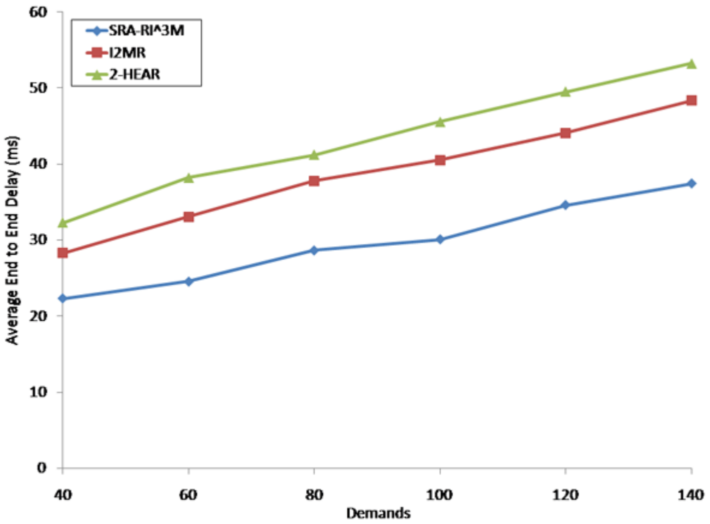
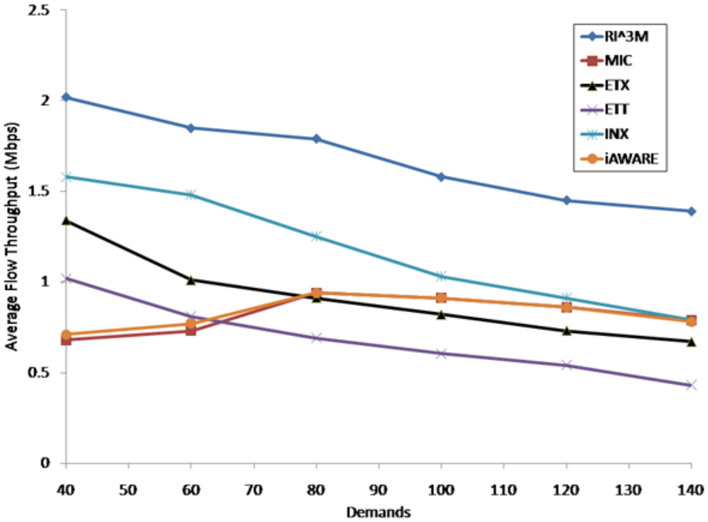


Figure 5. Average flow throughput generated by RI^{3}M versus prominent routing metrics in the literature



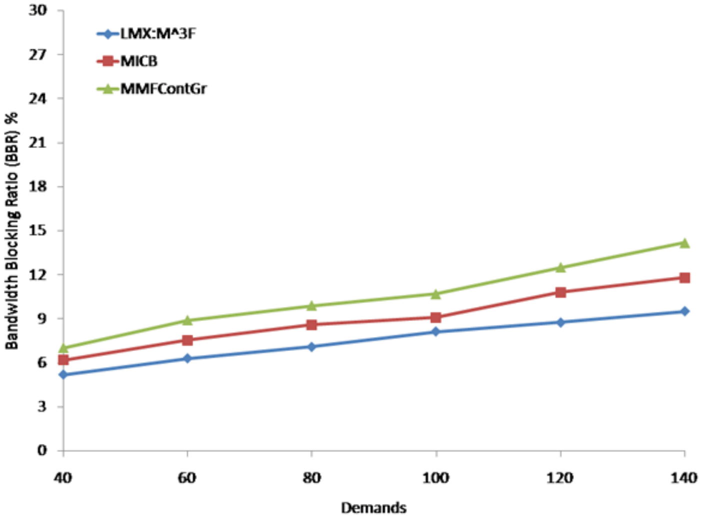
node only includes those nodes within a 2-hop range which means that even if interference beyond this range occurs, it is not captured in the routing metric (interflow and intraflow interference not fully accounted for). If the interference level is high beyond the 2-hop range, then any paths built may not be successful as interference may cause a drop in packets and a retransmission is required. This obviously incurs delay. A similar argument can be used with the I2MR algorithm. In this case, *RI^{3}M* quantifies the interference from both within flows and in the neighboring area.

