Channel Assignment Schemes for Infrastructure-Based 802.11 WLANs: A Survey

Surachai Chieochan, Ekram Hossain, and Jeffrey Diamond

***Abstract*—Efficient channel assignment is crucial for successful deployment and operation of IEEE 802.11-based WLANs. In this article we present a survey on the state of the art channel assignment schemes in IEEE 802.11-based WLANs. After detailing out all the schemes, we provide a qualitative comparison among different schemes in terms of algorithm execution behaviors, complexity, and scalability. We then conclude the survey with several research issues open for further investigation.**

***Index Terms*—Channel allocation, channel assignment, IEEE 802.11, network planning, resource allocation, wireless networking.**

I. Introduction

DUE primarily to its unlicensed frequency band of operation and low-cost equipments, the IEEE 802.11-based wireless access technology, also known as WiFi, has been widely deployed in local area networks (LAN) such as homes, coffee shops, public hotspots, inventories, airports, large organizations, etc. A typical deployment of this technology is shown in Fig. 1. Based on how they are managed, wireless LANs (WLAN) can be categorized into one of the following: 1) centrally managed or 2) uncoordinated [1]. Centrally managed deployments are usually seen in places such as university campuses, offices or airports where all access points (AP) and associated clients are managed by a central entity. On the other hand, uncoordinated WLANs operate in the absence of a central control and are typical in places such as residential neighborhoods or private hotspots managed by different service providers (e.g., restaurants, coffee shops, etc.). Successful deployment in either case requires efficient mechanisms for addressing performance issues such as excessive interference which usually translates into low throughputs. In the literature, several techniques have been proposed to address such performance issues. In particular, association control (or load balancing), in which a central entity associates (respectively, disassociates) clients with (respectively, from) APs in order to balance traffic in a network, is usually proposed for the centrally managed deployments [2]. Proposed for the uncoordinated deployments, on the other hand, are such techniques as power control [3], [4] and careful carrier-sensing [5], in which transmission power is dynamically tuned, and unnecessary carrier sensing is avoided, respectively. One other technique that is extensively considered and applicable to both centrally managed and uncoordinated environments is channel assignment, in which a frequency channel is assigned to each AP for use for a certain duration of time. In this article, we present a survey on recent developments in such channel assignment technique. We identify and discuss several major approaches applicable to either deployment scenario. Subsequently, a qualitative comparison is made among these approaches. Some comments on current practice in channel assignment are also presented. Finally, future research directions are outlined as a conclusion to this survey. In the following section we describe the system under consideration.

Manuscript received 19 July 2008; revised 9 October 2008 and 5 January 2009. This work was supported by a scholarship from TR*Labs* and in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

S. Chieochan and E. Hossain are with the Department of Electrical and Computer Engineering, University of Manitoba, and with TR*Labs*, Winnipeg, Canada (email: ekram@ee.umanitoba.ca).

J. Diamond is with TR*Labs*, Winnipeg.

Digital Object Identifier 10.1109/SURV.2010.020110.00047

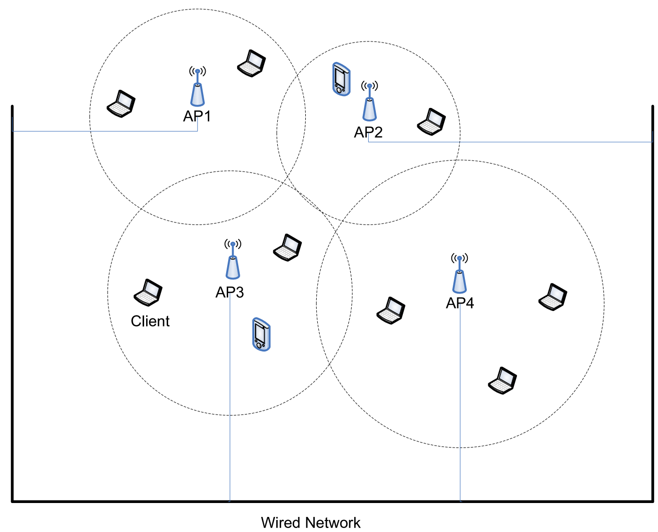

Fig. 1. Typical Infrastructure-based IEEE 802.11 WLAN.

II. System under Consideration

A. Network Topology

This survey focuses only on an IEEE 802.11 WLAN with an infrastructure network topology as shown in Fig. 1, where APs and clients resort to existing communication infrastructures such as legacy LAN to facilitate their communication. A fixed AP operating on a certain channel interconnects its associated clients to the infrastructure. All communication activities must be facilitated via this AP. A single instance of such a topology is referred to as a basic service set (BSS) or cell. If more BSSs exist in the same infrastructure, the system is referred to as an extended service set (ESS). In this survey, we focus on either a single ESS managed by one particular administrator, or multiple ESSs each managed by a different administrator.

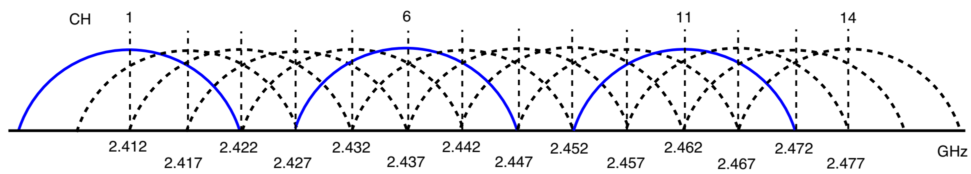

Fig. 2. 802.11 channels in the 2.4 GHz ISM band.

B. Channelization

Currently, two unlicensed frequency spectrum bands are available for use in IEEE 802.11 WLANs: 1) 2.4 GHz Industrial, Scientific, and Medical (ISM) band, and 2) 5 GHz Unlicensed National Information Infrastructure (UNII) band, [6] and [7]. While the legacy IEEE 802.11 and enhanced IEEE 802.11b/g WLANs operate on the 2.4-GHz band, the IEEE 802.11a WLANs employ the 5-GHz band. Both bands are available internationally. The number of allowable channels however varies from country to country due to each country's regulations on radio spectrum allocation. In particular, while most European countries and Australia allow channels 1 up to 13 in the 802.11b/g band, most North, Central and South American countries only allow up to channel 11 in the same band [8]. In Japan, all 14 channels are allowed. These regulations are however subject to change.

