Urban-X: Towards Distributed Channel Assignment in Cognitive Multi-Radio Mesh Networks

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Abstract—Researches about multi-radio mesh networks have mostly focused on channel allocation under internal interference. However, the deployment of WMNs in unlicensed bands of dense urban areas imposes many challenges regarding co-existence with residential access points. In this paper, we propose Urban-X, which is a first attempt towards a new architecture for Multi-Radio Cognitive Mesh Networks. We develop a novel channel assignment that reflects channel and residential traffic state of external users to minimize network throughput. We evaluate our approach using an enhancement of the ns-2 simulator. Urban-X demonstrate the feasibility of our approach and show robustness to variation of channel environment and external user traffic.

Index Terms—Wireless Mesh Networks, Channel Assignment, Cognitive Networks

I. INTRODUCTION

Currently, wireless mesh networks (WMNs) are a hot topic and several municipalities (e.g. Chaska) and user communities such as Freifunk (e.g. in Berlin or Vienna) run WMNs in dense urban areas. Urban mesh networks enable interesting services such as content sharing, multicast video delivery, sensor network backhaul, and vehicular network infrastructure support in addition to wireless Internet access. Typically, WMNs use wireless technologies like 802.11a/b/g operating in unlicensed bands, where they suffer heavy interference from various wireless devices especially in dense urban areas.

In order to increase the capacity, it is necessary 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 to achieve high capacity, as it impacts the topology and routing. Compared to static CA schemes, semi-dynamic CA schemes re-assign channels over time (i.e. several minutes or hours) to cope with external interference [2] and changes in traffic demand [3], [4]. In addition, static CA results in low performance since a network flow can be routed through a longer path at a given network topology and suffers from ripple effect and network disconnections once an assigned channel of a node is updated. Hybrid CA [5], [6] solves such problems by enabling a radio interface to switch very rapidly among the fixed channels of neighbor nodes (on a per-msec basis) to maintain full connectivity while the other interface stays tuned for the fixed channel to avoid deafness/disconnection problem.

The Hybrid CA, however, only consider intra-mesh traffic when assigning channels to minimize intra- and inter-flow interference. For practical deployment of mesh networks in dense urban areas, interference from external entities such as residential access points that do not belong to the WMN needs to be considered. We call such external entities primary nodes (PNs). For instance, in RoofNet such PNs are considered to be one of the primary reasons for low performance [7]. Our goal is developing high capacity multiple channel and multiple radio (MC-MR) WMNs that can efficiently coexist with the PNs.

In this paper, we present Urban-X, a new architecture for cognitive mesh networks composed of cognitive multi-radio mesh nodes (CMNs) operating in ISM bands. Urban-X adopts a hybrid CA approach denoted as Urban-X channel assignment (UCA), which allows to maintain full connectivity while maximizing channel diversity. Based on spectrum sensing and spectrum resource awareness, UCA balances the impact of intra- and inter-flow interference caused by PNs to achieve robustness and high performance. In contrast to conventional cognitive radio networks, CMNs do not need to vacate frequency bands immediately even if PN traffic is detected. Instead, we take advantage of frequency bands that are less utilized by PNs in order to maximize performance for both mesh networks and existing PNs. For that purpose, Urban-X contributes a collaborative channel load estimation to derive PN traffics as input to our channel assignment algorithm.

Using a detailed evaluation of Urban-X in the ns-2 simulator, which has been extended to model MC-MR operation and PN traffic, we show that Urban-X achieves high throughput and robustness under a large range of PN traffic conditions in particular. Urban-X achieves around 30% higher throughput compared to distributed channel allocation that only considers interference among mesh nodes.

The remainder of this work is structured as follows: Section II and III describe our Urban-X architecture along with our channel assignment algorithm and implementation details. Evaluation results are shown in section IV. Section V reviews related works. The paper concludes in section VI.
In this section, we present our cognitive wireless mesh network architecture Urban-X, together with our channel assignment algorithm.

A. Urban-X architecture

Urban-X consists of mesh clients, cognitive mesh nodes (CMNs) and PNs. Figure 1 shows an Urban-X deployment at the UCLA campus, where residential WLAN access points (APs), denoted as P, are scattered around 11 Urban-X CMNs. The PNs occupy most 802.11b channels and available channels depend on physical location. In addition, non-802.11 nodes like Bluetooth and Zigbee devices can be PNs as well.

