ABSTRACT
Wireless Mesh Networks (WMNs) that operate in license-free spectrum portions (e.g., ISM bands) in dense urban areas face heavy interference from coexisting devices such as residential access points. We address this challenge by designing Urban-X which is a new architecture for Multi-Radio Cognitive Mesh Networks. It combines principles from Dynamic Spectrum Access Networks to develop novel spectrum aware channel assignment and routing algorithms. However, spectrum sensing and channel switching overhead may lead to a large variation in delay and available bandwidth. In this study, we evaluate the impact of Urban-X on TCP. More specifically we analyze the impact of different external interference patterns and Urban-X configurations on TCP performance. Finally, we compare Urban-X with traditional multi-radio networks and demonstrate the superiority of our spectrum aware architecture.

Categories and Subject Descriptors
C.2.1 [Computer-Communication Networks]: Network Architecture and Design—Wireless communication

General Terms
Experimentation, Performance Evaluation

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Wireless Mesh Networks, Transport Control Protocol, Cognitive Networks

1. INTRODUCTION

Wireless mesh networks (WMNs) are a promising technology to build broadband wireless access networks with high capacity and rapid deployment. Recently, the feasibility of mesh networks as alternatives or complements of carrier owned infrastructure networks has been explored by projects such as Carmen (http://www.ict-carmen.eu/) or EU-Mesh (http://www.eu-mesh.eu/). For this usage area, capacity and resilience are important issues which are typically tackled using multiple radios capable to operate on a diverse set of channels. Deploying such 802.11a/b/g based networks in dense urban areas leads to several problems of interference and coexistence with existing equipment as such networks typically operate in the unlicensed ISM bands.

Recently, we have proposed Urban-X, which is a new multi-channel multi-radio WMN architecture borrowing concepts from flexible and cognitive radio platforms [8]. In Urban-X, cognitive mesh nodes (CMNs) form the wireless backhaul. They have built-in functionality to efficiently coexist with external nodes such as residential access points (AP). However, due to the operation in ISM bands, Urban-X nodes do not need to immediately vacate the spectrum once external mesh traffic is detected. This is in contrast to existing approaches in the area of White Spectrum Access networks, where Primary Nodes (PNs) are licensed and thus are strictly protected from cognitive nodes (CN) interference. In Urban-X the key to increase the capacity is the efficient multi-radio operation, which allows cognitive nodes to exploit diverse frequency bands in parallel. In order to assign channels to radios, Urban-X nodes use hybrid channel assignment similar to [10], where nodes dynamically switch channels for their sending radios in order to maintain full connectivity while avoiding multi-channel deafness problems. A channel assignment protocol is used to determine the channel for the sending radio, which tries to balance the number of nodes on each channel without taking into account external interference. In our approach, the receive radio channel is selected by a spectrum aware algorithm from the knowledge of the load on different frequency bands acquired using periodic spectrum sensing. As a result, channels are frequently re-assigned to minimize interference from external users.

Fluctuations in wireless channel quality and congestion are the main problems that affect the performance of transport layer protocols in WMNs. Moreover, at the end nodes, the transport layer has limited information about reasons for packet loss. Therefore, packet loss due to interference caused by external PNs may be wrongly interpreted as congestion, resulting in unnecessary throughput degradation. Several efforts have been undertaken to optimize TCP for such wireless (multi-hop) environment, mostly focusing on improving the performance problems introduced due to node mobility and route breaks. For example, different approaches utilize explicit feedback messages provided by the network layer [3][14] in order to distinguish a temporary disconnection due to deep fading or mobility from congestion.

Such approaches, however, do not consider the unique properties of cognitive radio based environments like Urban-X.
For example, during the time nodes sense different spectrum segments in order to detect external user presence and estimate channel workload, transmission or forwarding is not possible eventually leading to increased packet loss. While shorter sensing time may reduce the RTT variance, it may lead to ineffective estimation of external traffic and increased interference [6]. Switching channels in a hybrid multi-radio approach may also contribute to significant additional delay and jitter when forwarding packets. Such RTT variation induced by spectrum sensing and channel switching distorts bandwidth estimation and retransmission timeout (RTO), degrading TCP performance and leading to low throughput.

In this paper, we evaluate in detail the performance of different transport protocol variants over Urban-X in an environment, where external interference due to deployed PNs is present. We vary different characteristics such as the load and intensity of external traffic and find optimum parameters for spectrum sensing and channel switching configuration. Finally, we compare the performance of Urban-X with that of traditional wireless multi-radio mesh networks, which are spectrum unaware. Using the network simulator ns-2 with extensions for spectrum sensing, channel switching, and external interference, we show that TP-UrbanX achieves high throughput and robustness under a broad range of external interference from PN traffic.