Next, the average flow throughput that results from the use of the various routing metrics is discussed. Figure 5 shows the average flow throughput using *RI^{3}M* and prominent routing metrics in the literature. It can be seen that MIC and iAWARE have the lowest throughput at low traffic demands in comparison to the other metrics. ETX and INX have better throughput with low loads, but their performance decreases with high traffic demands. In Figure 5, the ETT metric exhibits unstable behavior primarily because it overestimates link quality by inaccurately probing the channel. Moreover, ETT does not depend on the traffic load. Although MIC and iAWARE partially rely on ETT, these metrics employ normalization functions to smoothen ETT values, and therefore, become more stable. This indicates the unpredictability of the results for the three metrics: ETT, MIC, and iAWARE. The remaining metrics behave intuitively, i.e., lower throughput as demands increase. Overall, *RI^{3}M* is able to achieve higher throughput than the remaining metrics over the varying traffic demands shown.

Performance Evaluation of LMX:M^{3}F

For the *LMX:M^{3}F* algorithm, it is first evaluated in terms of BBR. It is compared with MICB (Tang et al., 2005) and MMFContGr (Wang et al., 2008), respectively, as shown in the simulation graphs. All three algorithms are run on networks with different densities. Figure 6 shows the BBR results from the simulated networks with 46 (6 relays and 40 users). The networks have only one base station each. It can be seen that the *LMX:M^{3}F* algorithm performs the best in most cases. The blocking ratio increases no matter which algorithm is used because of heavier traffic load. The average blocking ratio difference between the proposed solution of *LMX:M^{3}F* and that of MICB and

Figure 6. BBR comparison for networks with 46 nodes (6 relays and 40 users)



MMFContGr is 16 and 13 percent, respectively for the network of size 46 nodes. Essentially, the BBR indicates if a connection request for traffic is blocked. If traffic is blocked, it means that there is less bandwidth on a link than there should be to accommodate the offered traffic. For the best performance, the BBR should be kept as low as possible. Given the BBR results in Figure 6, the BBR of *LMX:M*^{3}*F* is lower than that of the MICB and MMFContGr algorithms. Therefore, it can be claimed that the network performance improves under the proposed algorithm. Similar results were observed with varying sizes of networks.

Next, the real-time network resource usage for all three algorithms is shown. Figure 7 shows the results of the bandwidth usage for the three algorithms. As expected, *LMX:M*^{3}*F* uses the least amount of bandwidth for varying demands. In the case of 46 nodes, on average, the bandwidth usage of *LMX:M*^{3}*F* compared to MICB and MMFContGr is 11 and 14 percent less, respectively. Similar simulations were conducted on networks with less density (i.e., less number of nodes) and it was observed that there was less clarity in the total bandwidth usage for such networks. In other words, there was little variation in bandwidth usage between the three algorithms. The conclusion is that the proposed algorithm is more effective in network resource usage in higher density networks. Given that BWA networks are generally used in dense urban settings, the *LMX:M*^{3}*F* fits the application. However, the *LMX:M*^{3}*F* algorithm is time consuming to solve for very large networks with thousands of demands because each demand must be checked for bandwidth satisfaction (see Problem C). Thus, the algorithm is limited to a certain extent because of scalability.

Lastly, the impact that the *LMX:M*^{3}*F* algorithm has on the load balancing of the network across various links is discussed. The *LMX:M*^{3}*F* algorithm is compared with that of an unbalanced routing scheme (no fairness incorporated) and a traditional max-min fair routing approach, which minimizes the load of only the maximally loaded link in the network (does not look for the lexicographically highest). Networks with 10 (2 relays and 8 users) nodes (each network has one base station) are simulated. Figure 8 shows the link load on various links for networks of 10 nodes. The link number represents each individually numbered link in the network. It can be seen that the unbalanced routing scheme has some links

Figure 7. Comparison of total bandwidth usage for networks with 46 nodes (6 relays and 40 users)

