Enhancing Multi-hop Wireless Mesh Networks with a Ring Overlay

Abu (Sayeem) Reaz[1], **Vishwanath Ramamurthi**[1], **Dipak Ghosal**[1],
John Benko[2], **Wei Li**[2], **Sudhir Dixit**[3], and **Biswanath Mukherjee**[1]
[1]University of California, Davis, USA
[2]France Telecom, South San Francisco, CA USA
[3]Nokia Research Center, Palo Alto, CA USA
Email: {asreaz,rama,dghosal,bmukherjee}@ucdavis.edu, {john.benko,wei3.li}@orange-ftgroup.com,
sudhir.dixit@ieee.org

***Abstract*—Wireless Mesh Network (`WMN`) has become a popular access network architecture. But because of its multi-hop nature, co-channel interference and contention, the attainable capacity of a wireless node in a `WMN` is significantly less than the radio capacity. We propose a overlay architecture for a `WMN`, where a wireless-ring (`WRing`) is deployed over the regular mesh for carrying wireless mesh traffic only. Our analysis shows that `WRing` improves the performance of a `WMN` significantly by reducing the interference and contention.**

Keywords: Wireless mesh network, overlay network, ring topology, routing, delay

I. INTRODUCTION

Wireless Mesh Network (`WMN`) is a cost-effective access-network architecture, suitable for deploying over an area where it is expensive, or difficult to lay wire. `WMN` is gaining popularity, especially for city-wide deployment in different parts of the world. A `WMN` is formed with a set of fixed wireless nodes, which are usually wireless routers [1], interconnected with each other over a wireless channel. When a wireless node is within the transmission range of another node, they are considered as neighbors, and there is a wireless link between them. End users, both mobile and stationary, connect to the network through these wireless nodes. A selected set of these nodes, called gateways, are connected to the wired part of the network, which connects the `WMN` to rest of the Internet. Figure 1 shows the architecture of a `WMN`.

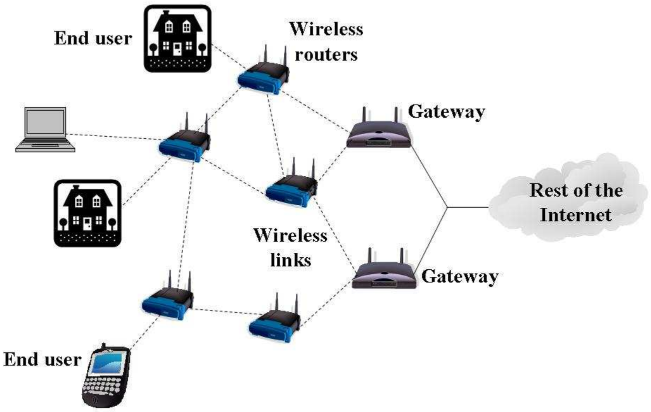


Fig. 1: Architecture of a `WMN`.

An end user sends packets to a nearby wireless node of the `WMN`. These packets travel through the wireless mesh, possibly over multiple hops, and reach rest of the Internet via the gateways. `WMN` nodes are usually equipped with two radios, which are commercially available [2], operating on two orthogonal channels. One radio (Radio 1) is used to communicate with the end users and the other one (Radio 2) is used to carry the mesh traffic, also referred as wireless backhaul traffic. Because the packets travel through multiple hops, usually the Radio 2 of all the nodes are tuned to the same channel to inter-communicate. Because of the channel sharing, the wireless nodes face co-channel interference and cannot utilize the wireless capacity, which leads to much lower attainable capacity than the actual radio capacity [3]. So, a `WMN` cannot carry high intensity wireless backhaul traffic needed for many end-user applications. To enable users to be able to use more bandwidth-hungry applications, we need to reduce the wireless interference and contention and utilize the capacity of the wireless nodes.

There have been several routing algorithms proposed in literature for `WMN` to utilize the limited wireless resources. Delay-Aware Routing Algorithm (DARA) is proposed in [4] to reduce the average packet delay in the `WMN` relative to previous approaches. An improved algorithm for Capacity and Delay-Aware Routing Algorithm (`CaDAR`) is proposed in [5] which exploits the work by Fratta et al. [6] and Kleinrock [7] on capacity assignment (CA) and flow assignment (FA), which were originally designed for general packet networks using optimal capacity assignment and flow deviation on links to minimize delay.

