Cognitive Multi-Radio Mesh Networks for the Future Wireless Internet

Wooseong Kim*, Andreas J. Kassler†, Marco Di Felice‡ and Mario Gerla*
*Department of Computer Science, University of California, Los Angeles, USA
Email: {wooseong@cs.ucla.edu, gerla@cs.ucla.edu}
† Department of Computer Science, Karlstad University, Karlstad, Sweden
Email: kassler@ieee.org
‡Department of Computer Science, University of Bologna, Bologna, Italy
Email: difelice@cs.unibo.it

New developments in the area of interference management, modulation, coding, etc, push the capacity of wireless access networks towards the Shannon Limit. With increasing number of wireless subscribers and the advent of more powerful smartphones, demand for bandwidth will significantly increase in the next decade. Therefore, current wireless systems will face a capacity problem and new architectures need to be considered for the future wireless internet. Among the many possibilities to increase capacity significantly, we identify two important concepts to be considered: Wireless Mesh/Relay based access networks and Dynamic Spectrum Access (DSA). In wireless mesh networks (WMNs), nodes relay packets over the air interface towards the destination or internet gateways. In DSA based solutions, nodes share a frequency portion dynamically and adapt according to specific rules in order to achieve some performance objectives.

WMNs are used already by several municipalities (such as Chaska in the USA) or user communities such as Freifunk (e.g. in Berlin, Germany or Vienna, Austria) in dense urban areas. Such *Urban mesh networks* enable interesting services in addition to wireless internet access, such as content sharing, multicast video delivery, sensor network backhaul, or vehicular network infrastructure support. WMNs are an interesting architectural candidate for the future wireless internet because there is no need to wire the meshed access points. This allows to build up rapidly a dense access network at reasonable cost using a different topology compared to cellular systems. Such dense deployment is seen as a key mechanism to significantly increase capacity. However, WMNs use wireless technologies like 802.11a/b/g WLAN operating in unlicensed bands, where they suffer heavy interference from various wireless devices especially in dense urban areas.

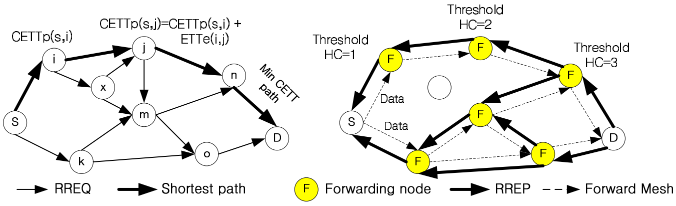
For higher capacity and reduced interference, it is mandatory that WMNs use multiple radios operating in parallel on a diverse set of channels [1]. In such multi-radio mesh networks, effective channel assignment (CA) is important as it impacts the topology and routing. Comparing to static CA schemes, semi-dynamic CA schemes re-assign channels on longer timescale (e.g. minutes or hours) to cope with external interference [2] or changes in traffic demand [3]. However, such schemes result in low performance due to problems with routing and network disconnections. Hybrid approaches [4] solve such problems by allowing an interface to switch dynamically among the fixed channels of neighbor nodes to support full connectivity while the other interface is fixed to avoid multi-channel deafness problems.

Practical deployment of mesh networks in dense urban areas needs to consider external interference caused by so called primary nodes (PNs) such as residential access points who do not belong to the WMN. For example, in RoofNet such PNs are considered to be a major problem and one of the reasons for low performance [5]. The main motivation for our architecture is to use ideas from the area of DSA which allows us to develop high capacity multiple channel and multiple radio (MC-MR) WMNs that coexist efficiently with PN users.

In this work, we present Urban-X which is a new architecture for the future wireless internet composed of cognitive multi-radio mesh nodes (CMNs). In each CMN, three radios (i.e. R1, R2 and R3) are used to build a cognitive forwarding mesh. R1 and R2 are used to receive or transmit packets simultaneously on different channels. Interface R1 is tuned to a semi-dynamic channel, which changes according to PN activity and mesh network traffic. Interface R2 is dynamically switching among those channels where the R1 interface of neighbor CMNs are tuned to. Once switched to a given channel, R2 stays there for a small switching interval to reduce overhead. In addition, we use a designated interface for control (R3), which is fixed to a common control channel (CCC) to disseminate routing information and changes in the channel assignment. For efficient coexistence with PNs, we developed several novel algorithms in the area of collaborative spectrum sensing, interference aware channel assignment, routing, forwarding and scheduling.