The CMNs are wireless routers equipped with multiple radios. 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 and R3 is used for exchanging control messages. R1 for Rx is tuned to a semi-dynamic channel that changes according to PN activity and mesh network traffic. The R2 for Tx is dynamically switching among channels of neighbor nodes’ R1. In current platforms, switching delay is around 1 msec which is too long to switch channels on a per-packet basis [5]. Therefore, once tuned to a given channel, R2 stays for predefined switching interval (e.g. 40 msec). Such a hybrid multi-radio approach achieves high capacity while maintaining connectivity with neighbor CMNs using the switchable transmitting interface. 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.

B. Spectrum Sensing and Primary Traffic Load Estimation

The CMNs sense spectrum and measure PN channel and traffic workloads as an important input parameter for channel selection. For spectrum sensing, clear channel assessment (CCA) that detects a signal with energy during a single symbol duration (e.g. 4 µsec in case of 802.11a) is used. Following the IEEE 802.11k standards for radio resources measurements based on channel occupancy and/or interference [8], the CMNs periodically measure PN channel and traffic workloads by sensing channel spectrum. PN load varies in time and in space. Figure 1 depicts spatially different channel usage by PNs on the campus. Also, PN traffic patterns are different as illustrated in Figure 2. Unlike channel 4 with most burst traffic, channel 2 has the lowest traffic demand among all channels. These PN traffic patterns can be captured by a semi-Markov model with two states, busy and idle as in the Figure 2, which matches well the empirical results [9]. Expected idle, \( T_{idle} \) and busy durations, \( T_{busy} \) based on cumulative distribution functions (CDFs) of two exponential distributions with rate \( \lambda \) and \( \mu \) are given by,

\[
P(T_{idle} < t) = 1 - e^{-\lambda t}, \quad P(T_{busy} < t) = 1 - e^{-\mu t}
\]

The PN traffic pattern and workload (\( \omega \)) can be estimated by sampling channel status (busy or idle) during a sensing period as described in [8]. The reliability of the estimated result depends on the sensing period and the sampling rate. As the sensing period becomes longer and the sampling rate higher, the results are more reliable. According to our simulation study, a sensing period larger than 300 msec is required to get a workload estimate with 10% error. This result is acquired from simulation using a discrete Gilbert model [8] with 30% workload and busy duration \( E[T_{busy}] = 1 \) msec by sampling every 1 msec. In addition, estimating the busy or idle durations needs a sampling rate at least as high as the Nyquist sampling rate (e.g. 0.5 msec). Here, the calculated workload \( \omega = \frac{T_{busy}}{T_{busy} + T_{idle}} \) with estimated \( T_{busy} \) and \( T_{idle} \), is referred to verify a measured workload value.

A long sensing period for each channel (e.g. 50, 100, 200 msec per second) would limit the network performance. A CMN is not allowed to send packets during the sensing period since the CMN cannot distinguish between PN and own traffics. Synchronization for the period among CMNs could be achieved using the CCC and methods similar to [10]. Therefore CMNs cooperate in exchanging sensing information with one hop neighbors to enhance measurement performance. In addition, measurement should be executed on both the receiving R1 and the transmitting R2 since channel status in receive and transmit nodes can be asymmetric.

CMNs access a channel using 802.11 DCF MAC, which does not require any modification to a MAC protocol compared to MAC protocols for agile spectrum access in cognitive radio networks. Therefore, our channel model takes mutual interference between CMNs and PNs transmitting in the same channel into account. For example, CMN transmissions can collide with PNs; at channel 4 in Figure 2. Also, PN traffics can result in interference; in channel 2 and 3. The goal of Urban-X is to minimize such interference using channel assignment rather than avoiding it completely.

C. Interference Aware Channel Assignment in Urban-X

Channel assignment in Urban-X defines the semi-dynamic channel to be used by the fixed radio R1. The main idea is to use a channel that maximizes network throughput in the
sense that it is least impacted by PN traffic while at the same time minimizing internal interference caused by CMN traffic along the path to the receiver or gateway (intra- and inter flow interference). As the PN and CMN traffic intensity may vary over time, the channel assigned to R1 also changes.

From the results of channel workload measurement in the previous section, we can approximately derive an expected capacity of each channel under given PN activity. For example if PN traffic creates 30% channel workload, we get a channel capacity, $C_i = C_{ul}(1 - \omega)$ where $\omega$ is 0.3 and $C_{ul}$ denotes theoretically achievable data rate (e.g.1~11Mbps in 802.11b).