There are several works in the literature that propose to improve the performance of multi-radio wireless mesh. In [8], authors propose a two-radio wireless mesh architecture. They exploit spatial reuse and self-organize the network for channel allocation through clustering. The Bay Area Research Wireless Access Network (BARWAN) is a solution to heterogenous gateway-based multi-layer wireless overlay network proposed in [9]. A multi-layer Wireless LAN test bed is presented in [10], which focuses on performance evaluation of the indoor positioning systems [10]. In [11], authors presents an algorithm called "Localized sElf-reconfiGuration algOrithms" (LEGO) that detects the failures locally and generates a local network reconfiguration plan and self-heal multi-radio wireless mesh. An interference-aware channel assignment algorithm and protocol for multi-radio wireless mesh networks is presented in [12] that assigns channels to radios to minimize interference in the wireless mesh. In [13], the authors present a new metric for routing in a multi-radio, multi-hop WMN. The metric assigns weights to individual links based on the Expected Transmission Time (ETT) of a packet over the link and chooses a high-throughput path between the source and the destination. An interference-aware routing metric, iAWARE, for a multi-radio WMN is proposed in [14]. We propose a Wireless Ring (`WRing`) over the regular wireless mesh, which works like a "Ring Highway" by carrying high-bandwidth data and enables us to get more capacity from the wireless nodes through higher utilization of wireless radios by reducing co-channel interference. It is important to note that a "wireless highway" need not to be a ring; based on the underlying topology, the wireless highway can take different form, such as a tree, or a line. Here, we focus on ring topology for its ease of deployment and operation.

Our *contributions* are: i) a simple, yet effective architecture, called `WRing`, to enable `WMN`s to carry bandwidth-intense traffic more efficiently; and ii) performance analysis and effectiveness of `WRing`.

The rest of the paper is organized as follows: Section II discusses the issues with WMN and how they can be addressed. Section III introduces the architecture of `WRing`. Section IV presents different design aspects of `WRing`. We show our performance evaluation of `WRing` in Section V. We conclude in Section VI.

II. ISSUES WITH `WMN`

Figure 2 shows the flow on a multi-hop wireless network. Node u sends data to node x with traffic intensity γ_{ux}. Similarly, nodes v and w send data to node x with traffic intensities γ_{vx} and γ_{wx} respectively. Now, as we can see in Fig. 2, link (u, v) carries traffic from u only. On the other hand, (w, x) carries traffic from u, v and w. So, we can find the flows on each of the links as $\lambda_{uv} = \gamma_{ux}$, $\lambda_{vw} = \gamma_{ux} + \gamma_{vx}$, and $\lambda_{wx} = \gamma_{ux} + \gamma_{vx} + \gamma_{wx}$. As the flow on a link cannot be greater than its capacity, a link with higher flow, (w, x), becomes more saturated than a link with lower flow, (u, v), and becomes a bottleneck for the multi-hop wireless mesh network. Now, if node u wants to send more data to x, it cannot, because a link downstream, (w, x), is over utilized.

Here, we identify several issues with a multi-hop `WMN`:

1) **Bottleneck:** Due to the fact that the traffic flows in a `WMN` are between the wireless nodes and the gateways, some links may get overloaded while others may remain under-utilized. If we consider node x in Fig. 2 as a gateway, we observe that traffic gets aggregated near the gateways. In Fig. 2, we see that $\lambda_{wx} > \lambda_{vw} > \lambda_{uv}$, and node w has become a bottleneck for the network.

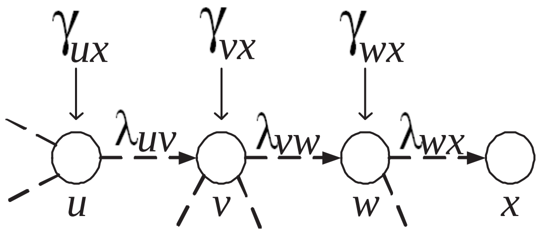


Fig. 2: Flow on a multi-hop wireless network.