1) Spectrum Sensing: In contrast to cognitive radio, Urban-X nodes operating in ISM bands do not need to vacate frequency bands immediately if PN traffic is detected. Therefore, instead of focusing on detecting PN signals itself, Urban-X contributes a novel collaborative channel load estimation based on 802.11k to derive PN workload as input to a load and interference aware channel assignment algorithm.

2) Interference and Traffic Aware Channel Assignment: While existing hybrid Channel Assignment (CA) algorithms



(a) Mutiple RREQ

(b)RREP−4hop threshold (α =1)

Fig. 1: Multipath routing procedure in UrbanX

only consider intra-mesh interference, Urban-X CA (UCA) uses input from collaborative spectrum sensing to balance the impact of interference caused by PNs with intra- and inter-flow interference to achieve robustness and high performance. In addition, the CA algorithm makes sure that a node serving many flows compared to its link capacity or suffering heavy external interference from PN gets prioritized in the channel assignment since it could be a bottleneck node. Based on the input available from collaborative spectrum sensing, the channel assignment algorithm first estimates the per channel available capacity taking into account the number of flows being served by the channel in the two hop neighborhood. It then selects with a certain probability the channel which has the highest available spare capacity estimate per flow for its R1 interface and broadcasts this information along with its estimate on channel capacity and the information gathered from its one-hop neighbors on the R3 interface.

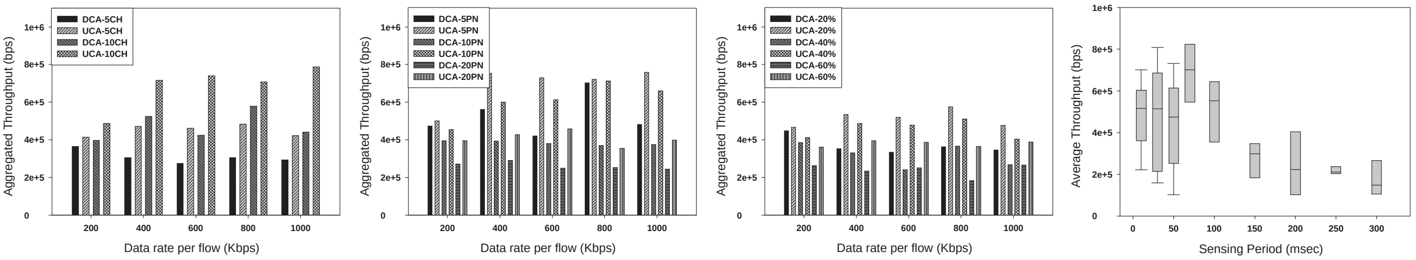
3) Multipath Routing: Urban-X effectively utilizes the availability of multiple paths by maintaining a forwarding mesh centered around the best metric path. Our multipath routing protocol UCAMP extends AODV by maintaining a set of candidate forwarders at each node for each source/destination pair. In contrast to existing work, our approach can dynamically change individual path segments on a per packet basis to effectively cope with interference caused by variation in PN traffic and intra-mesh congestion. A detailed procedure of the multipath routing protocol is illustrated in Figure 1. A source node broadcasts a route request (RREQ) message through R3. Intermediate nodes rebroadcast RREQ messages from different upstream nodes. In contrast to AODV, an intermediate node can forward a duplicate RREQ message if it contains a lower metric value (we also use a novel routing metric to take into account impact by PN traffic) in the routing table. The metric value within the RREQ is updated before forwarding as shown in Figure 1. After receiving multiple RREQ messages, a destination node replies with multiple route reply (RREP) messages by unicasting. Instead of replying immediately, the destination waits a small amount (e.g. 1 second depending on network size), which allows to accumulate multiple RREQs. In order to limit the forwarding mesh structure and avoiding loops, the mesh is constructed of individual paths that are not longer than a certain hop count. The destination node calculates the threshold hop count, $ThresholdHC = \alpha \cdot hop_{min}$ for the RREP message, where $\alpha \geq 1$ and hop_{min} is the hop count of the shortest path that has the lowest metric among multiple RREQ messages. Intermediate nodes decrement $ThresholdHC$ and forward the RREP towards all upstream nodes only if $ThresholdHC$ is not smaller than 0 as shown in Figure 1b. They become forwarders of the given flows only when the hop count from them to the source is less than $ThresholdHC$. Otherwise they drop the RREP and remove the routing entry for the flow. A wider forwarding mesh structure can be built using a larger threshold hop count (by e.g. setting α=2). While such a broader mesh structure allows more spatial diversity to cope with local PN traffic, it also may lead to longer paths.