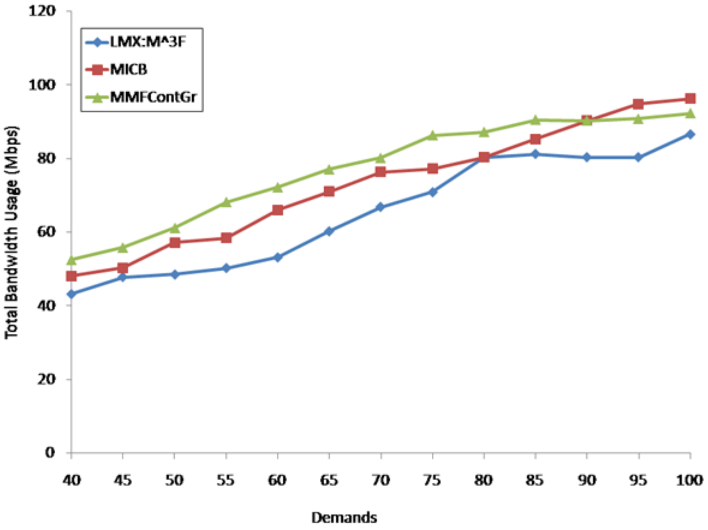
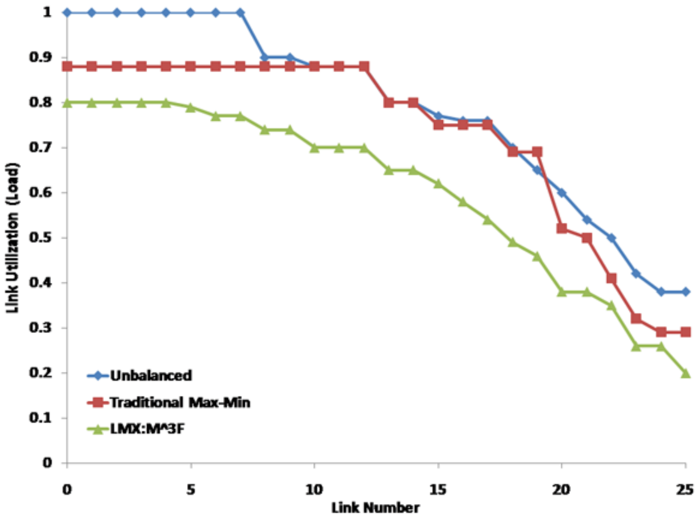


Figure 8. Link loads on various links for network with 10 nodes



with 100 percent utilization. When the traditional max-min routing approach is used, the link load utilization is better, but there are still some links that are nearly 90 percent loaded. The lexicographic bandwidth allocation algorithm performs an optimization of all the links and presents a better load balance of the traffic load, as can be seen in the results. It can be observed that the *LMX:M*^{3}*F* algorithm generally results in approximately 75 percent of the links having the same load. It can also be seen that the maximum load of any link is less than 1. This allows for spare capacity to exist on the link so that a proportionate increase in demands can be tolerated.

FUTURE RESEARCH DIRECTIONS

In this chapter, key research issues related to interference aware resource allocation have been presented. The results demonstrate the effectiveness of the proposed routing metric and the bandwidth allocation algorithm. From this research, important future research directions to improve system performance have been revealed. This chapter is the first step to understanding the impact of interference on resource management in broadband wireless access networks. Further research directions should address the following important issues.

Relay Node Displacement

Employing various relay nodes alleviates the problem of traffic congestion and single points of failure. In the presence of multiple gateways, traffic load can be balanced more effectively and efficiently, thereby facilitating traffic routing, packet scheduling, and QoS provisioning. With better traffic distribution, co-channel interference can be reduced to a greater extent. However, to achieve optimal interference reduction, the placement of the relay nodes has to be carefully determined. Interference aware algorithms for relay node placement need to be investigated to study the potential capacity gains that can be derived. Frequency reuse coupled with directional antennas can achieve interference mitigation.