2) **Physical Limitation:** The most popular wireless standard, 802.11g [1], has a radio capacity of 54 Mbps. Gupta and Kumar [15] showed that even for a relatively simple `WMN` shown in Fig. 2, the attainable capacity of a wireless node with 802.11 g radio is about 18 Mbps. The average capacity for a outgoing link of node v in Fig. 2 is about 4.5 Mbps for wireless backhaul, which is considerably low compared to optical fiber based access network [16].
3) **Interference:** As wireless mesh nodes usually operate on the same channel, interference constraints significantly reduces the attainable radio capacity of the node [3], [15]. Due to the co-channel interference, a radio at a wireless node remains idle for a significant amount of time and remains under utilized. In Fig. 2, when node v is transmitting to node w, neither of its other 3 neighbors can receive. Similarly, node v cannot receive from nodes u and w at the same time.
4) **Lack of Universal Services:** As `WMN` is an access network technology, it is important that it can enable the end users to have the universal services, such as triple-play of voice, video and data, that operators usually provide as bundles. Simultaneous run of several of these flows can increase the wireless contention significantly, leading to loss of limited wireless resource [3].
5) **Architectural Limitations:** A `WMN` is designed for high user coverage and forwarding aggregated traffic. As each node collects user traffic as well as forwarding traffic from other nodes, each user gets only a small chunk of the wireless backhaul capacity, which sometimes is not feasible for many applications.

From this discussion, we can conclude that we are not reaching the full potential of the `WMN` as an access network architecture. There are several efforts to improve performance through channel assignment, multi-radio and efficient routing (Section I). But still we face some major issues regarding `WMN`. We summarize these issues and a set of requirement for future development of `WMN`s in Table I. We observe that, we need a new design for `WMN` which can meet these requirement and can co-operate with the existing `WMN`s.

III. WIRELESS RING (`WRing`)

As shown in Table I, a `WMN` faces some challenges to be a successful access technology, and requires a set of

TABLE I: Issues with `WMN`

Issues	Reasons	What is required?
Bottleneck	Traffic gets aggregated near the gateways	Bottleneck-free flow of traffic for wireless backhaul
Physical Limitation	Limited physical capacity which is shared among several links	Higher capacity radio like 802.11n which should operate with minimum sharing
Interference	Co-channel interference with higher number of neighboring nodes makes the radio-capacity under-utilized	Place the nodes physically apart and with less neighbors to avoid co-channel interference
Lack of Universal Services	Wireless backhaul of `WMN` cannot take several traffic-intense flows	Dedicated routes for such applications
Architectural Limitations	Simultaneous end-user data collection and forwarding limits the wireless capacity	Design architecture dedicated for backhaul traffic

improvements to make it more suitable for today's end users. We propose Wireless Ring (`WRing`) to incorporate these requirement in a cost-effective way.

A. Motivation for `WRing`

A `WMN` is analogous to the road system of a city. Because of the cross traffic, the internal roads of a city need to have signals, which stop the flow of traffic to a particular direction periodically. Moreover, as the traffic on the internal roads tend to go towards the destinations, overall speed limit on the roads is low. As a solution to this problem, highways are built to facilitate vehicles to move without any stops and with higher velocity. Especially for large cities, such as Beijing and Singapore City, where the traffic-intensity within the city itself is very high, ring-highways are built around the city, so that any vehicle can travel around the city quicker and at the same time can get inside the city into the internal roads.

Similarly, in a `WMN`, because of the co-channel interferences, and traffic moving about in different directions, the radios cannot send data most of the time. So, we propose a "ring-highway", Wireless Ring (`WRing`), over the regular wireless mesh that can carry traffic with higher bandwidth and less contention. Nodes on `WRing` use existing technology, without requiring any expensive add-ons. Essentially, the `WRing` nodes use same type of wireless routers used in the regular `WMN`. `WRing` addresses the requirements for improvement of `WMN` described in Table I as follows:

- `WRing` is created with the wireless routers, as in regular wireless mesh; so there is no issue of compatibility of technology.
- In a ring, different parts operate at the same time because they are physically apart avoiding co-channel interferences.
- `WRing` is placed such a way that all the nodes in the regular wireless mesh are reachable in a small number of hops.
- `WRing` is dedicated for wireless backhaul traffic, so all the resources can be used for forwarding.
- Because of the linear path, there can be bottleneck free flow of data over `WRing`.
- Each wireless node has only two nodes for unidirectional `WRing`: one for sending and one for receiving. This leads to minimum sharing of wireless resources and increased capacity on the links.
- Broadcast traffic, essential for universal services, can be sent over the `WRing` without interrupting regular traffic within the mesh.