As shown in Fig. 2, the 2.4-GHz band consists of 14 overlapping channels each of which occupies a bandwidth of 22 MHz. Due to the spectral overlaps of channels within this band, the standard also specifies the allowable levels of power overlaps between overlapping channels. Specifically, as shown in Fig. 3, the signal must drop 30 dB and 50 dB below its peak power when operating at ± 11 MHz and ± 22 MHz apart from the center frequency, respectively [6].

The 5-GHz UNII band contains three subbands referred to as *low*, *middle*, and *high*, each of which contains four non-overlapping channels as shown in Fig. 4. Each channel occupies a bandwidth of 20 MHz. Currently, the 5 GHz band is still significantly less populated than the 2.4 GHz band because 1) 802.11a equipments are not so widespread as 802.11b/g equipment, and 2) due to the higher frequency, 802.11a signals cannot penetrate as far as 802.11b/g signals and are absorbed more readily by obstacles. As in the 2.4 GHz band, the power spectrum mask is also specified in the 5-GHz band [8]. This is shown in Fig. 5 where the signal must drop 20 dB, 28 dB, and 40 dB at 11 MHz, 20 MHz, and 30 MHz apart from the center frequency, respectively.

C. Medium Access Control

To accommodate multiple clients in a WLAN, a mode of contention-based medium access called distributed coordination function (DCF) is employed [6]. DCF uses the carrier sense multiple access/collision avoidance (CSMA/CA) technique in which a station, either an AP or its respective associated clients, senses the wireless medium for transmission opportunity. If the medium is idle, the station starts its transmission. Otherwise, it backs off and waits for a random period of time before contending again for the medium. In case two stations sense an idle channel and start their transmissions simultaneously, *collision* is said to occur. If collided, both stations will have to back off for a random period of time and then retry, reducing the probability of further collision. In order to lower the collision probability, clients may adopt an optional handshake-based medium access mechanism known as Request-To-Send/Clear-To-Send (RTS/CTS) signaling. Prior to transmitting packets, a station broadcasts an RTS packet to reserve the medium. If the medium is idle, the destination responds with a CTS signal. The station then seizes the medium and starts transmitting.

III. Channel Assignment and AP Placement in IEEE 802.11 WLANs

A. Channel Assignment

We now define channel assignment in the context of IEEE 802.11 WLANs. Consider a WLAN consisting of a set of k APs pre-installed in a given geographical area as shown in Fig. 1. Each AP supports all wireless clients residing in a BSS. A pool of j channels, either overlapping or non-overlapping, is available for this WLAN (see Figs. 2 and 4). Channel assignment is then defined as a strategy in which one of the j channels is allocated to each AP such that the interference generated as a result of such assignment is minimized. In other words, capacity required to handle the traffic load generated by stations (APs and clients) within the WLAN should be maximized as a result of such channel assignment. All the existing channel assignment strategies considered in this survey are developed based on this underlying concept. The formulation of all the channel assignment schemes are based on optimization theory. The way interference is modeled, however, differs from one scheme to another.

To give an example, let us consider Fig. 1. Each BSS has different coverage. Assuming that only three non-overlapping channels from the 2.4-GHz band are used, one simple solution for assigning channels to APs in Fig.1 would be to assign channel 1, 6, 11 and 1 to AP1, AP2, AP3 and AP4, respectively. In this case, there would be no interference. Possibly, one could assign channel 6, 1, 11 and 6 to AP1, AP2, AP3 and AP4, respectively. In reality, the system is more complicated, of course, with many more APs or BSSs coexisting either in the same management domain (centrally managed) or in different management domains (uncoordinated). In this survey, we identify and explain channel assignment schemes that fall into one of these two categories: 1) centrally managed and 2) uncoordinated.

B. AP Placement

We define AP placement as a strategy in which APs are assigned and installed to particular geographical locations so

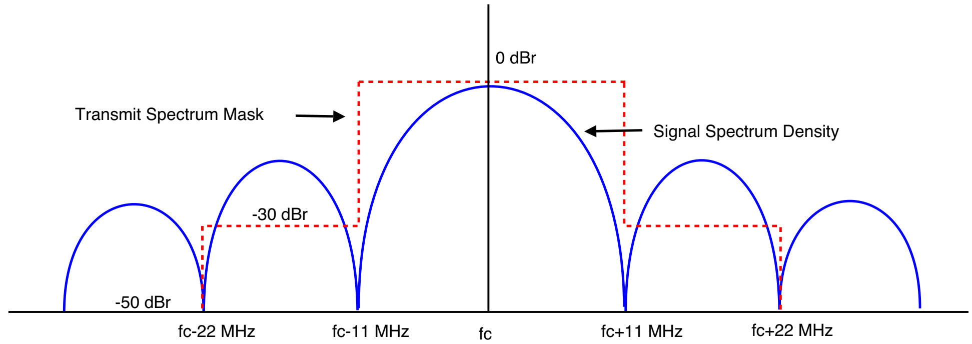

Fig. 3. Power spectrum mask of the 2.4 GHz ISM channels illustrated with a particular signal spectrum density $|\frac{\sin(x)}{x}|$.

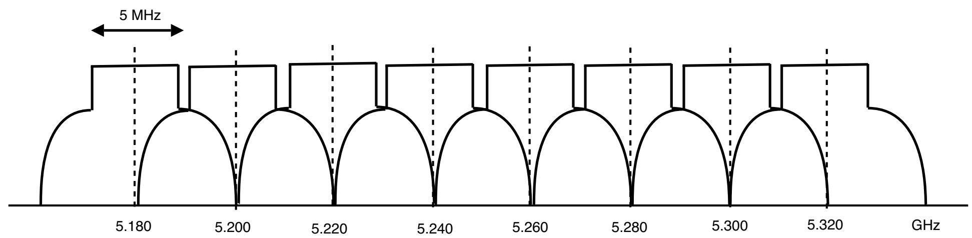

Fig. 4. Two lower subbands of the 5 GHz UNII band.