Topology Control for Interference

Topology control is a technique used mainly in wireless ad hoc and sensor networks in order to reduce the initial topology of the network to save energy and extend the lifetime of the network. The main goal is to reduce the number of active nodes and active links, preserving the saved resources for future maintenance. Much of the research in the literature deals with topology control for energy consumption. The natural question that arises is what are the best topologies from the radio interference point of view? Answering this question can be simplified if all the nodes use the same transmit power level, however, that is not a practical scenario. Thus, setting an accurate transmitting range is critical for connectivity and reducing interference. The issue of determining interference-optimal topologies has not been addressed in the literature. This study would further enhance the deployment of broadband wireless access networks.

Handoff Management Exploiting SINR

Related to the relay placement problem, mobility plays a role in achieving interference limited performance. Handoff to base stations across a multi-cell network is an important aspect of mobility management. A handoff management architecture using the SINR of the present and neighboring base stations can improve service continuity. Maintaining this continuity is increasingly important for multimedia applications. Using a mobile user’s speed, handoff signaling delay information can be maintained while enhancing the handoff performance. Specifically, integrating SINR into the handoff scheme can reduce false handoff initiations which create unnecessary traffic loads.

CONCLUSION

The success of achieving ubiquitous wireless connectivity in broadband wireless access networks is contingent upon how resources are allocated to ensure that each user has service availability. With increasing number of users demanding multimedia services (i.e., video and voice data), the limited spectrum of wireless networks make resource allocation techniques indispensable. In addition to spectrum limitations, wireless networks are inhibited by other inherent characteristics.

Specifically, wireless interference has been shown to be the most critical factors in hindering performance. Therefore, new and realistic paradigms for resource allocation considering the impact of interference and mobility are necessary to support high throughput and provide QoS guarantees. In this chapter, a framework for interference aware resource allocation has been introduced. A novel routing metric, RI^3M, is proposed by considering both interflow and intraflow interference to enhance the selection of good quality paths. Using virtual network decomposition, it is shown that RI^3M is an isotonic routing metric that outperforms the most prominent and relevant routing metrics used in the literature in terms of end-to-end delay and throughput. In addition, an MMF bandwidth allocation algorithm for multipath flow routing in multihop wireless networks is developed. To ensure QoS, the $LMX{:}M^3F$ optimization formulation has been shown to provide better utilization of bandwidth resources in comparison to well-respected MMF algorithms established in the literature particularly in terms of blocking ratio, bandwidth usage and link load.

REFERENCES

Alicherry, M., Bhatia, R., & Li, E. (2006). Joint channel assignment and routing for throughput optimization in multiradio wireless mesh networks. *IEEE Journal on Selected Areas in Communications*, *24*(11), 1960–1971. doi:10.1109/JSAC.2006.881641

Allalouf, M., & Shavitt, Y. (2008). Centralized and distributed algorithms for routing and weighted max-min fair bandwidth allocation. *IEEE/ACM Transactions on Networking*, *16*(5), 1015–1024. doi:10.1109/TNET.2007.905605

Athanasiou, G., Korakis, T., Ercetin, O., & Tassiulas, L. (2009). Cross-layer framework for association control in wireless mesh networks. *IEEE Transactions on Mobile Computing*, *8*(1), 65–80. doi:10.1109/TMC.2008.75

Bagchi, A., Chaudhary, A., & Kolman, P. (2005). Short length Menger's theorem and reliable optical routing. *Theoretical Computer Science*, *339*(2), 315–332. doi:10.1016/j.tcs.2005.03.009

Bertsekas, D., & Gallagher, R. (1992). *Data networks*. Englewood Cliffs, NJ: Prentice- Hall.

Bhandari, R. (1999). *Survivable networks: Algorithms for diverse routing*. Boston, MA: Kluwer Academic Publishers.

Brar, G., Blough, D. M., & Santi, P. (2006). Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks. In *Proceedings of ACM International Conference on Mobile Computing and Networking (MobiCom)*, (pp. 2-13). Los Angeles, CA.

Cheng, H., & Zhuang, W. (2008). An optimization framework for balancing throughput and fairness in wireless networks with QoS support. *IEEE Transactions on Wireless Communications*, *7*(2), 584–593. doi:10.1109/TWC.2008.060507

Chou, J., & Lin, B. (2009). Optimal multi-path routing and bandwidth allocation under utility max-min fairness. In *Proceedings of ACM/IEEE International Workshop on Quality of Service (IWQoS)*, (pp. 1-9). Charleston, SC.