B. Architecture of `WRing`

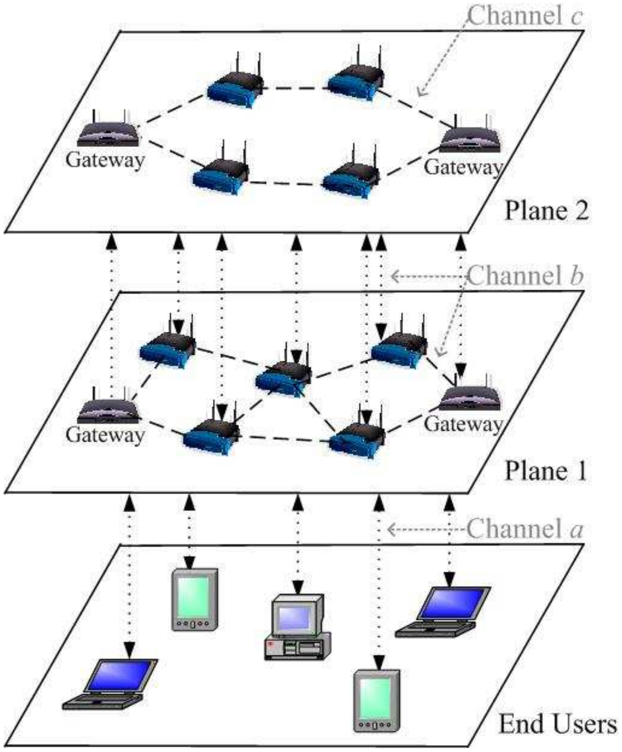
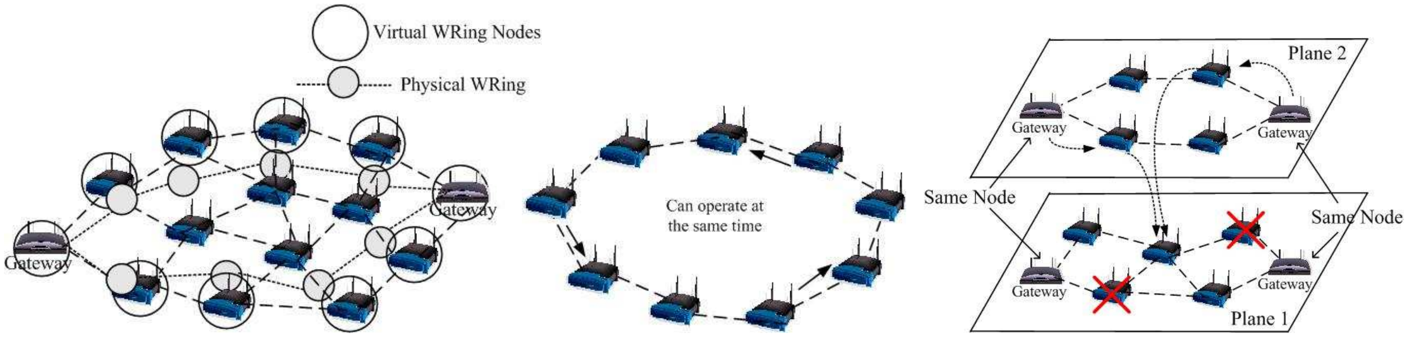


Fig. 3: `WRing` Architecture.

We design `WRing` such that it meets the requirements described in Section III-A. All the recent wireless nodes for `WMN` are usually equipped with multiple radios. `WRing` utilizes both the radios. If the spectrum on which the wireless routers operate, has any three orthogonal channels a, b, and c [1], as shown in Fig. 3, a `WMN` with `WRing` can be viewed as a overlay network with two planes:

- **Plane 1:** This is the regular `WMN` front end of a `WMN`. The two radios on the node are assigned as: Radio 1 for communicating with users on channel a, Radio 2 for mesh backhaul traffic on channel b. As channels a and b are orthogonal, radio 1 and 2 operate in parallel.
- **Plane 2:** This is the proposed `WRing`. The two radios on the node are assigned as follows: Radio 1 for communicating with plane 1 nodes on channel b, and Radio 2 for forwarding traffic over `WRing` on channel c. As



(a) `WRing` placement.