The remainder of this work is structured as follows: Section 2 reviews related works. Section 3 describes our Urban-X architecture along with our spectrum sensing and channel assignment algorithms. Simulation results focusing on TCP performance in conventional wireless mesh and Urban-X are shown in section 4. The paper concludes in section 5.

2. RELATED WORK

TCP is the de-facto transport layer protocol of the Internet. It provides a connection-oriented service between end nodes together with congestion control mechanism in order to help the network to recover from arising congestion. The congestion control is composed of several states such as slow start, congestion avoidance, fast retransmission and recovery and different TCP variants (such as TCP Reno [7], TCP-SACK [13], TCP Vegas [1], TCP Westwood [12]) have been developed to cope differently with detected or inferred packet loss.

When nodes use mechanisms commonly used by cognitive radios, TCP may be additionally adversely affected. Such principles include periodic channel sensing, or spectrum mobility including channel switching for transmitter channel diversity. In addition, the variation of available channel bandwidth due to different external load cannot be ignored in terms of TCP performance as well. Here, several previous works investigating TCP performance under those features are introduced.

Slingerland et. al. [16] analyzed TCP performance in dynamic spectrum access (DSA) scenarios using a single hop cognitive radio access network such as considered by e.g. 802.22 WRAN. Felice et al [6] evaluated various TCP versions such as TCP Reno, New Reno, Vegas and Sack in a cognitive multi-hop ad hoc network under varying PN workload, sensing duration and heterogeneity of channel bandwidth. However, they do not consider the impact of channel switching on TCP performance and ignore the impact of channel (re-)assignment on performance.

Chowdhury et. al. [4] proposed a new transport layer protocol, TP-CRAHN for cognitive ad hoc networks. TP-CRAHN uses additional states considering different effects from cognitive ad hoc networks, such as delay from spectrum sensing or spectrum mobility. Due to the additional states and messages, it is complex to implement and requires additional buffer space information along the path. Sarkar et al [15] proposed TCP Everglades (TCPE) for single-hop cognitive radio networks. Authors assumed spectrum sensing duration is longer than RTO and extended TCP Westwood with several rules of a knowledge based module that decides TCP operation. As TCPE is designed for a single-hop cognitive wireless environment, it is not appropriate for multi-hop wireless cognitive radio based networks like Urban-X where channel switching, spectrum mobility and interference due to PNs happen frequently along multiple links.

3. COGNITIVE MULTI-RADIO MESHES

In this section, we give an overview on Urban-X, a novel multi-radio multi-channel cross-layer architecture based on principles of cognitive radio ad-hoc networks.

3.1 Urban-X network architecture

Urban-X networks are typically deployed in dense urban areas where interference is common. A network is typically composed of mesh clients, cognitive mesh nodes (also denoted as CMNs) and primary nodes (PNs) as shown in Figure 1. PNs and CMNs have to co-exist in the same spectrum bands (e.g. using the 2.4 or 5 GHz ISM bands). In our scenario, typical PN nodes are residential WLAN Access points or bluetoot devices, which have relatively short radio range. This is in contrast to typical cognitive radio assumptions, where PNs are assumed to be TV stations or microphones. Therefore, CMNs have no need to immediately vacate the spectrum once PNs are detected. Rather, CMNs have an incentive to select channels which have the least interference from external traffic.

![Figure 1: Model of Urban Wireless Mesh Networks](image)
there for a configurable switching interval (e.g. between 20 and 60 msec).

The link layer maintains a separate queue per channel which holds packets to be sent to neighbors which have tuned their receiving interface to the corresponding channel. A channel scheduler is implemented which decides which channel to serve next in order to avoid starvation while still providing the required QoS to applications. Note, that a given channel is only served if the corresponding packet queue has packets to serve. While more complex channel schedulers (e.g. taking into account QoS constraints [2]) are possible, in this work we use simple Round-Robin scheduling. Finally, R3 is tuned to a common control channel (CCC) in order to convey routing and channel (re-) assignment messages to its two hop neighbors. Selecting a suitable CCC is outside the scope of this paper. The benefit of such a hybrid multi-radio approach is its high capacity while maintaining full connectivity with neighbor CMNs using the switchable R2 interface.