4) Forwarding and Scheduling: Urban-X is based on novel packet scheduling algorithms for selecting the best next hop and frequency channel among all forwarding candidates in the forwarding mesh. Although a practical approach based on back-pressure scheduling [6][7] has been developed in a single radio mesh network [8], Urban-X is the first work that extends it to hybrid MC-MR WMNs taking into account channel switching cost.

Using a detailed evaluation of Urban-X in the ns-2 simulator, which has been extended to model multi-channel multiradio operation and PN traffic, we show that Urban-X achieves high throughput and robustness under a large range of PN traffic conditions. We simulated a large scale Urban-X deployment using 50 randomly positioned CMNs inside an area of 1000m by 1000m. Three CBR flows with varying data rates from 200 to 1000 Kbps were run between random source destination pairs, limiting the destination nodes to be within three hop distance from sources. Different number of PNs with varying workload were randomly placed. We compared aggregated throughput between DCA [4], which does not consider mesh external interference caused by PNs and UCA.

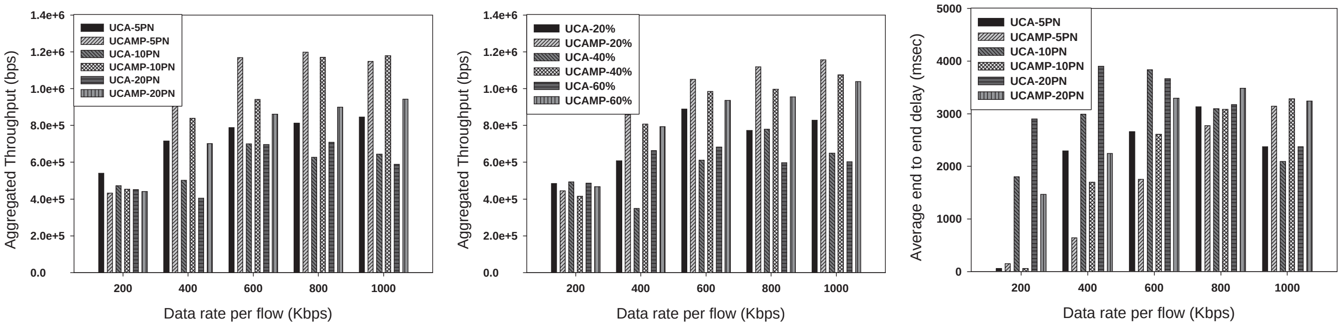
As shown in Figure 2a, UCA outperforms DCA under all data rates and channels because it considers PN traffic based on spectrum sensing and channel load estimation. Results show that the performance increase of UCA comparing to DCA for 10 channels is 35% higher than for 5 channels. Again, this shows that the effect of channel diversity is tightly related to the number of available channels to avoid PN traffic. What we also observe is that inter-flow interference occurs in both channel assignment strategies when flows cross the same node, which is a drawback of the hybrid channel assignment schema when there is just one receiving channel per node.