(b) `WRing` routing.

(c) `WRing` fault tolerance.

Fig. 4: Design Issues of `WRing`.

channels b and c are orthogonal, `WRing` carries wireless backhaul traffic in parallel to plane 1. From hereon, we use the terms plane 2 and `WRing` interchangeably.

From the above description, we can see that `WRing` makes a `WMN` use one more orthogonal channel, adding an additional plane for backhaul traffic. Capacities on optical fiber are significantly higher than that of wireless; adding another plane for wireless backhaul data reduces the disparity of capacity between the wireless and wired parts of the network. Moreover, bandwidth-hungry applications have another plane to communicate, without disrupting traffic at plane 1.

`WRing` is placed over the plane 1 of a `WMN` such that each node in plane 1 is reachable from plane 2 in minimum, possibly single, hop. This way, the data from plane 2 can be delivered to the end users without with minimum disruption on the flows on plane 1. As shown in Fig. 3, gateways are part of both plane 1 and plane 2. This implies that, gateways need to have 3 radios. Such wireless nodes are commercially available from multiple vendors [2], operating on orthogonal channels, where radio 1 is used to connect end users, radio 2 is used for plane 1 and radio 3 is used for plane 2.

IV. DESIGN ISSUES OF `WRing`

There are several design issues that need to be addressed for implementing `WRing`. In this section, we elaborate on these issues.

A. `WRing` *Placement*

`WRing` nodes need to be placed such a way that it can carry the bandwidth-hungry traffic while reaching plane 1 with minimum hop. If `WRing` becomes too big, then the traffic on plane 2 may need to travel several wireless hops, which is not desirable. Depending on the size the `WMN` is covering, there can be multiple `WRing`s, with at least one gateway as part of each of the `WRing`s. The placement of `WRing` depends on the type of wireless routers used in plane 1 [2]. There are two aspects of `WRing` placement based on the topology, available channels, and number of radios available in plane 1.

1) Physical `WRing`*:* If the number of radios on the wireless nodes is maximum 2, then, a physical `WRing` is required to be created with additional wireless nodes, and placed over existing plane 1, as shown in Fig. 4a. In that case, nodes on `WRing` need to be placed such a way that the following conditions are incorporated:

(a) Depending on the size of a `WMN`, determine the number of `WRing`s required to cover plane 1 such that the average number of hops in plane 2 is within reasonable limit.
(b) At least one gateway is included in each `WRing`. If only one `WRing` is being deployed, then include all the gateways.
(c) Plane 1 is reachable from plane 2 in minimum, possibly 1 hop.
(d) Each of the nodes on the ring is within wireless transmission range of its neighbors.
(e) A node u is within the interference range of node v only if u is a neighbor of v.

The tradeoff for physical `WRing` is that it requires nodes on plane 1 to increase their number of neighbors by one, which reduces the capacity on the links in plane 1.

2) Virtual `WRing`*:* To avoid the tradeoff described in Section IV-A1, we can consider a virtual `WRing`. If the nodes in plane 1 has more than 2 radios, they can operate in at least three orthogonal channels. A selected set of nodes in plane 1 can form the `WRing` with their 3rd radio on another orthogonal channel, not used in plane 1, while maintaining the conditions mentioned in Section IV-A1. Figure 4c shows how a virtual `WRing` can be placed over plane 1. The 3rd radio at the nodes on `WRing` and the rest of the nodes should be tuned on separate orthogonal channels.

B. `WRing` *Routing*

As implemented in most of the wireless mesh routers [2] for wireless backhaul traffic, `WRing` can be operated on Time-Division Multiple Access (TDMA) [17]. As each node on `WRing` has 2 neighbors, each TDMA time frame is divided into time-slots to transmit and receive from these 2 neighbors [5].

`WRing` can be operated on fixed routing because of the ring architecture. As different parts of `WRing` are physically apart, even if they operate on the same channel, they can operate in parallel, as shown in Fig. 4b.

The routing can be unidirectional or bidirectional. For bidirectional routing, the average number of hops will be reduced, and for nodes closer to the gateways on both sides, data can be delivered in fewer number of hops. But in that case, the TDMA time-slots per time-frame are required for sending and receiving data from both directions, which will have higher interference, and lead to lower effective capacity per link [3]. On the other hand, for unidirectional routing, the capacities on the links are higher, but the number of hops is increased. So, depending on the size of the `WRing` and the topology of plane 1, the directionality for routing over `WRing` needs to be decided.