Algorithm 1 Fixed channel allocation at node $x$

```plaintext
1: for each channel $i$ in $K$ do
2: $C_i = C_{ul}(1 - \omega), C_i = C_i/N(i)$
3: $LCPF_i = C_i/N(\text{Flows})$
4: $Q1 ← LCPF_i$
5: end for
6: $LCPF_x ← \text{EXTRACT-MIN}(Q1)$
7: $Q2 ← LCPF_x$
8: $max,i ← \text{EXTRACT-MAX}(Q1)$
9: $i_{R1} = \arg\max C_{max,i}$
10: $\text{prob} = 1 - (LCPF_x - C_{min,y})/C_{CR}$
11: if $\text{prob} \geq \text{Random}[0, 1]$ then
12: Select $i_{R1}$ as a fixed channel, $i_x$
13: end if
14: Broadcast HELLO with $LCPF_x$ and $i_x$
15: $Q2 ← LCPF_x$, received from neighbor nodes, $n$
16: Update $N(i_n)$
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Algorithm 1 illustrates Urban-X channel assignment (UCA), which 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 in a route. Prioritization is achieved by giving a node who has the lowest least capacity per flow (LCPF) the highest probability to select the most capable channel. The probability is determined by its own estimated LCPF and the LCPF values received through neighbors broadcast information. LCPF is derived by dividing the minimum channel capacity by the number of active flows $N(\text{Flows})$. First, each node estimates $C_i$ for every channel $i$ based on spectrum sensing information and the number of nodes $N(i)$, which have selected the same channel $i$ within the two hop neighborhood and inserts them into queue Q1. Then, a node $x$ selects the maximum capacity channel $i_{R1}$ for the receiving interface R1 and minimum $C_{LCPF_x}$. It periodically broadcasts own $C_{LCPF_x}$ and selected channel($i_x$) for R1 through the CCC within two hop neighborhood using hello messages and also store received neighbors’ $C_{LCPF_n}$ into queue Q2, which is used to update own probability. Also, they periodically update $N(\text{Flows})$ to reflect intra or interflow interference. Our algorithm approximates the intra-mesh CMN traffic evenly by the number of active network flows obtained from routing table information.

III. IMPLEMENTATION

We have implemented Urban-X in ns-2 through a routing protocol module and a channel management module integrated into the MAC layer. The routing protocol module extends existing AODV, which maintains a table of 2-hop neighborhood information including address, channel of a receiving interface R1 and LCPF that is refreshed using periodic HELLO messages broadcasted on the control channel.

The channel management module is responsible for measuring the channel workload under given PN traffics. The PN traffic is individually generated based on a CTMC model approximated from empirical data (see Table 5 of [9]). PN information is logged in a PN data file according to [11] in the format $<$channel, sender position, receiver position, workload, Tx power for propagation range$. The module senses PN signals at a given sampling rate, e.g. 1 msec during a sensing period e.g. 30,70,100 msec at R1 and R2. Then it estimates the channel workload by calculating a mean value of the sample data [8] and stores it in the channel information table. For cross-layer implementation, the table is shared between routing and MAC layer.

We implemented a radio channel model to take into account the mutual interference between CMNs and PNs transmitting in the same spectrum band. In our model, the CMN drops an interfered packet with a probability of PER derived by collision duration and a BER table in the MAC layer. The collision can occur due to e.g. hidden terminal, detection error of PN (e.g.10%).

IV. EVALUATION

We evaluated the proposed architecture using different scenarios and topologies. Each node is equipped with three radio interfaces (see section II.A) using 2 Mbps data rate. Radios can use 11 channels in total but channel 1 is designated for CCC. Sensing period for channel workload measurement is 70 msec per second. We use CBR flows at a rate varying from 200 Kbps to 1Mbps and compute aggregated throughput and average end-to-end delay as evaluation metrics.

We compare Urban-X channel assignment (UCA) against the distributed channel assignment (DCA) that minimizes intra-mesh interference, where the number of neighbor nodes on a given channel is balanced within two hop neighborhood [6]. We evaluate UCA performance in a simple chain topology with 6 nodes in absence of routing effect and general performance in random topology is investigated later.

A. Chain topology

In the chain topology, 6 nodes from 0 to 5 are evenly placed at 200 m. We create a 1 Mbps CBR flow at node 0 and a varying destination from 1 to 5. Number of transmitting PNs near node 1 is varying from 1 to 10, having randomly varying
workload, i.e. 20%, 40% and 60%. Here, each PN occupies a separate channel. We do not allocate more PNs than channels; when we use only 5 channels for evaluation, we let just 5 PNs transmit.