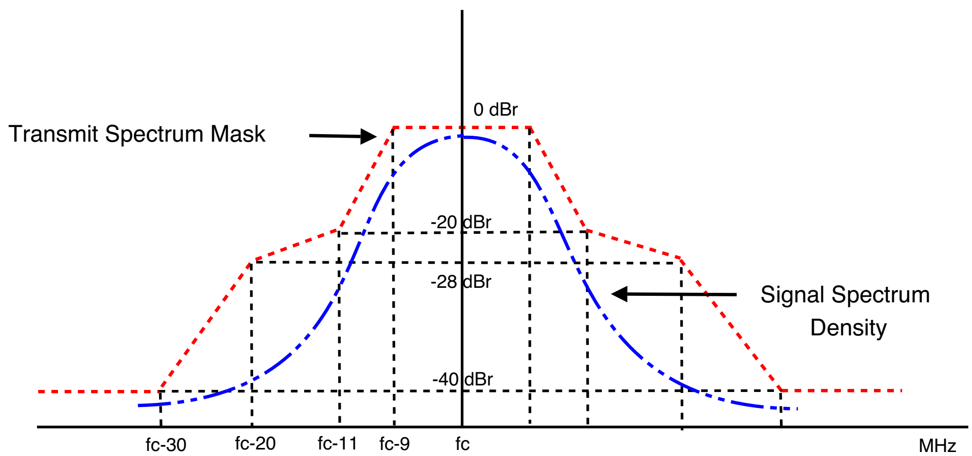

Fig. 5. Power spectrum mask of the 5 GHz UNII channel illustrated with some random signal spectrum density.

as to provide maximum radio coverage to clients subject to certain QoS requirements. Such a strategy is usually performed during the initial phase of network planning and coupled with most channel assignment strategies developed specifically for a centrally managed network. In an uncoordinated network, however, AP placement completely disappears from the framework of channel assignment due to the lack of any centralized control over all APs managed by different network administrators. In this case, AP locations are simply taken as given and the focus is only on channel assignment.

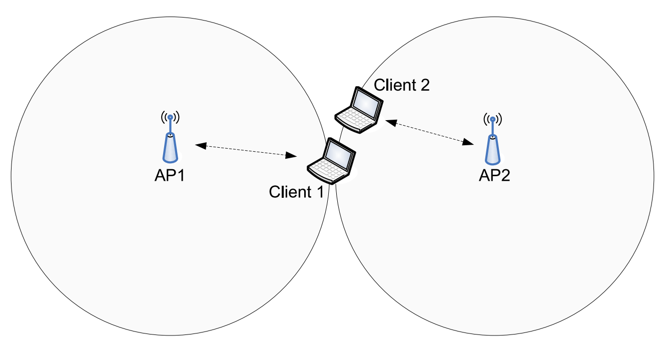

Fig. 6. Effect of CSMA/CA on Channel Assignment.

IV. Challenges in Channel Assignment in IEEE 802.11 WLANs

In most cases, channel assignment is more complicated than the example given in the previous section, especially when the number of BSSs and clients grows. Reusing channels in a WLAN is more challenging compared to that in a cellular network whose coverage area is typically well planned and has regular cell shapes. Such regularity does not exist in WLANs whose deployment is usually done indoor, where building layout and construction materials usually complicate the coverage areas, and have a significant effect on the overall network performance. Moreover, as WLAN deployments start to move outdoor (e.g., metropolitan hotspots in big cities), WLANs will most likely experience the same network dynamics as cellular networks. Even worse is the situation where cell coverage cannot be planned or controlled at all, i.e., uncoordinated environments.

Even though geographically disjoint cell coverage can be planned in such area, as shown in Fig. 6, inevitable co-channel (or adjacent-channel) interference still remains due to the nature of CSMA protocol. To illustrate this, let us consider Fig. 6. Due to disjoint coverage, both APs can be assigned the same channel. Client 1 and Client 2 are associated with AP1 and AP2, respectively. Client 1 sitting at the boundaries of both cells is however within the transmission ranges of both AP1 and AP2. Assume further that AP2 is transmitting to Client 2. Even though the channel assigned to AP1 is idle, Client 1, who wants to transmit to AP1, will always sense the channel as busy because AP2's transmission interferes with Client 1's sensing. Client 1 will have to defer its transmission, just as it would when its own channel is busy. Similarly, suppose Client 1 is transmitting to AP1, and at the same time the channel assigned to AP2 is idle. Even residing outside AP1's coverage, Client 2, who wants to transmit to AP2, suffers from co-channel interference from Client 1's transmission because Client 2 is in the transmission range of Client 1 (not drawn). Therefore, both random channel access mechanisms and random locations of clients complicate channel assignment in WLANs. Also, the mobility of the clients [10] should be considered for efficient channel allocations.

Finally, channel assignment techniques as employed in cellular mobile systems cannot be applied directly in WLAN scenarios. In cellular networks, data traffic and control signaling traffic are usually carried in separate channels. That is, while a certain set of channels is devoted to data transmission, a common channel is usually used to convey control information (e.g., information related to channel assignment and reassignment) within the network. Various channel assignment strategies in the cellular domain are designed and implemented just around this concept [9]. In WLANs, however, both data and control traffic have to share the same channel. For more information on classical frequency assignment problems appeared in wireless communication systems as early as 1960, interested readers are referred to a classic paper by Hale [11].

V. Channel Assignment Schemes in Centrally Managed Environments

We describe channel assignment schemes as applied to a centrally managed network in this section. In a centrally managed network, there exists a central entity that decides and assigns a channel to each AP such that a certain performance metric of the network is optimized. A typical metric of interest is interference, which usually translates to a capacity measure. In addition to channel assignment, the placement of APs may also be controlled by this central entity to maximize the radio coverage of the network. Two sub-categories of channel assignment schemes as applied to a centrally managed network are in order: 1) channel assignment with AP placement and 2) channel assignment without AP placement.