Simulations with 10 channels under different number of PNs under randomly varying workloads (Fig. 2b) and where PN activity varies (Fig. 2c) show the PN effects on aggregated throughput. Interference from PNs has more impact when the link capacity becomes saturated due to higher offered load as shown in Figure 2b and 2c. At low data rates, there is not much difference between UCA and DCA since there is enough capacity to handle flows of CMNs. Results under high data rate show that PN detection is important in order to select channels which have the lowest interference by PN traffic. In addition, we observe that the number of occupied channels due to PN activity is more critical to network performance than workload of a given PN population since throughput difference between workloads in Figure 2c is smaller compared to Figure 2b.



(a) Varying number of channels (b) Varying number of PNs (c) Varying workload (d) Varying sensing period

Fig. 2: Channel allocation performance comparison in random topology



(a) Varying number of PNs (b) Varying workload (c) Delay with varing PNs

Fig. 3: Multipath performance comparison in random topology

Figure 2d shows the tradeoff between sensing period and throughput for a single CBR flow (1 Mbps) under 20 PNs with randomly varying workloads. Until 70 msec, the throughput increases since workload estimation for PN traffic becomes more reliable. This is because a larger number of samples are available when the sensing period is longer. While for short sensing periods the estimated workload shows a large confidence interval. After 70 msec, the average throughput decreases because of the reduced transmission opportunities and the higher overhead due to longer sensing period.

To evaluate the general performance of the multipath and scheduling approach, we used the same test scenarios from the channel assignment, but this time using 100 CMNs. UCAMP outperforms UCA in almost every scenario under varying number of PNs and workloads as shown in Figure 3a and 3b except for 200 Kbps data rate where the advantages of multipath are penalized by the higher overhead and the additional self interference. UCAMP also shows about 20% higher delivery ratio compared to UCA. Interestingly, the aggregated throughput of UCAMP increases with increasing data rate, which indicates that UCAMP can effectively reduce inter-flow interference. Also, UCAMP reduces end-to-end delay compared to UCA that is mostly generated from queuing along the path except at low data rates. At low data rate, switching delay becomes more critical since network congestion is not severe and the number of PNs are scarce in the network. In figure 3c, UCMAP shows longer delay with 5 PNs at 200 Kbps compared to UCA. As the number of PNs and data rate of flows increases, average delay of UCAMP is much less than UCA until 800 and 1000Kbps.

ACKNOWLEDGMENT

This research is supported by grant YR2009-7003 from Stiftelsen för interntionalisering av högre utbildning och forskning (STINT).

REFERENCES

[1] J. Li, C. Blake, D. S. J. D. Couto, H. I. Lee, and R. Morris, “Capacity of ad hoc wireless networks,” in *Proc. of 7th ACM MOBICOM*, 2001.

[2] K. N. Ramachandran, E. M. Belding, K. C. Almeroth, and M. M. Buddhikot, “Interference-aware channel assignment in multi-radio wireless mesh networks,” *Proc. of INFOCOM 2006*, 2006.

[3] M. Alicherry, R. Bhatia, and L. E. Li, “Joint channel assignment and routing for throughput. optimization in multi-radio wireless mesh networks,” in *Proc. of ACM MOBICOM*, 2005.

[4] P. Kyasanur, C.Chereddi, and N. Vaidya, “Netx:system extensions for supporting multiple channels, multiple interfaces and other interface capabilities,” in *Technical Report, CSL, UIUC*, 2006.

[5] D. Gokhale, S. Sen, K. Chebrolu, and B. Raman, “On the feasibility of the link abstraction in (rural) mesh networks,” in *Proc. Infocom 2008*, Phoenix, AZ, USA, April 2008.

[6] L. Tassiulas and A. Ephremides, “Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks,” *IEEE Transaction on Automatic Control*, vol. 37, no. 12, 1992.

[7] M. Chen, S. Low, M. Chiang, and J. Doyle, “Cross-layer congestion control, routing and scheduling design in ad hoc wireless networks,” in *Proc. of IEEE INFOCOM*, 2006.

[8] B. Radunovic, C. Gkantsidis, D. Gunawardena, and P. Key, “Horizon: Balancing tcp over multiple paths in wireless mesh network,” in *In Proc. of ACM MOBICOM*, 2008.