De Couto, D. S. J., Aguayo, D., Bicket, J., & Morris, R. (2003). A high throughput path metric for multihop wireless routing. In *Proceedings of ACM International Conference on Mobile Computing and Networking (MobiCom)*, (pp. 134-146). San Diego, CA.

Draves, R., Padhye, J., & Zill, B. (2004). Routing in multi-radio, multi-hop wireless mesh networks. In *Proceedings of ACM MobiCom*, (pp. 114-128). Philadelphia, PA.

Gupta, P., & Kumar, P. R. (2000). The capacity of wireless networks. *IEEE Transactions on Information Theory*, *46*(2), 388–404. doi:10.1109/18.825799

Huang, X., & Fang, Y. (2008). Multiconstrained QoS multipath routing in wireless sensor networks. *Wireless Networks*, *14*(4), 465–478. doi:10.1007/s11276-006-0731-9

Huang, X., Feng, S., & Zhuang, H. (2009). Cross-layer fair resource allocation for multi-radio multi-channel wireless mesh networks. In *Proceedings of 5th International Conference on Wireless Communications, Networking and Mobile Computing (WiCom)*, (pp. 2639-2643). Beijing, China.

Iyer, A., Rosenberg, C., & Karnik, A. (2009). What is the right model for wireless channel interference. *IEEE Transactions on Wireless Communications*, *8*(5), 2662–2671. doi:10.1109/TWC.2009.080720

Jain, K., Padhye, J., Padmanabhan, V., & Qiu, L. (2003). Impact of interference on multihop wireless network performance. In *Proceedings of ACM MobiCom*, (pp. 66-80). San Diego, CA.

Kar, K., Kodialam, M., & Lakshman, T. V. (2000). Minimum interference routing of bandwidth guaranteed tunnels with MPLS traffic engineering applications. *IEEE Journal on Selected Areas in Communications*, *18*(12), 2566–2579. doi:10.1109/49.898737

Kleinberg, J., Rabani, Y., & Tardos, E. (2001). Fairness in routing and load balancing. *Journal of Computer and System Sciences*, *63*(1), 568–578. doi:10.1006/jcss.2001.1752

Kortebi, R., Gourhant, Y., & Agoulmine, N. (2007). On the user of SINR for interference-aware routing in wireless multi-hop networks. In *Proceedings of ACM International Workshop Modeling, Analysis, and Simulation of Wireless and Mobile Systems (MSWiM),* (pp. 395-399). Crete Island, Greece.

Langar, R., Bouabdallah, N., & Boutaba, R. (2009). Mobility-aware clustering algorithms with interference constraints. *Computer Networks*, *53*(1), 25–44. doi:10.1016/j.comnet.2008.09.012

Maatta, J., & Braysy, T. (2009). A novel approach to fair routing in wireless mesh networks. *EURASIP Journal on Wireless Communications and Networking, Special Issue on Fairness in radio Resource Magement for Wireless Networks*, 1-13.

Mansouri, V. S., Mohsenian-Rad, A. H., & Wong, V. W. S. (2009). Lexicographically optimal routing for wireless sensor networks with multiple sinks. *IEEE Transactions on Vehicular Technology*, *58*(3), 1490–1500. doi:10.1109/TVT.2008.928898

Mauve, M., Widmer, J., & Hartenstein, H. (2001). A survey on position based routing in mobile ad hoc networks. *IEEE Network*, *15*(6), 30–39. doi:10.1109/65.967595

Nace, D. (2002). A linear programming based approach for computing optimal fair splittable routing. In *Proceedings of IEEE Symposium on Computers and Communication (ISCC)*, (pp. 468-474). Taormina, Italy.