3.2 Spectrum Sensing / Channel Assignment

The goal of Channel Assignment in Urban-X is to minimize the impact of interference created by mesh external (e.g. caused by PNs) and internal traffic (due to the forwarding). In order to minimize external interference, CMNs sense spectrum periodically on all interfaces and estimate PN traffic workload. The key idea is that a CMN assigns a channel i to its receiving radio R1 which has the highest available capacity (i.e. which has the smallest external load). For inferring the available capacity, CMNs first sense the spectrum periodically by sampling the energy level on the given frequency bands. Given the spectrum load characterisation, we derive a semi-Markov model (using busy and idle states) to capture the characteristics of the PN traffic for each channel. Expected idle $T_{idle}$ and busy durations $T_{busy}$ are based on cumulative distribution functions (CDFs) using two exponential distributions with rate $\lambda$ and $\mu$:

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

The PN traffic workload ($\omega$) can then be estimated by sampling the channel status (busy or idle) during the given sensing window of sensing duration time. In order to distinguish external PN traffic from forwarded traffic, CMNs use a synchronised sensing window where CMNs do not send any traffic. Synchronization for the sensing can be achieved using a dedicated protocol utilizing the CCC and methods similar to [5]. The longer the sensing duration, the better the workload estimation [11] but the more overhead the sensing will take. Once the sensing duration is over, nodes resume their transmission for the next transmission duration time.

Based on the measured workload of mesh external traffic $\omega$ and the available capacity without interference $R_0$ for a given channel (e.g. 5.5 Mbps for 11 mbps PHY layer speed), we can approximate the expected available capacity $R_i$ for channel $i$ as follows:

$$R_i = R_0 \cdot (1 - \omega) \quad (1)$$

Then, each CMN approximates the channel capacity per-node $R'_{i}$ as follows:

$$R'_i = \frac{R_i}{N(i)} \quad (2)$$

where $N(i)$ is the number of CMNs nodes selecting channel $i$ within the two hop neighborhood. Combining the information about PN workload (Eq. 1) with the information about the number of neighbors (Eq. 2), the CMNs can consider both external (caused by other CMNs) and external (caused by PNs) interference while selecting their channels. To this aim, each CMN estimates the available capacity per flow by dividing $R'_i$ by the number of active flows to serve. Then, the maximum capacity channel $i_k$ is chosen for the R1 interface with a probability $P_{i_k}$ which is a function of the least capacity per flow of the neighbor nodes. Here, the main idea is that a node serving many flows compared to the available link capacity or suffering heavy external traffic due to PN interference gets priority in selecting the channel with highest available capacity.

Once the channel for R1 is selected after each sensing interval, a node immediately broadcasts this information together with the least capacity per flow and a neighbor information table using a Hello message sent on the R3 interface tuned to the CCC (to minimize collisions, Hellos are randomized). Once a node receives such a Hello message, it updates its neighborhood information table. By this mechanism, nodes learn about available channel capacity and channels assigned to R1 interfaces in the two hop neighborhood. More information on our channel assignment can be found in [8].

4. TCP PERFORMANCE IN URBAN-X

TCP is the de-facto standard for transport protocols when operating over the internet. Therefore, efficient operation over cognitive multi-hop networks as Urban-X is important. However, there are major challenges for the transport layer and especially for the congestion control mechanism which may significantly reduce achievable throughput:

- **Unpredictable External Interference:** Due to co-existing PNs creating interference, CMN transmissions may face heavy packet loss. Such packet loss can lead to increased RTT due to MAC layer retransmits. This may result in low TCP throughput due to frequently triggered slow-start. The channel assignment in Urban-X has been designed exactly to minimize the probability of external interference by selecting the channel least impacted by PN traffic.

- **Spectrum Sensing:** For the channel assignment, CMNs estimate PN traffic workload based on spectrum sensing. However, during such cooperative sensing nodes are not able to transmit, potentially leading to TCP retransmit timeouts (RTO). There is a trade off between estimation accuracy and sensing overhead. To reduce the total sensing time, CMNs can exchange sensed channel workload information. Such collaboration among CMNs can decrease the required sensing window, which eventually may improve TCP throughput [8].

- **Channel Mobility/switching:** In Urban-X, nodes adjust the receive channel R1 dynamically and inform neighbors with Hello messages transmitted on the CCC. During this switch over, CMN links become disconnected, leading to potential packet loss. Likewise, nodes switch the transmitting radio channel (R2) to send packets to different neighbors. Once the R2 radio switches to the next channel, it stays there for a predefined switching interval. Packets arriving to the receiving interface are queued at the correct channel queue for the next hop.

If a node serves many neighbors, there may be a potential large switching delay until a given specific channel.
is served again. Such large delay can be detrimental to TCP performance as the number of intermediate forwarding nodes in the path increases. This is because channel switching jitter distorts RTT estimates and negatively affects RTO and throughput.