The first sub-category reflects the early developments in this field, which usually assume that a network administrator has complete control over the placement of APs and the assignment of channels to APs. This assumption makes sense as, in the early days, WLANs were meant to provide data communications only within organizations, just like a typical legacy LAN does. Deployment of WLANs in nearby sites, if there exist any at all, is thus not much of a concern. The main challenge the schemes under this sub-category try to address is how to overcome the irregularity in cell shapes of BSSs as well as the varying traffic demands over a given area, by means of channel assignment and AP placement (This is actually the first challenge mentioned in Section IV). One common requirement of the schemes under this sub-category is thus an accurate estimation of traffic demands in a given area to which APs are to be installed. The way each scheme estimates and exploits the traffic demands however differs from scheme to scheme. We describe each scheme in this sub-category in Section V-A.

On the other hand, the approaches under the second sub-category ignore the placement of APs and focus only on channel assignment. The main challenge these approaches try to address is the interference induced by MAC contention, which is the second challenge, and partly the third challenge, described in Section IV. While [12] focuses only on the interference induced by MAC contention among APs only, the recent approaches ([13] and [14]) take into account the interference induced by MAC contention among APs and clients. We describe each scheme under this sub-category in Section V-B.

A. Channel Assignment with AP Placement

1) Traditional Approach: In the first generation WLANs, the channel assignment problem is usually solved as part of the initial network planning. That is, assigning channels to APs is performed after the possible AP locations are determined. In specifying the trial locations of APs, network parameters and requirements such as mobility, user population, surrounding physical infrastructure, prospective applications, and security levels are taken into consideration [15]. After that, the planning design is refined via a site survey which usually involves measuring signal levels at various traffic demand locations to generate a radio coverage layout and optimal AP locations. Implicitly, the site survey helps to discover actual unforeseen interference and re-adjust the channel assignment, and perhaps, AP locations accordingly. Using this approach, the work in [16] treats the channel assignment problem as a map coloring problem in which each AP represents a vertex and a non-overlapping channel a color. Its objective is to assign one of the non-overlapping channels to an AP such that the co-channel coverage overlap between adjacent cells is minimized.

The scheme recommends no specific map coloring algorithm to use, but does suggest that channel assignment be done first for those areas with high traffic demand followed by those with light traffic. In the high traffic demand areas, multiple channels are usually provided through multiple APs located densely close to one another to boost network capacity. For example, three APs with three non-overlapping channels

(1, 6, and 11) may be provided to support traffic in a small but busy conference room. With all the high traffic demand areas covered, subsequent channel assignment to those APs located in the adjacent, light traffic areas can now be performed by taking into consideration co-channel signal spillovers from those APs situated in the high traffic areas. These spillovers thus represent (co-channel) interference which in turn creates a co-channel coverage overlap - a quantity this scheme aims to minimize.

One other work similar to this approach can be found in [17], where the real experience on WLAN design and capacity planning is reported.

2) Integer Linear Programming Approach: In [18], the problems of channel assignment and AP placement are solved simultaneously by using Integer Linear Programming (ILP). The approach considers not only radio coverage but also load balancing among APs because the authors argue that the number of active wireless clients connected to the APs affects network performance. That is, traffic congestion at the APs degrades the network performance such as throughput. The basic idea is therefore to distribute clients to the APs in a WLAN such that congestion at APs is minimized. Correspondingly, the throughput is maximized.

A floor plan is assumed to consist of traffic demand points, each of which is given an expected traffic demand volume. A set of AP candidate locations is also given. If a signal from the AP to the demand point is above a certain threshold, an edge is drawn between a traffic demand point and a particular AP. Similarly, an edge is drawn between two APs, whenever they are within a co-channel interference distance defined as a transmission range at which, if assigned the same channel, these two APs can interfere to some extent with one another. The objective is to minimize the maximum channel utilization (a measure of congestion) at each AP, while keeping a certain level of traffic demand satisfied at each demand point. Each demand point is assigned to exactly one AP. If at least one demand point is assigned to an AP, that AP will be included in the solution set. If an edge exists between two APs, each AP will be assigned a different non-overlapping channel.

As mentioned earlier, the goal is to distribute clients throughout the network such that the overall network throughput is maximized. This requires an accurate network layout containing the descriptions of demand points with estimated traffic, client distribution, and received signal levels at each demand location. In general, since such a network layout is very dynamic, new assignment of demand points to APs and channels to APs is necessary. The new assignment however may cause a certain amount of disruption to client traffic. The authors propose another ILP that aims to minimize the amount of client traffic disruption due to the new assignment process, while maintaining the resulting channel utilization below that of the previous assignment.

3) Priority-Map Approach: In [19], the channel assignment problem is solved in tandem with the AP placement problem. A floor plan of interest is first divided into pixels. Each pixel is prioritized based on its traffic requirements, i.e., how much capacity the pixel may need and for how long. A highest-priority pixel is thus designated as one having highest demand of capacity and availability, and similarly a lowest-priority pixel having lowest demand of capacity and availability. Intermediate levels of priority are possible[1].

With the priority map created, the strategy is to first come up with a set of possible AP locations which can provide adequate radio coverage to every pixel of the floor plan. Adequate coverage here means a minimum level of capacity and availability required by each pixel. To achieve this, a wave propagation prediction model such as a ray tracing technique can be used to predict the coverage area generated by each candidate AP. As can be expected, more than one set of possible AP locations may result from this process. For each set of possible AP locations, the next step is to eliminate those APs which create unacceptably large coverage overlap[2] between their adjacent neighbors, provided that adequate capacity and availability are still supplied to every pixel affected by this elimination. To quantify this overlap, the mean difference between the received power of two adjacent APs is used. That is, if the difference in received power averaged over every pixel in the overlap area falls below a certain threshold, one of the APs should be eliminated. This step thus eliminates the possible interference created by the radio coverage overlap of adjacent APs.