C. `WRing` *Fault Tolerance*

Physical `WRing` can play very significant role for failure recovery in a `WMN`. As any node in plane 1 is reachable from plane 2 in minimum hops, if any node on plane 1 fails, all the data destined to that node can be redirected over plane 2. Moreover, because of the ring architecture, if any node on `WRing` suffers a failure, data can still be routed over other part of the `WRing`. As all the gateways of plane 1 is included in plane 2, if a gateway fails, then traffic can be redirected to the other gateway, and `WRing` can carry the traffic from the other gateway, and deliver the packets. Failure recovery schemes described in [18] can be integrated with `WRing` for protection. Figure 4a shows how `WRing` can be used for fault tolerance in a `WMN`.

D. `WRing` *Data Classifier*

It is essential to decide what data should be routed over `WRing`. When any packet arrives at the gateway, it needs to decide whether to forward the packet over plane 1 or plane 2. There can be several criteria for this selection. There are several candidates of traffic that can be routed over the `WRing`:

1) Broadcast Traffic: can travel over `WRing`, and reach each node in turn, without interrupting regular traffic flow on plane 1.
2) High-bandwidth Traffic: links on `WRing` can provide sufficient bandwidth for heavy traffic, while less intense traffic can travel over plane 1.
3) Self-organizing Traffic: if any node in plane 1 fails, traffic can be rerouted over plane 2.

V. ILLUSTRATIVE NUMERICAL EXAMPLES

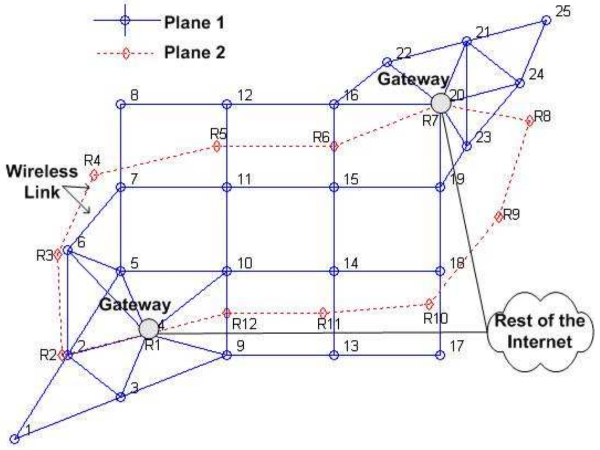


Fig. 5: Topology for analytical study.

In this section, we present the performance study of planes 1 and 2 *individually* to show that many of the issues, described in Section II, is addressed by `WRing`. As planes 1 and 2 operate on separate channels, by comparing them individually, we show how the `WRing` outperforms a regular mesh.

We use the 25-node network configuration for plane 1 and a 12-node physical `WRing` in Fig. 5 to study the effect of multi-layer WMN. Each radio has a capacity of 54 Mbps. We use the model in [15] to approximate the capacities of the wireless nodes. We use `CaDAR` [5] and fixed routing to obtain the flows on plane 1 and plane 2, respectively. For simplicity, we do not show the intercommunication between plane 1 and plane 2; we show the individual performance analysis of two layers. Each of the nodes has a load, which is the rate of traffic from the gateways to the wireless nodes. Usually the downstream traffic is higher than upstream traffic. So, in our study, load at each node indicates 60% downstream and 40% upstream traffic. We use performance parameters presented by Kleinrock [7] to evaluate the networks in Fig. 5.

Figure 6 shows the system delay, or the network-wide average packet delay, with load at each node for plane 1 and 2, individually, for the topology in Fig. 5. We see that, deployed over the same area, and operating on individual channels, in a multi-layer `WMN`, plane 2 can carry almost 3 times more traffic than plane 1, for both unidirectional and bidirectional `WRing`. Because of the ring architecture, different parts of `WRing` can operate at the same time avoiding the co-channel interference, and as a result, the links have higher capacity. We also observe that, a unidirectional `WRing` can carry higher traffic than bidirectional link with lower system delay.