Nace, D., Doan, L., Klopfenstein, O., & Bashllari, A. (2008). Max-min fairness in multicommodity flows. *Computers & Operations Research*, *35*(2), 557–573. doi:10.1016/j.cor.2006.03.020

Nace, D., Doan, N., Gourdin, E., & Liau, B. (2006). Computing optimal max-min fair resource allocation for elastic flows. *IEEE/ACM Transactions on Networking*, *14*(6), 1272–1281. doi:10.1109/TNET.2006.886331

Nace, D., & Pioro, M. (2008). Max-min fairness and its applications to routing and load balancing in communications networks: A tutorial. *IEEE Communications Surveys and Tutorials*, *10*(4), 5–17. doi:10.1109/SURV.2008.080403

Pabst, R., Walke, B. H., Schultz, D., Herhold, P., Yanikomeroglu, H., & Mukherjee, S. (2004). Relay-based deployment concepts for wireless and mobile broadband radio. *IEEE Communications Magazine*, *42*(9), 80–89. doi:10.1109/MCOM.2004.1336724

Pal, R. (2008). A lexicographically optimal load balanced routing scheme for wireless mesh networks. In *Proceedings of IEEE International Confernence on Communications (ICC)*, (pp. 2393-2397). Beijing, China.

Park, W., & Bakh, S. (2009). Resource management policies for fixed relays in cellular networks. *Computer Networks*, *32*(4), 703–711.

Qi, B., Biaz, S., Wu, S., & Ji, Y. (2007). An interference-aware routing metric in multi-radio multihop networks. In *Proceedings of the ACM 45th Annual Southeast Regional Conference*, (pp. 549-500). Salem, MA, USA.

Ramachandran, K., Belding, E. M., Almeroth, K. C., & Buddhikot, M. M. (2006). Interference aware channel assignment in multiradio wireless mesh networks. In *Proceedings of IEEE International Conference on Computer Communications (INFOCOM)*, (pp. 1-12). Barcelona, Spain.

Rappaport, T. (2002). *Wireless communications: Principles and practice* (2nd ed.). Prentice Hall.

Shahrokhi, F., & Matula, D. W. (1990). The maximum concurrent flow problem. *Journal of the ACM*, *37*(2), 318–334. doi:10.1145/77600.77620

Shi, Y., Hou, Y. T., Liu, J., & Kompella, S. (2009). How to correctly use the protocol interference model for multihop wireless networks. In *Proceedings of ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, (pp. 239-248). New Orleans, LA.

Soldani, D., & Dixit, S. (2008). Wireless relays for broadband access. *IEEE Communications Magazine*, *46*(3), 58–66. doi:10.1109/MCOM.2008.4463772

Subramanian, A. P., Buddhikot, M. M., & Miller, S. (2006). Interference aware routing in multi-radio wireless mesh networks. In *Proceedings of IEEE Workshop in Wireless Mesh Networks (WiMesh)*, (pp. 55-63). Reston, VA.

Takai, M., Martin, J., & Bragodia, R. (2001). Effects of wireless physical layer modeling in mobile ad hoc networks. In *Proceedings of ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc),* (pp. 87-94). Long Beach, CA.

Tang, J., Hincapie, R., Xue, G., Zhang, W., & Bustamente, R. (2010). Fair bandwidth allocation in wireless mesh networks with cognitive radios. *IEEE Transactions on Vehicular Technology*, *59*(3), 1487–1496. doi:10.1109/TVT.2009.2038478

Tang, J., Xue, G., Chandler, C., & Zhang, W. (2005). Interference-aware routing in multihop wireless networks using directional antennas. *Proceedings of IEEE International Conference on Computer Communications (INFOCOM)*, (pp. 751-760). Miami, FL.

Tassiulas, L., & Sarkar, S. (2005). Maxmin fair scheduling in wireless ad hoc networks. *IEEE Journal on Selected Areas in Communications*, *23*(1), 163–173. doi:10.1109/JSAC.2004.837365

Teo, J.-Y., Ha, Y., & Tham, C.-K. (2008). Interference minimized multipath routing with congestion control in wireless sensor network with high rate streaming. *IEEE Transactions on Mobile Computing*, *7*(9), 1124–1137. doi:10.1109/TMC.2008.24

Thulasiraman, P., Chen, J., & Shen, X. (2010). Max-min fair multipath routing with physical interference constraints for multihop wireless networks. In *Proceedings of IEEE International Conference on Communications (ICC)*, (pp. 1-6). Cape Town, South Africa.