- **Heterogeneous Channel Bandwidth Availability:** When a node change the receive channel on the R1, the new channel may show a significant available capacity increase. However, due to the TCP congestion avoidance scheme, the congestion window does not ramp up fast enough to immediately utilize the available bandwidth, leading to unnecessarily low throughput.

In the following, we use the extended ns-2 simulator [6] to evaluate the performance of different TCP variants over Urban-X multihop networks, with variable PN external interference. In addition, we evaluate the benefit of Urban-X spectrum aware architecture by comparing its performance to traditional multi-radio mesh networks. Every simulation was repeated 50 times and a data point denotes the average of those simulation runs. PHY Layer speed was configured to be 2 mbps.

We evaluate the performance of TCP Reno over Urban-X under different PN traffic patterns by varying the idle and busy duration ($\lambda$ and $\mu$). We send a single TCP flow over the chain topology (Figure 2(a)) from node 0 to node 4. In this scenario, 11 PNs are present which occupy all 11 available channels using the same workload. Unless otherwise stated, the following parameters are used: a node periodically senses the spectrum for 70 msecs, followed by 1 sec transmission time. During the transmission time, the node switches to a channel with non empty queue and stays there for a switching interval of 50msec. The channel switching overhead, i.e. the time for the hardware to reconfigure the card once the channel switch is triggered, is assumed to be 1 ms.

As shown in Fig. 3, TCP throughput is highest when PNs have long idle and short busy duration. This allows TCP to effectively ramp up its congestion window. Rapid ON/OFF patterns of PNs lead to low TCP throughput as TCP cannot increase its window size fast enough. At fixed idle duration (e.g., 0.5 s), throughput increases slightly when busy duration decreases because the smaller the busy duration, the more time for TCP to transmit. TCP throughput decreases drastically as the workload of PN traffic ($\omega = \frac{\mu}{\lambda + \mu}$) increases as the available capacity for the mesh decreases. Interestingly, the TCP throughput decreases more than the reduction of available channel capacity, $R_t = R_0 \cdot (1 - \omega)$ due to PN traffic load. This is the additional negative effect on TCP of packet loss caused by PN interference.

Fig. 4 shows the impact of the ratio sensing/transmission duration under fixed PN traffic pattern ($T_{idle} = 2s, T_{trans} = 0.5s$) on achievable TCP throughput. TCP performance

![Figure 2: Network topology for TCP evaluation](image1)

![Figure 3: TCP Reno performance under varying PN traffic pattern(idle, busy)](image2)

![Figure 4: TCP Reno performance under varying sensing and transmission duration](image3)

![Figure 5: TCP Reno performance under varying switching interval and transmission duration](image4)
increases with transmission duration. The higher this value, the less overhead due to sensing and the longer time TCP has to increase its congestion window. For very short transmission duration, throughput is very low as sensing overhead is quite high. When the additional channel switching delay is considered (Fig. 5), the transmission duration should be larger than 500 ms for reasonable performance. When the sensing duration is larger than 200 msec, throughput again is penalized as packets need to wait too long in the buffers. Therefore, the sensing period should be lower than 100 msec.

An important parameter to consider is the switching interval as it directly impacts the delay jitter and the achievable TCP throughput. Once the transmitting interface R2 switches to a given channel with non empty queue, it stays on that channel for a predefined switching interval (awaiting for more packets to arrive to the queue) in order to minimize switching overhead. A small switching interval leads to smaller jitter but less time on a given channel. Fig. 5 shows the TCP Reno throughput in a chain topology (see Figure 2(a)) when we vary switching interval and transmission duration. As the switching interval decreases, TCP throughput generally increases unless a very small switching interval and transmission duration is used, which significantly reduces throughput due to overhead. Also, longer transmission duration increases TCP throughput. However, there should be a constraint on the maximum transmission duration (e.g. such as the channel detection time - CDT and the channel move time - CMT as defined by 802.22 based cognitive radio networks) to protect primary users.

For representative transmission durations, the switching interval considerably affects TCP performance in multihop networks. This is because the switching interval duration accumulates hop by hop leading to significant end-to-end delay variation. To investigate this problem, we measure the TCP throughput for different path lengths (fixing the sender at node 0 and varying the receiver from node 1 to 4) while ignoring the impact of PNs. We configure the switching interval as 40 msec, use 10 msec for spectrum sensing duration and do not create any PN interference. Table 1 shows TCP Reno performance for different path length. When path length increases to 4 hops, the packet drop rate increases only to around 5% because of the absence of PN interference. The throughput however decreases much more severely.