Figure 7 shows the average number of hops for plane 1 and 2. As we perform fixed routing on plane 2, we see the average number of hops remains fixed with increasing load for plane 2. But for unidirectional `WRing`, the average number of hops is higher, because even if a node is closer to a gateway, it may need to receive packets from the other gateway because packets are forwarded in one direction only. We see the tradeoff between unidirectional and bidirectional `WRings`, that if we use unidirectional `WRing`, it carries higher load with lower delay, but the average path length is increased.

Figure 8 shows the delay on the maximum delay path for plane 1 and 2. Here, we can see that, a single path in `WRing` can carry significantly higher traffic than plane 1, with lower delay. We also observe that, as bidirectional `WRing` has lower average path length than unidirectional `WRing` (Fig. 7), the delay on the maximum delay path is lower for bidirectional `WRing`.

Figure 9 shows the load balancing for the two planes. We can see that the bidirectional `WRing` performs better load balancing than unidirectional `WRing`, because unidirectional `WRing` cannot divert packet to achieve load balance. This also shows the tradeoff between the two types of `WRings`.

VI. CONCLUSION

In a `WMN`, the optical backhaul has higher capacity than the wireless front end. We propose a overlay architecture for

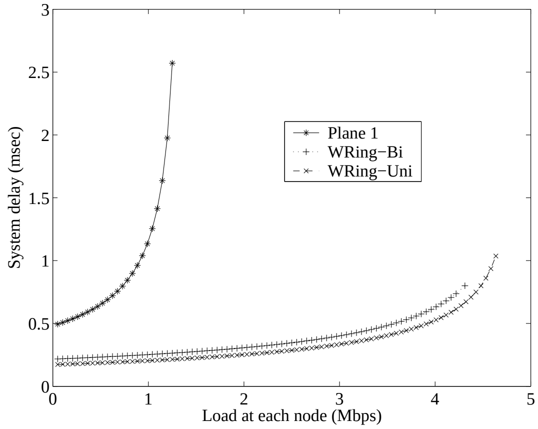


Fig. 6: System delay vs. load.

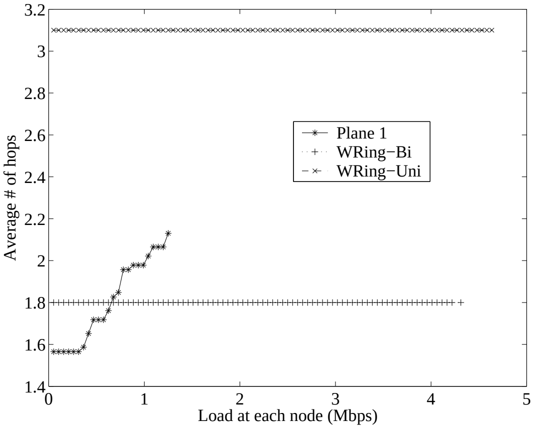


Fig. 7: Average number of hops vs. load.

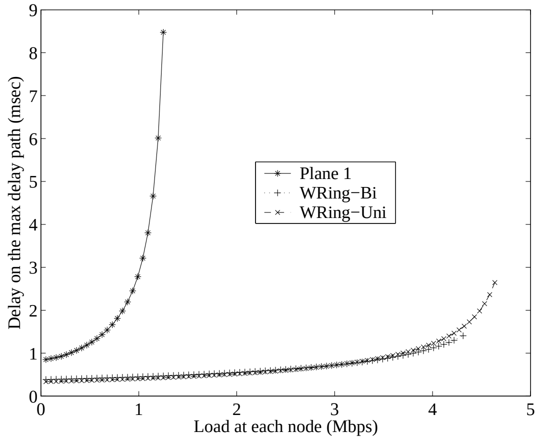


Fig. 8: Delay on the maximum delay path vs. load.

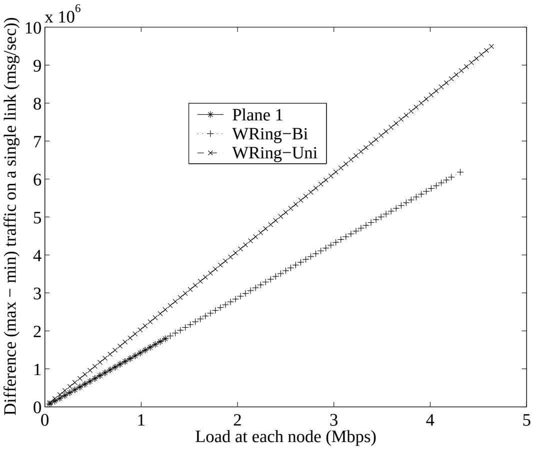


Fig. 9: Overall load balancing of the network.