Thulasiraman, P., Chen, J., & Shen, X. (2011). Multipath routing and max-min fair QoS provisioning under interference constraints in wireless multihop networks. *IEEE Transactions on Parallel and Distributed Systems*, *22*(5), 716–728. doi:10.1109/TPDS.2010.145

Thulasiraman, P., Ramasubramanian, S., & Krunz, M. (2006). Disjoint multipath routing in dual homing networks using colored trees. In *Proceedings of IEEE Global Communications Conference (GLOBECOM)*, (pp. 1-5). San Francisco, CA.

Thulasiraman, P., Ramasubramanian, S., & Krunz, M. (2007). Disjoint multipath routing to two distinct drains in a multi-drain sensor network. In *Proceedings of IEEE International Conference on Computer Communications (INFOCOM)*, (pp. 643-651). Anchorage, AK.

Thulasiraman, P., & Shen, X. (2010). Disjoint multipath routing and QoS provisioning under physical interference constraints. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, (pp. 1-6). Sydney, Australia.

Walke, B. H., Mangold, S., & Berlemann, L. (2006). *IEEE 802 Wireless systems: Protocols,multi-hop mesh/relaying, performance and spectrum coexistence*. West Sussex, UK: John Wiley. doi:10.1002/9780470058800

Wang, P., Jiang, H., Zhuang, W., & Poor, H. V. (2008). Redefinition of max-min fairness in multi-hop wireless networks. *IEEE Transactions on Wireless Communications*, *7*(12), 4786–4791. doi:10.1109/T-WC.2008.070804

Wen, Y.-F., & Lin, Y.-S. (2007). Fair bandwidth allocation and end to end delay routing algorithms for wireless mesh networks. *IEICE Transactions on Communications*, *90-B*(5), 1042–1051. doi:10.1093/ietcom/e90-b.5.1042

Xu, Z., Huang, C., & Cheng, Y. (2008). Interference-aware QoS routing in wireless mesh networks. In *Proceedings of 4th International Conference on Mobile Ad-Hoc and Sensor Networks*, (pp. 95-98). Wuhan, China.

Yang, Y., Wang, J., & Kravets, R. (2005). Designing routing metrics for mesh networks. In *Proceedings of IEEE Workshop in Wireless Mesh Networks (WiMesh).* Santa Clara, CA.

Zhou, J., & Mitchell, K. (2010). A scalable delay based analytical framework for CSMA/CA wireless mesh networks. *Computer Networks*, *54*(2), 304–318. doi:10.1016/j.comnet.2009.05.013

ADDITIONAL READING

Fleischer, L. (2000). Approximating fractional multicommodity flows independent of the number of commodities. *SIAM Journal on Discrete Mathematics*, *13*(4), 505–520. doi:10.1137/S0895480199355754

Frederikos, V., & Papadaki, K. (2008). Interference aware routing for minimum frame length schedules in wireless mesh networks. *EURASIP Journal on Wireless Communications and Networking*, 1–13. doi:10.1155/2008/817876

Genc, V., Murphy, S., Yang, Y., & Murphy, J. (2008). IEEE 802.16j relay-based wireless access networks: an overview. *IEEE Wireless Communications*, *15*(5), 56–63. doi:10.1109/MWC.2008.4653133

Huang, L., Rong, M., Wang, L., Xue, Y., & Schulz, E. (2008). Resource scheduling for OFDMA/TDD based relay enhanced cellular networks. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, (pp. 1544-1548). Las Vegas, NV.

Kwon, S., & Shroff, N. B. (2009). Energy-efficient SINR based routing for multihop wireless networks. *IEEE Transactions on Mobile Computing*, *8*(5), 668–681. doi:10.1109/TMC.2008.165

Lee, K. D., & Leung, V. C. M. (2006). Fair allocation of subcarrier and power in an OFDMA wireless mesh network. *IEEE Journal on Selected Areas in Communications*, *24*(11), 2051–2060. doi:10.1109/JSAC.2006.881628

Li, G., & Liu, H. (2006). Resource allocation for OFDMA relay networks with fairness constraints. *IEEE Journal on Selected Areas in Communications*, *24*(11), 2061–2069. doi:10.1109/JSAC.2006.881627