After the above elimination process, the channel assignment is now applied to each set of possible AP locations. The assignment starts in a greedy manner in which a non-overlapping channel is assigned first to the AP that covers the area (a group of pixels) with highest priority. The assignment process always continues to the next AP which exhibits the lowest signal propagation pathloss (i.e., the lowest amount of signal power drop) with respect to the previous AP. In other words, continue with the AP which might have caused greatest interference if assigned the same channel. Another non-overlapping channel is then assigned to this AP. The process continues until the number of non-overlapping channels is exhausted. At this point, the process may follow one of the two proposed algorithms. In the first algorithm called *Mutual Interference Algorithm*, the carrier-to-interference ratios (CIR) of the signals from all the APs already assigned a channel are evaluated at the next AP. The channel (or carrier) whose signal is received with the lowest CIR is then assigned to this AP. The process continues to the next of remaining APs and so on.

In the second algorithm called *Received Power Algorithm*, after the number of non-overlapping channels is exhausted, the received power of the signals from all the APs already assigned a channel is evaluated at the next AP. The channel whose signal is received with the lowest power is then assigned to this AP. The process continues to the next of remaining APs and so on. The final solution is that set of AP locations (with channel assignment) which gives the highest value to the following objective function:

$$f = w_{cir}A_{cir} + w_{cov}A_{cov}, \quad (1)$$

where A_{cir} and A_{cov} are the mean CIR and received power

[1]Note that, since in practice traffic demand at a particular pixel may vary from time to time, this prioritization of pixels can only serve as a rough estimate of traffic requirements in a long run.

[2]Overlap is defined as a common area covered by two or more adjacent APs.

averaged over all the pixels in the floor, respectively. w_{cir} and w_{cov} are the respective weighing factors. While the first term in (1) represents the capacity requirement, the second term serves as the radio coverage measure.

4) Patching Algorithm: AP placement and channel assignment are jointly optimized in [20]. The objective is to jointly maximize throughput and fairness among wireless clients. Uplink traffic is considered. The throughput is estimated for each client based on [21] in which the throughput expression is only valid for clients residing in a single cell (or BSS) and depends only on the number of clients within that cell. The estimated throughput used in this approach is however extended to include the effect of co-channel interference generated by neighboring cells. Precisely, the throughput of client i depends not only on the number of wireless clients within its cell but also on a metric called the number of its restrainers. Restrainers of client i are defined as those clients residing in client i's neighboring cells, whose transmission can cause enough co-channel interference for client i to sense its own channel busy. The higher the metric, the lower the throughput that client i will experience. The assignment of channels to client i's neighboring cells (APs) thus affects client i's throughput. The objective function is calculated as the product of the sum of these estimated throughputs (i.e., aggregate throughput) and the fairness index. The fairness index captures the deviations of the individual estimated throughputs from one client to another. The fairness index is calculated as follows:

$$F = \frac{(\sum_i^N Th_i)^2}{N \times \sum_i^N (Th_i)^2}, \quad (2)$$

where N is the total number of clients in the network and Th_i is the throughput of client i. Clearly, the fairness index is one if all the clients have exactly the same throughput, whereas the index approaches $1/N$ when the individual throughputs are heavily unbalanced.

A unique global optimal solution involves high computational complexity. A heuristic algorithm called *Patching* is thus proposed. The algorithm starts with a set of candidate AP locations on the floor plan, and a set of non-overlapping channels. The algorithm then tests to see which AP assigned to which channel yields the largest value of the objective function. Such an AP with an appropriate channel is then selected, placed (or patched) on the floor, and removed from the candidate set. The process repeats with the remaining AP candidates and the same set of non-overlapping channels until a pre-determined number of APs is reached. In each iteration, since a newly placed AP may cause some clients to re-associate with it, the individual estimated throughputs of those clients affected by this re-association will change and should be re-estimated accordingly.

5) Coverage-Oriented Approach: In [22], AP placement and channel assignment are optimized both sequentially and jointly. Using the integer linear programming model, the objective of the AP placement problem is to maximize the total throughput over all the service area while satisfying the specified number of APs. The net throughput function is obtained by fitting the throughput measurements to a polynomial function as the received signal power varies. The measurements are performed using a specialized network performance tool which measures the average downlink data throughput while streaming TCP traffic from an AP to only one active client who sits at the various locations or pixels of the entire coverage area. The received signal power level associated with each throughput measurement is then recorded. Given the net throughput function, the AP placement problem is formulated as:

$$max[\Sigma_{a,j}\Phi(p^r_{aj})x_{aj}], \quad (3)$$

where $\Phi(p^r_{aj})$ is the net throughput function which depends on received signal strength p^r_{aj} at pixel j located at some distance away from AP a. The binary variable x_{aj} is 1 if pixel j is associated with AP a, and 0 otherwise. The above objective function is evaluated such that each pixel is assigned to only one AP, and the number of APs to be installed is specified beforehand.

The objective of the channel assignment problem is to minimize the physical overlapping area supported by the APs operating on either the same channel or adjacent channels. The overlap area metric is obtained by actually counting the pixels that hear interfering transmissions from the other neighboring APs. This metric therefore depends on a receive sensitivity threshold defined for each pixel as the minimum received signal power required for sensing a channel busy. The objective function for the co-channel interference case is as follows:

$$min[\Sigma_{ab}v_{ab}w_{ab}], \quad (4)$$

where v_{ab} is the number of pixels located between APs a and b, and interfered by either a or b. The binary variable w_{ab} is 1 if APs a and b operate on the same channel, and 0 otherwise. For the adjacent channel interference case, the weighing factor which depends on channel distance between two adjacent channels can be integrated into (4).

As mentioned earlier, both of the objectives shown in (3) and (4) can be solved sequentially – AP placement followed by channel assignment. For joint optimization, both objectives are linearly combined. A weighting factor is used for each objective to prioritize the two separate goals, i.e., to trade off the total throughput against the channel overlapping area which in turn represents interference. This weight is actually a design parameter that, if chosen appropriately, can drive the joint approach to outperform the sequential one in terms of the net throughput and the amount of the physical overlapping area. For a small number of APs, the problem can be solved for optimality. For a larger network, the approach has to resort to heuristic algorithms.

