Supplementary Material

I. RELATED WORK

Much work has been done with the primary objective to reduce interference and increase total throughput of WLANs. Optimal AP placement schemes optimizing power level and network throughput have been proposed in [1]–[3]. Measurement based WLAN deployment schemes have been proposed in [4] and [5]. Unlike our work, these studies all assume that network administrators conduct site surveys and do propagation modeling before network deployment. In [3], the authors propose methods to identify hot spots where high traffic is *expected* and try to assign channels accordingly. This is a static approach, and any changes or deviation from the expected traffic pattern can lead to suboptimal channel assignment. Athanasiou et al. propose Load-Aware Channel Selection (LAC) [6], a distributed scheme making use of traffic information. However, this scheme cannot dynamically adjust channel assignments according to changes in traffic patterns. Our approach, however, is a dynamic one, where we assign channels depending on the *existing* network conditions. The channel assignment problem in multi-radio, multi-channel wireless networks has been studied recently in [7] and [8], while in our research we consider the more commonly-used single-radio, single-channel case.

The work of Akella et al. [9] shows that interference in unplanned 802.11 WLANs can significantly degrade user performance. They propose an automated power control and rate adaptation algorithm to reduce network interference. Mhatre et al. propose another power control approach to mitigate interference problem in high-density 802.11 WLANs [10]. CACAO differs from these two approaches in that it addresses the *channel assignment issue* to reduce interference among networks.

Mishra et al. propose a dynamic channel assignment algorithm called CFAssign-RaC to achieve load-balancing based on a "conflict set coloring" formulation [11]. Ahmed et al. propose an algorithm using successive refinement to solve a joint channel assignment and power control problem [12]. Kauffmann et al. propose a measurement-based self-organization approach for channel assignment [13]. Unlike our work, all of these approaches focus on networks where all the participating devices belong to the same enterprise. Later proposed traffic-aware approaches in [14] and [15] consider the changing traffic pattern to make channel assignment decisions. Being traffic-aware, these two approaches are able to reduce interference dramatically. However, their algorithms are centralized in nature (which implies the existence of network administrator and central management). It means that these works are not directly applicable to uncoordinated WLANs as we discuss here. Wong et al. propose Peer-Assisted Channel Assignment (PACA) [16], a fully distributed channel assignment algorithm making use of local information. Yang et al. propose FLEX [17], a distributed architecture for APs to dynamically access a spectrum according to user demands. However, these approaches require heavy communication and coordination among APs, which is not possible for uncoordinated WLANs. A preliminary version of this work has been reported in [18]. We extend the work here by giving more details on the problem formulation, NP-hardness proof, performance metrics and interference problems.

Mishra et al. propose a distributed algorithm called MAXChop [19], which addresses channel assignment problem based on standard graph coloring formulation and calculates a channel hopping sequence at each AP to reduce interference. However, such a hopping sequence needs to be periodically communicated among APs, and frequent hopping introduces much overhead into the system. Moreover, the MAXChop algorithm has not taken into consideration traffic pattern. As a result, it is possible that heavily loaded adjacent APs are assigned to the same channel at some hopping slots, leading to high interference. Arbaugh et al. propose Hminmax [20] and formulate the channel assignment problem as a weighted coloring graph problem. Their approach is based on the interference experienced by clients (e.g., the number of interfering devices). CACAO differs by taking into account the real traffic load of *both* APs and clients, which leads to better interference mitigation and better performance. In this paper, we compare the two recent schemes (MAXChop and Hminmax) with CACAO.

A. Interference Problems in Uncoordinated WLANs

Many traditional approaches have been used for WLAN channel assignment. LCCS is one of the standard features provided by many commercial wireless APs to search for a "least congested" channel in terms of the number of devices in the interference range [21]. Using this traditional approach, an AP assigns its channel mainly based on scanning and counting the number of interfering wireless devices. Although this approach is widely used, it suffers from the hidden interference problem and non-uniform traffic distribution problem explained below.