`WMN`, called `WRing`, which is a "ring-highway" that operates on an orthogonal channel, reduces co-channel interference to achieve higher capacity, and overcomes different limitations of a `WMN`. We present the different design issues of implementing `WRing`, and discuss the various approaches to address these. We show through a preliminary performance study that `WRing` can carry significantly higher traffic with lower delay, which is essential for performance improvement of a `WMN`.

REFERENCES

[1] http://standards.ieee.org/getieee802/802.11.html.

[2] Wi-Fi Planet, "Wi-fi products." http://products.wi-fiplanet.com/wifi/mesh/.

[3] V. Ramamurthi, A. Reaz, and B. Mukherjee, "Optimal capacity allocation in wireless mesh networks." http://networks.cs.ucdavis.edu/~sayeem/Pub/wireless-capacity.pdf.

[4] S. Sarkar, H. Yen, S. Dixit, and B. Mukherjee, "DARA: Delay-Aware Routing Algorithm in a Hybrid Wireless-Optical Broadband Access Network (WOBAN)," in *Proc. IEEE ICC*, Glasgow, Scotland, June 2007.

[5] A. Reaz, V. Ramamurthi, S. Sarkar, D. Ghosal, S. Dixit, and B. Mukherjee, "CaDAR: an efficient routing algorithm for wireless-optical broadband access network," in *Proc. IEEE ICC*, Beijing, China, May 2008, to appear.

[6] L. Fratta, M. Gerla, and L. Kleinrock, "The flow deviation method: An approach to store-and-forward communication network design," *Networks*, vol. 3, no. 2, pp. 97 – 133, Mar. 2007.

[7] L. Kleinrock, *Queueing Systems, Volume II: Computer Applications*, Wiley-Interscience, 1976.

[8] J. Zhu and S. Roy, "802.11 mesh networks with two-radio access points," in *Proc. IEEE ICC*, Seoul, Korea, pp. 3609–3615, May 2005.

[9] R. H. Katz, E. A. Brewer, E. Amir, H. Balakrishnan, A. Fox, S. Gribble, T. Hodes, D. Jiang, G. T. Nguyen, V. Padmanabhan, and M. Stemm, "The bay area research wireless access network (BARWAN)," in *Proc. IEEE COMPCON*, Santa Clara, CA, pp. 15 – 20, Feb. 1996.

[10] Worcester Polytechnic Institute, "An integrated multi-layer Wireless LAN testbed." http://www.cwins.wpi.edu/projects/scripts/nsf_wlan_03.html.

[11] K. Kim and K. Shin, "Self-healing multi-radio wireless mesh networks," in *Proc. ACM MobiCom*, Montral, Canada, pp. 326–329, Sep. 2007.

[12] K. Ramachandran, E. Belding, K. Almeroth, and M. Buddhikot, "Interference-aware channel assignment in multi-radio wireless mesh networks," in *Proc. IEEE INFOCOM*, Barcelona, Spain, pp. 1–12, Apr. 2006.

[13] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. ACM MobiCom*, Philadelphia, PA, pp. 114–128, Sep. 2004.

[14] A. Subramanian, M. Buddhikot, and S. Miller, "Interference aware routing in multi-radio wireless mesh networks," in *Proc. IEEE International Workshop on Wireless Mesh Networks (WiMesh)*, Reston, VA, Sep. 2006.

[15] P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Transaction on Information Theory*, vol. 26, no. 2, pp. 388–404, Mar. 2000.

[16] http://www.ieee802.org/3/ah/index.html.

[17] http://en.wikipedia.org/wiki/Time_division_multiple_access.

[18] S. Sarkar, B. Mukherjee, and S. Dixit, "RADAR: Risk-and-Delay Aware Routing Algorithm in a Hybrid Wireless-Optical Broadband Access Network (WOBAN)," in *Proc. IEEE OFC*, Anaheim, CA, Mar. 2007.