B. Channel Assignment without AP Placement

1) DSATUR - Vertex Coloring Based Approach: In graph coloring, APs are treated as vertices of a graph, and a single edge of the graph represents potential interference induced by a pair of adjacent interfering APs. A set of colors corresponds to a set of overlapping channels. The problem of frequency assignment is then reduced to coloring the vertices such that the number of colors used is minimal and no interfering (connected) nodes have the same color. Optimal coloring is

NP-hard. In [12], an algorithm based on the concept of a saturation degree (so called *DSATUR*) is introduced to obtain a sub-optimal solution. The saturation degree of a vertex is defined as the number of differently colored vertices to which the vertex is adjacent. These different colors used by the neighboring vertices then constitute a set of non-admissible colors for the vertex in question. The basic idea behind this algorithm is to choose for each iteration a vertex with the highest saturation degree and color it with the least admissible color. For example, assume that AP i (vertex i) with the highest saturation degree is surrounded by two APs one of which is colored with color (channel) 1 and the other with color (channel) 6. These two colors then constitute a set of non-admissible colors for AP i. For non-overlapping 802.11b channels, the next possible color (channel) that can be assigned to AP i is therefore color (channel) 11 which is first on the list of admissible colors. The coloring is greedy in the sense that the first available color in the admissible set is always selected. The algorithm continues in this manner until all the vertices are colored.

Under this algorithm, construction of an accurate graph is the key to the channel assignment. The Inter-AP Protocol (IAPP) is then needed for APs to cooperate and construct such a graph. One way of constructing such a graph is to have all the APs in the service area listen to the beacons generated by their neighboring APs. In the beacons, such information as MAC addresses of their respective senders, signal-to-noise ratios, and received signal strength can be extracted. After identifying its neighbors, each AP sends this information to the other APs in the network via a distribution system such as a legacy LAN. The algorithm then can be applied at any AP in the network either periodically or whenever new information about the network topology arrives. To make this cooperation among APs possible, recommended practice is specified in the 802.11F.[3] Similar approaches are reported in [24] and [25].

2) CFAssign-RaC: Conflict-free Set Coloring: With a detailed definition and classification of channel interference, the work in [13] solves the problem of channel assignment in conjunction with the problem of load balancing. The authors emphasize on the interference model that tries to capture total interference as seen by clients while employing all the available channels in a network. In effect, the model is able to capture the so-called *hidden* interference not seen from the AP perspective. In this model, interference as seen by clients is said to originate from two different sources, i.e., (1) from those APs located within a communication range of the client of interest, regardless of channel choices of operation, and (2) from those stations, either APs or wireless clients (in neighboring BSSs), located within a one-hop distance of the AP-client link of interest. In both cases, the client is said to suffer from channel conflict.

The main idea of this strategy is to assign channels to APs so that the clients are distributed (associated to APs) in such a way that *conflict* is minimized. Under this scheme, *conflict* is used to denote scenarios where any two stations (APs or clients) belonging to different BSSs interfere with each other by the virtue of sharing the same channel [13]. By this, the problem of load balancing is implicitly addressed. Based on this formulation, a centralized algorithm *CFAssign-RaC* is proposed for channel assignment. The algorithm attempts to maximize the number of clients with zero conflict. The efficiency of the algorithm with respect to the number of clients with zero conflict depends on how the range and the interference sets formed by all the stations really reflect the real channel conditions in the network. Thus, accurate site reports consisting of the list of channels each client is able to hear at its present location must be submitted by all the clients to their respective APs either periodically or dynamically.

[3]Currently, the 802.11F standard has been administratively withdrawn, and only the documentation on recommended practice is available [23].

3) Measurement-Based Local-Coord: In this measurement-based approach [14], the cost function is the weighted interference which captures interference as seen by both APs and wireless clients in a local area network. To obtain such interference, wireless clients are required to physically measure the in-situ interference power on all the frequency channels used in the network whenever their associated APs are idle. The clients then average this measured interference power over all the channels and report the metric to their respective APs. The APs themselves also have to measure and average this in-situ interference power. The weighted interference now can be calculated for each BSS or cell. The weighing factors may include such metrics as the average traffic volume and average received signal power of the clients within the cell. That is, higher traffic volume should contribute more to the interference metric whereas higher received signal power should contribute less because that implies higher tolerance to interference.

Clearly, when one cell switches from channel k to operate on channel k', this cell itself and its neighbors who operate on either k or k' will see changes in their respective weighted interference metrics. Based on these changes, the Local-Coord algorithm is proposed. The basic idea is that a particular cell switches from channel k to channel k' if and only if the switching does not increase the maximum weighted interference seen by all the neighboring cells which operate on either k or k'. This operation therefore implies that some kind of coordination among the local cells is necessary. That is, before this particular cell can switch to a new channel, it needs to know the weighted interference metrics of its neighbors who reside on channel k and k'. This process of channel switching continues at different cells (APs) in the network until the channel assignment converges.

One variant of this algorithm, called *Global-Coord*, triggers a channel switching at an AP if and only if the overall co-channel weighted interference, as defined for the Local-coord algorithm, in a network operating on a new set of channels is lower than that on a current set of channels. As a result, this algorithm needs to be executed at a central agent that retrieves interference information from all APs in the network.