The hidden interference problem is illustrated in Figure 1, where we show two APs from different and independent WLANs labeled as AP_1 and AP_2 and mobile nodes labeled as A and B. The circle of a particular node indicates its transmission range. Since AP_1 and AP_2 share no overlapping area, they are unable to detect each other's existence, so they will configure themselves to operate on a random or default channel (based on firmware settings). As discussed before, the

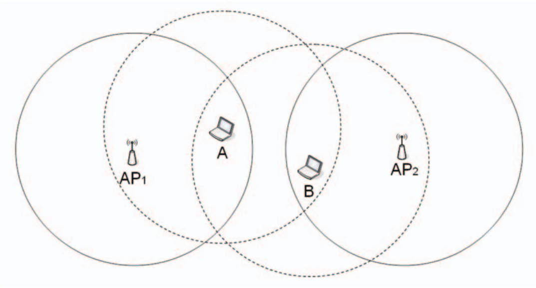

Fig. 1. Hidden interference problem.

channel chosen is likely to overlap (with the default channel) [9].

Suppose AP_1 and AP_2 are operating on the same channel. Although the signals of AP_1 and AP_2 do not interfere with each other, it does not mean that the devices in the two WLANs do not interfere with each other. In Figure 1, nodes A and B are associated with AP_1 and AP_2, respectively, and are within each other's transmission range. Because they transmit data using the same physical channel, they interfere with each other. This is the so-called hidden interference problem.

CACAO addresses the hidden interference problem by using a client-assisted approach such that every client in a WLAN can detect interference in its neighborhood and feeds the information back to its associated AP. In our example, node A can detect interference created by B. By informing AP_1 that there is a nearby device using the same channel and transmitting some amount of traffic, AP_1 can make a better channel assignment decision dynamically.

Traditional approaches also suffer from the traffic distribution problem. We illustrate this in Figure 2 with four APs using three non-overlapping channels (channels 1, 6 and 11). Clearly, at least two APs have to operate on the same non-overlapping channel. Suppose that initially AP_1, AP_2 and AP_3 use channels 1, 6 and 11, respectively. If a new AP, AP_4, applies LCCS, it will find that the number of associated clients of channels 1 (AP_1), 6 (AP_2) and 11 (AP_3) are 1, 2 and 3, respectively. It will then operate on the least congested channel, which is channel 1.

Clearly, this bandwidth-blind approach does not always lead to good throughput. For example, nodes A, B and C may be running bandwidth intensive applications such as real-time video streaming applications, whereas nodes D, E and F may be running some low-bandwidth applications such as POP3 email clients. In this case, AP_4 should choose channel 11 instead of channel 1, because this way the amount of interfering traffic is the lowest. This example shows that in order to decide which channel to operate on, traffic information should be taken into consideration, which is the idea behind CACAO.

II. IMPLEMENTATION ISSUE

Clients associated with an AP will switch to each non-overlapping channel to measure and collect channel utilization information; this is the channel utilization query process. All

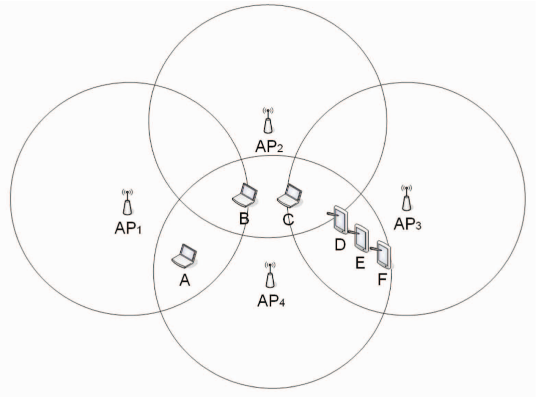

Fig. 2. Traffic distribution problem.

clients of an AP will enter channel utilization query process during every channel switching interval. All non-overlapping channels will be measured. We consider only non-overlapping channels. When the node "snoops" another channel, the AP buffers packets for it. This can be done by using the Power Saving Mode (PSM) available from IEEE 802.11 [22]. As mentioned previously, the query process can be done by any protocol, such as 802.11k standard for Radio Resource Management specification (currently being discussed) for interoperability.