We repeated the same simulation using UDP. This time, however, the throughput was 1.3 Mbps for a 4 hop path although the delivery ratio was low (around 60%). This is because UDP’s traffic pattern is unidirectional. In contrast, TCP data packets are acknowledged leading to a two way traffic pattern. As a result, the chain topology leads to frequent channel switches for the intermediate nodes in Figure 2(a) as they need to switch between transmissions towards their upstream and downstream neighbor nodes to send TCP data and TCP-ACK. Such channel switch delay leads to large end-to-end delay variations affecting RTO and leading to frequent TCP timeouts. As the number of hops increases, channel switching mainly limits TCP throughput. As a conclusion, either the hybrid channel assignment architecture needs to be adapted to reduce the delay variation or TCP’s congestion control should be re-evaluated to cope with those effects.

In order to assess the benefit of Urban-X spectrum aware design, we compare the TCP performance of various TCP versions that have different congestion control mechanisms in normal wireless mesh networks and Urban-X, respectively.

For the WMN setup, we still use the hybrid channel assignment strategy using fixed/switchable approach and the same number of radios and channels. However, nodes do not perform spectrum sensing. Also, channel assignment for the standard WMN is not spectrum aware. Instead, it randomly assigns channels to the R1 interface and does not change the channel during the whole simulation. PNs are located as shown in Figure 2 and distributed in random channels with random workloads. Spectrum sensing duration and switching interval are configured as 70 msec and 40 msec respectively.

A detailed comparison regarding the TCP performance in spectrum and interference unaware hybrid multi-radio multi-channel WMNs and our spectrum and interference aware Urban-X CMNs is plotted in Figure 6. Figure 6 (top left) shows the throughput achievable for TCP Reno, New Reno, Vegas and SACK. Throughput of TCP is significantly higher for Urban-X (white bars) compared to WMNs across all TCP versions, because the channel assignment selects the least interfered channel having highest available capacity and least probability for collisions due to PN traffic. This is confirmed by observed packet loss rates, which are around 20% for WMNs compared to below 10% of CMNs. In addition, Fig. 6 (top right) shows that the SRTT of WMNs is lower than in Urban-X due to the absence of spectrum sensing. In Figure 6(lower right), the average cwnd size also shows that the sending data rate for TCP in Urban-X based CMNs is higher than for standard WMNs. As a conclusion, the spectrum aware channel assignment helps effectively to reduce external interference due to PN traffic, which in turns leads to lower packet loss rate and significantly higher TCP throughput. The additional price to pay for the spectrum sensing is well utilized in higher throughput. It is interesting to note that TCP Vegas has the lowest throughput of all variants. This is
because Vegas adjusts its sending rate according to estimated RTTs. Due to spectrum sensing and channel switching, this estimate seems to be conservative.

In order to evaluate the fairness aspects, Figure 7 shows simulation results from two flows in a dumbbell topology (see Figure 2(b)). Flow F1 and F2 use the same TCP variant but different destination source (node 0 and 1 respectively) and destination nodes (node 5 and node 6 respectively). Independent from the TCP variant, the TCP throughput is more than double in Urban-X compared to traditional WMNs. However, the aggregated throughput was not higher than that of a single flow in Figure 6 because of the shared bottleneck links. Although the shared links are not fully utilized by the two flows, the additional channel switching in node 2 and 4 limits the aggregate throughput. While in the previous topology intermediate nodes need to switch between two channels because of the TCP ACK forwarding, in the dumbbell topology node 2 switches among three channels to send packets to node 0, 1 and 3. Nevertheless, fairness between the two flows was mostly achieved as shown in Figure 7(right), which shows the aggregated throughput and the throughput of one flow in Urban-X.

5. CONCLUSION

In this paper, we have investigated TCP performance for multi-radio multi-channel mesh networks, which use techniques from cognitive radio based approaches in order to effectively co-exist with deployed infrastructure in the ISM bands. Our architecture Urban-X uses spectrum sensing in order to classify frequency bands according to available capacity and external interference. This information is subsequently used in a novel channel assignment algorithm. We compared several TCP schemes in Urban-X and reported the performance achieved in conventional hybrid multi-radio multi-channel meshed networks. According to ns-2 simulation results, Urban-X improved TCP throughput by around 300% by avoiding channels that face heavy external interference. The additional price to pay is periodic spectrum sensing and frequent channel re-assignment for the receiving radio. In future work, we plan to evaluate performance of Urban-X in large scale deployments.

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6. REFERENCES