VI. CHANNEL ASSIGNMENT SCHEMES IN UNCOORDINATED ENVIRONMENTS

Recently, IEEE 802.11 deployment has grown in an uncoordinated fashion, where hotspots and private WLANs managed by different network administrators coexist in various densities throughout the geographical area of interest, as

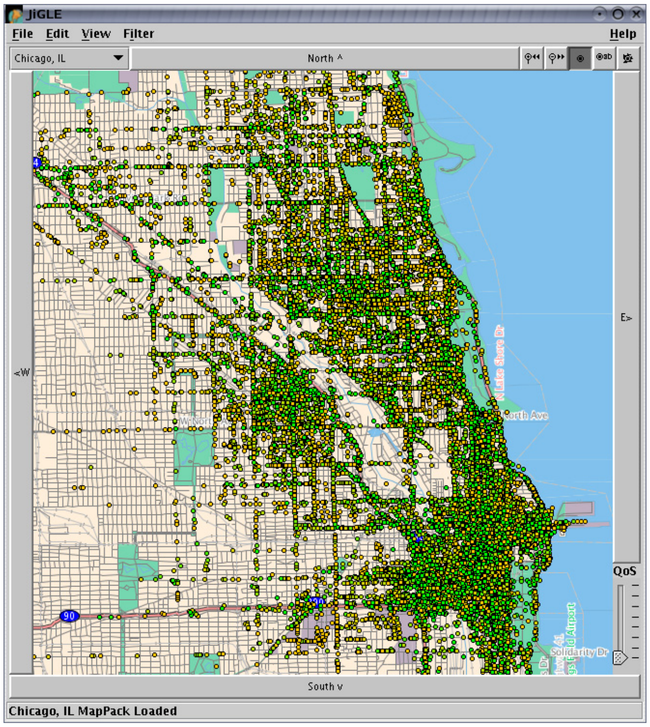

Fig. 7. IEEE 802.11 WLAN hotspots in Chicago area (Courtesy of www.wigle.net).

shown in Fig. 7. Taking the locations of APs as given, recent developments then try to focus only on the channel assignment problem and completely ignore the AP placement problem. This concept of improving the network performance by adjusting channel assignment alone is attractive, especially in a residential environment where an ISP providing a managed wireless service will likely have little control over the locations of APs in different homes. Moreover, even if the homeowners were open to having their APs moved, it would be very expensive for the ISP to send out technicians to move them. Several channel assignment strategies are developed just around these constraints. The main feature of such strategies in this category is the *distributed* execution in which channel assignment is performed distributively by each AP instead of a central controller.

A. Least Congested Channel Search (LCCS)

In Least Congested Channel Search (LCCS) [26], each AP autonomously searches for the most lightly loaded channel, e.g., the channel with the fewest number of wireless clients. It switches to operate on that channel until the next scan finds a less congested channel. To achieve this, an AP first scans each channel for distinguishable beacons published by neighboring APs, i.e., each distinguishable beacon corresponds to each individual AP. Since each beacon contains information such as the number of wireless clients associated with each AP, the AP then determines from each beacon how many clients are associated with each AP. After scanning all available channels, the AP knows how many clients are associated with each channel, and will choose to operate on the channel with the fewest number of associated clients. When using this criterion for channel assignment, the LCCS algorithm also implicitly deals with load balancing with the assumption that every wireless client carries the same amount of traffic. That is, the higher number of associated clients indicates the higher amount of traffic.

Instead of choosing the channel with the fewest number of associated clients, [26] also suggests to use traffic-related information, also obtained from beacons, in choosing a channel for an AP. In this case, the AP will "choose to operate on the channel with the least amount of traffic, irrespective of how many clients are associated with [26]. Such traffic-related information may include the average number of packets handled by an AP during, say, the past 5 minutes. Finally, it should be noted that these specific fields of a beacon frame, specifying the number of wireless clients associated with each AP and the average amount of traffic, are proprietary to Cisco.

B. MinMax Approach

In the MinMax scheme [27], a channel assignment problem is treated from the AP point of view based on the assumption that too heavily loaded APs to which certain channels are assigned can potentially degrade the network performance. A set of APs is assumed to be installed in an area of interest. Only downlink traffic is considered. The objective function is an AP's effective channel utilization defined as the fraction of time a channel assigned to an AP is used for transmission by the AP, or is sensed busy because of interference from its co-channel neighbors. In the proposed strategy, two classes of neighboring interferers are considered. For each AP i, co-channel APs are said to be in a class-1 interferer set $C_i(1)$ if their interfering signals are above a certain threshold that can cause enough interference for AP i to sense its channel busy. A class-2 interferer set $C_i(2)$ is defined as a set of pairs of co-channel interfering APs in which transmission by any pair of APs in the set can cause enough interference for AP i to detect its channel busy. To determine these interferer sets, the estimation of signal propagation pathloss between each pair of APs is required. Given $C_i(1)$, $C_i(2)$, N non-overlapping channels and fixed traffic load ρ_i at each AP i, the effective utilization is calculated as Eq. (5), where $x_{ij} = 1$ if channel j is assigned to AP i.

The objective of this approach is to minimize the maximum effective channel utilization at the most heavily loaded AP, given a different fixed traffic load at each AP. The problem is shown to be NP-complete. A heuristic algorithm is proposed to minimize this effective channel utilization of the most heavily loaded AP. Starting with a random channel assignment to all the APs in the network, the algorithm randomly readjusts the channel assignment of the bottleneck AP's interfering neighbors (those in $C_i(1)$ and $C_i(2)$) such that the effective channel utilization of the bottleneck AP is minimized, resulting in a least congested network. Being heuristic-based, the algorithm does not guarantee to give optimal solutions, especially in a large WLAN with several tens of APs. The algorithm can be applied after the initial locations of APs are determined.

C. MinMax II Approach

Based on the static model in [27], the strategy [28] attempts to assign channels in an adaptive manner to a set of APs such

$$U_i = \rho_i + \sum_{k=1}^{N} x_{ik} \left(\sum_{j=C_i(1)} \rho_j x_{jk} + \sum_{(m,n)=C_i(2)} \rho_m \rho_n x_{mk} x_{nk} \right) \tag{5}$$

that the maximum channel utilization at the most overloaded AP is minimized, for a given traffic load and an interfering set of APs. An interfering set for an AP is defined as the co-channel neighbors of this AP, whose transmissions can cause enough interference for this AP to sense its channel busy. Unlike [27], the channel utilization in [28] is formulated based on a dynamic MAC model found in [29], where the estimated number of active clients (i.e., including those clients associated with the AP of interest and those under the neighboring co-channel APs) is taken into account. The channel assignment algorithm is similar to the one in [27], but it is dynamic in the sense that the estimation of the number of active clients is done in real-time for each channel adjustment (assignment) period, and as a result of new channel assignment, a check on the network performance against some predefined QoS threshold is invoked at the end of the algorithm. To ensure quick convergence and to avoid infinite looping, an optimal channel switching is derived based on a Markov state transition diagram. Each AP optimizes its channel assignment simultaneously and independently without relying on inter-AP communication. The optimal solution exists for a small scale network. For a larger network, the proposed strategy may not be scalable. Another approach similar to that in [28] is proposed in [30].