Pareek, D. (2006). *WiMax: Taking wireless to the max*. Boca Raton, FL: Auerbach Publications. doi:10.1201/9781420013436

Peters, S. W., & Heather, R. W. (2009). The future of WiMax: Multihop relaying with IEEE 802.16j. *IEEE Communications Magazine*, *47*(1), 104–111. doi:10.1109/MCOM.2009.4752686

Prasad, P. S., & Agarwal, P. (2010). A generic framework for mobility prediction and resource utilization in wireless networks. In *Proceedings of IEEE International Conference on Communications Networks and Systems (COMSNETS),* (pp. 1-10). Bangalore, India.

Salem, M., Adinoyi, A., Rahman, M., Yanikomeroglu, H., Falconer, D., & Kim, Y. (2010). Opportunities and challenges in OFDMA based cellular relay networks: A radio resource management perspective. *IEEE Transactions on Vehicular Technology*, *59*(5), 2497–2510. doi:10.1109/TVT.2010.2042736

Shen, Z., Andrews, J. G., & Evans, B. L. (2005). Adaptive resource allocation in multiuser OFDM systems with proportional fairness. *IEEE Transactions on Wireless Communications*, *4*(6), 2726–2737. doi:10.1109/TWC.2005.858010

Shin, J., Kumarand, R., Shing, Y., & La Porta, T. F. (2008). Multihop wireless relay networks of mesh clients. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, (pp. 2717-2722). Las Vegas, NV.

Tam, Y. H., Benkoczi, H. S., Hassanein, H. S., & Akl, S. G. (2010). Channel assignment in multihop cellular networks: minimum delay. *IEEE Transactions on Mobile Computing*, *9*(7), 1022–1034. doi:10.1109/TMC.2010.41

Yang, Y., Hu, H., Xu, J., & Mao, G. (2009). Relay technologies for WiMax and LTE advanced mobile systems. *IEEE Communications Magazine*, *47*(10), 100–105. doi:10.1109/MCOM.2009.5273815

Yang, Y., Murphy, S., & Murphy, L. (2009). Interference aware relay station location planning for IEEE 802.16j mobile multihop relay network. In *Proceedings of 4th ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks (PM2HW2N),* (pp. 201-208). Canary Islands, Spain.

Zhang, W., Bai, S., Xue, G., Tang, J., & Wang, C. (2011). DARP: Distance aware relay placement in WiMax mesh networks. *Proceedings of IEEE Conference on Computer Communications (INFOCOM)*, (pp.2060-2069). Shanghai, China.

KEY TERMS AND DEFINITIONS

Broadband Wireless Access: A specific wireless technology that provides ubiquitous high speed internet services over a wide geographic area.

Fairness: the ability to distribute resources to users based on need and in a manner that does not unnecessarily starve or over allocate the end users.

Multicommodity Flow: Illustrates a network flow problem in which there are multiple traffic demands by multiple users that each flow through the network to different destinations.

Multipath Routing: The ability to use multiple paths for routing of traffic flows from source to destination such that the paths do not form loops and so as to increase load balancing, fault tolerance, and energy efficiency.

Quality of Service: Ability to provide different priority levels to different applications, users, or data traffic flow, or to guarantee a certain level of performance to a data flow given specific network characteristics and conditions.

Resource Allocation: The assignment of available resources and the scheduling of transmissions in computer networks in an efficient and fair manner.

Wireless Interference: The interference between simultaneous transmissions within a certain proximity due to inherent wireless characteristics that causes performance degradation in terms of packet loss, throughput, and latency.

ENDNOTES

[1] This chapter is based on work presented in (Thulasiraman, Chen, & Shen, 2011).

[2] It must be noted that maintaining two-connectivity is a necessary condition for finding two disjoint paths from each user to the base station. Guaranteeing two-connectivity is feasible in a static wireless environment as considered in this chapter. However, in the presence of mobility, two-connectivity of the network cannot be ensured due to time varying changes in the topology. Thus, this constraint and the solutions obtained in this chapter are pertinent for static wireless networks.