We first shows average throughput for DCA/UCA with varying number of PNs, channels and workloads in Figure 3 and 4. Under absence of PN traffic, average throughput was around 1 Mbps (not shown due to space limitations) regardless of the number of hops. This implies that intra-flow interference can be efficiently resolved using channel diversity, where at least 4 channels were required to completely avoid intra-flow interference. As the number of PN increases, the throughput decreases as shown in Figure 3a and 4a. Especially at 5 hops, performance degradation is visible due to intra-flow and PN interference since the probability to select a channel interfered by PNs or to have intra-flow interference increases with increasing number of hops. While UCA performance under two PNs is significantly higher, the throughput under 1 PN in UCA is slightly lower than DCA since CMNs have sensing overhead and continue changing their channel until the estimated channel capacity becomes stable. Therefore, in a sparse network, it may take more time to be stable due to imperfect collaboration of sensing PN traffic.

As shown in Figure 3b, DCA with 10 channels can effectively avoid intra-flow interference even at 5 hops but throughput is still limited by the number of PNs while UCA with 10 channels shows robust high throughput of around 800 Kbps in Figure 4b. Figure 3c illustrates the effect of PN traffic on throughput with different workloads; 10 PNs in 10 channels have workloads from 20% to 60%. Heavy workloads degrade throughput considerably by loosing transmission opportunity to avoid collision and by generating packet loss. Figure 3d and 4c show average throughput to different workloads under varying number of PNs.

From the results of this sub-section, we can conclude that UCA avoids effectively channels interfered from PNs and also behaves robust with increasing workload under varying PN activity.

B. Random topology

We simulated a large scale Urban-X deploying 50 CMNs randomly in an area of 1000m X 1000m. Three CBR flows with varying data rates from 200 to 1000 Kbps ran between random source destination pairs within three hop distance. Different numbers of PNs with varying workload were randomly placed. We compared average aggregated throughput between DCA and UCA.

As shown in Figure 5a, UCA outperforms DCA under all data rates and channels. The performance increase of UCA comparing to DCA for 10 channels is 35% higher than for 5 channels since the effect of channel diversity is obviously related to the number of available channels to avoid PN traffics. One interesting observation is that inter-flow interference cannot be completely resolved in both channel assignment when different flows cross at the same node.

Simulations with 10 channels under randomly varying workloads and PN activity in (Fig. 5b) and (Fig. 5c) show the PN effects on aggregated throughput. Results under high data rate show that PN detection becomes significant in order to select channels which have the lowest interference by PN traffic. However at low data rates, there is not much difference between UCA and DCA since there is enough capacity to handle flows of CMNs. In addition, we observe that the number of PNs is more critical to network performance than workload by comparing Figure 5c and Figure 5b.

Figure 5d depicts an interesting tradeoff between sensing period and average 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 gets longer. While for short sensing periods we can observe a large deviation from the mean average throughput, which means the estimated workload shows a large confidence interval. After 70 msec, the average throughput decreases because of the reduced transmission opportunities.

V. RELATED WORK

Using channel diversity using multiple radio (MR) interfaces constitutes a straightforward approach to increase the capacity of WMNs [6], [12], [13] without the tight synchronization problem required by single radio solutions (e.g. MMAC [12] or SSCH [14]). Furthermore, hybrid solutions have been proposed (c.f. NetX [15], [6]) to avoid the deafness problem and ripple effect of dynamic channel assignment. Here, each node is equipped with a receiving interface with a fixed channel and a switchable interface tuning to the channels of neighbor nodes.

Channel assignment for MR interfaces on a conflict graph is a NP-hard problem. In semi-dynamic approaches, nodes update a static channel assignment over time (e.g. on a minute or hour timescale) to cope with changes in environment. Several solutions have been proposed to address various optimization criteria [3], [4], [13] assuming traffic demands do not change frequently. However, in most cases such approaches are not feasible for dynamic environment where traffic demands and interference conditions can change rapidly like in Urban-X. Traffic independent heuristic algorithms were proposed to control topology with channel assignment to minimize interference between nodes using a centralized approach [16], also taking into account external interference [2]. However, they are not flexible to confront dynamically varying PN traffics or achieved in centralized way.

VI. CONCLUSION

In this paper, we have introduced Urban-X, a new architecture of MC-MR WMNs with channel sensing and assignment algorithms. Our algorithm effectively balanced external interference from PN traffic with internal interference. A detailed performance evaluation in ns-2 showed that our channel assignment algorithm outperformed a distributed random algorithm under a wide range of scenarios. In future work, we
plan to evaluate the impact of multipath routing and congestion control. Also, we will evaluate alternatives that do not require a common control channel.

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