The channel switching interval $SwitchingInterval$ is further sub-divided into several monitoring intervals by a factor $MonitoringIntervalFactor$. In each monitoring interval, a client enters the target channel for monitoring purpose under two conditions: (i) if the client has low activity for $LowActivity$ amount of time; or (ii) if the client has been busy the entire observation interval then it will enter the target channel at the last $ObserveTime$ amount of time. The client should switch back after $ObserveTime$ amount of time. When these variables are properly set, the cost of channel condition monitoring can be maintained at a very low level and will not affect the efficiency of the whole algorithm (we use in our simulation $SwitchingInterval$ = 600 secs, $MonitoringIntervalFactor$ = 20, $LowActivity$ = 3 secs, $ObserveTime$ = 3 secs). In every switching interval, each client participates in the channel monitoring activity at least once, ensuring certain quality and accuracy of the channel monitoring result. The values of the intervals are adjustable. Increasing the channel observation time will increase the accuracy of the channel condition measurement (with sacrifice of the performance). The values we use in the simulation have been tuned to generate reasonably accurate results and can be a baseline for adjustments.

Regarding traffic measurement, Mishra et el. [11] make a convincing argument that the client side approach is able to probe and get good information on the wireless environment. In CACAO, client side interference reports are best created by idle clients. These clients conduct interference measurement, collect information, generate statistics and send reports back to their APs for further calculation. A client that performs

TABLE I
MAJOR ELEMENTS OF THE STATISTIC REPORT USED IN CACAO.

Channel	Load Observed	Num of Neighbors	My Load

such action randomly picks a channel and switches to it. At the same time, the client's AP must buffer packets that are designated for that specific client. There are two conditions when the client needs to switch back to the original channel: (i) if the client needs to send data to the AP; and (ii) if the predefined interval of interference measurement ends. While the client is operating on another channel, it does not send out information and only records the amount of traffic during the specified time interval. The interval in which a client listens to another channel needs to be reasonably short, mainly because the AP has limited memory and cannot buffer large amount of content for the client. The AP only measures its own operating channel.

During a channel switching interval, every client measures and stores the average signal strength between it and its AP as $Signal_1$. While the client switches to another channel, it measures the incoming packet's signal strength at the MAC layer as $Signal_2$. When $Signal_2/Signal_1 \geq SNR$, it means the incoming packet will cause interference and this packet will be counted for the interference measurement. As a result, the case in which two interfering clients may have hidden interference problem is addressed. If node A is in the interference range of node B, the signal strength of B's traffic will be compared with the signal strength of A's AP. Packets that creates interference (i.e., $Signal_2/Signal_1 \geq SNR$) will be counted. Packets that does not create interference (i.e., $Signal_2/Signal_1 < SNR$) will be ignored.

After a client finishes its channel utilization query process, it switches back to the original channel and sends a statistic report to its AP. We show in Table I the major elements of the statistic report used in CACAO. The report mainly contains four fields, $Channel$, $LoadObserved$, $NumofNeighbor$ and $MyLoad$. $Channel$ is the reporting channel number. $LoadObserved$ stores the total amount of traffic observed from other networks in the recorded interval. $NumofNeighbor$ stores the number of nodes (both clients and APs included) contributing to $LoadObserved$. $MyLoad$ stores the client's own out-going traffic load during the time interval.

To prevent adjacent APs switching to the same channel at the same time, an AP informs its associated clients before it switches to another channel. The clients broadcast the channel switching decision as a beacon message. When nearby clients associated with other APs receive the beacon message, they inform their associated APs to delay the channel selection algorithm for one switching interval. These APs also dump the previously collected data to prevent the usage of stale information. They then resume the algorithm in the next channel switching interval.

Automatic PHY rate adaptation scheme is used in some of the APs. When transmission error is encountered, the PHY layer automatically reduces the sending PHY rate in order to reduce error and retransmission, which lead to slightly different interference characteristic. In order to extend our algorithm to work with auto rate adaptation schemes, we make use of the $Signal$ field in the 802.11 control frame. 802.11 standard specifies PLCP protocol data unit, which includes a $Signal$ field that indicates what PHY rate is used. By this value and the packet size, we can calculate how much time the channel is kept busy, and convert it into the equivalent data rate under default PHY rate. Then the calculation of interference level can be performed.

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