D. Hminmax/Hsum - Weighted Coloring Approach

In [31], frequency assignment is modeled as a minimum-sum weighted vertex coloring problem in which different weights are put on interference edges. Looking at interference from the clients' perspective, this approach attempts to minimize the maximum interference as seen by clients in all common interfering regions. This interference is captured through two functions: interference factor and weight functions. While the interference-factor accounts for the amount of channel overlapping between two interfering APs, the weight can represent the number of clients confined in a common region of these two interfering APs. Mathematically, the objective is to minimize the maximum product of the interference-factor and weight function, which is referred to as the I-value.

Based on this objective, two algorithms are proposed: *Hminmax* and *Hsum*. Requiring no coordination among APs, the *Hminmax* algorithm attempts to minimize the maximum interference weight among those edges connecting directly to a vertex (AP) of interest. Each AP executes the algorithm locally and independently in a periodic manner. Due to this distributed nature, *Hminmax* is most suited for co-existing WLANs managed by different administrators. In *Hsum*, APs are required to transmit their interference metrics to their AP peers. In this way, each AP can have a global view of the network topology. The maximum weighted interference is then minimized by *Hsum* in a global sense. Due to the IAPP requirements, *Hsum* is only suitable for WLANs supervised by the same administrator. In terms of net throughput, *Hsum* is shown to outperform *Hminmax*.

E. Pick-Rand and Pick-First Approach

In [32], the objective is to assign overlapping channels to APs in such a way that minimizes the total weighted interference as seen by each AP. Such interference is weighted by the so-called overlapping channel interference factor, the AP transmit power, and the path-loss between two interfering APs. The overlapping channel interference factor indicates how much two interfering channels are overlapped in frequency. Each AP independently runs the algorithm that minimizes such interference, either in a periodic manner or whenever the interference rises above a specified level. Two versions of the algorithm are proposed for breaking ties between channels that give the same interference: *Pick-Rand* and *Pick-First*. While *Pick-Rand* randomly picks a channel for assignment, *Pick-First* simply picks the first channel of the ascendingly ordered channel list.

F. Pick-Rand and Pick-First II Approach

As an extension to [32], the work in [33] incorporates the load balancing problem into the channel assignment framework. Wireless clients are initially characterized by their data rate requirement, hence signal strength. The AP then can decide to dis-associate (break a connection with) its clients through the reduction of its transmit power of beacon packets, whenever it becomes overly congested. Those clients whose data rates cannot be supported will eventually turn away and re-associate to a new AP that can accommodate their traffic requirements. A congestion indicator in this scheme is defined as the ratio of aggregate data rates, required by all currently associated clients, to the AP's available bandwidth. Mathematically, this problem is modeled as an ILP whose objective is to minimize the maximum congestion at the most congested AP. Once the optimal power levels and user associations are obtained, the channel assignment problem as formulated in [32] is invoked and directly solved without resorting to a heuristic. A similar approach can be found in [34].

G. Channel Hopping Approach

In [1], a distributed channel assignment algorithm based on the concept of channel hopping is specifically proposed for an uncoordinated WLAN. In particular, each AP is assigned a unique sequence of channels, and hops through this sequence over time so as to average out the throughputs of all APs in a long run. This is illustrated by an example shown in 8. Each AP is within the transmission ranges of three other APs. The

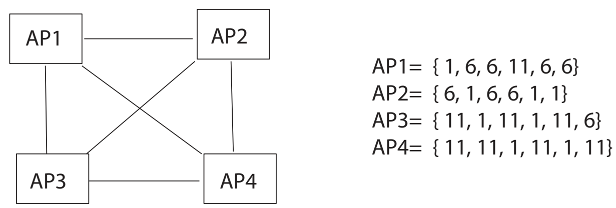

Fig. 8. Interfering APs and their Channel Hopping Sequence.

sequence assigned to each AP is also shown in Fig. 8. Each AP hops to the next channel at the end of each time slot. Suppose that only three non-overlapping channels, namely, 1, 6 and 11, are available for assignment, and that each AP always has data to transmit. The goal is to average out the throughputs of all APs in a long run. In the first time slot, AP3 and AP4 are assigned the same channel. Due to MAC contention, their normalized throughputs are therefore 0.5 each, while the throughputs of AP1 and AP2 are 1 each. In the second time slot, AP2 and AP3 are interfering. Their resulting throughputs are 0.5 each, and those for AP1 and AP4 are 1 each. Continuing in this manner, every AP will have the equal throughput of 0.75 at the end of the sixth time slot. Long-term fairness is then captured by this approach. The main requirement of this approach is the common notion of time among all APs. In other words, every AP must synchronize to the same clock so that channel hopping is performed by each AP at the same instant.

H. Measurement-based No-Coord

This is another variation of *Measurement-based Local-Coord* proposed to avoid the requirement of inter-cell coordination. The formulation is similar to that of *Measurement based Local-Coord*, but the algorithm itself is greedy in the sense that channel switching is based only on its own weighted interference. That is, each cell switches to operate on another channel if and only if the new weighted interference calculated based on the new channel is lower than the previous one.

VII. Comparison Among Various Channel Assignment Schemes

We provide a summary of the various channel assignment schemes in Table I. Various aspects are considered: 1) how often channel assignment is triggered (static or adaptive), 2) to which type of deployment a channel assignment is applicable (uncoordinated or centrally managed), 3) the type of frequency channels used (overlapping or non-overlapping channels), 4) the procedure in obtaining channel assignment solutions (heuristic or integer linear programming), 5) from which perspective interference is modeled (from AP's or clients' point of view), 6) whether inter-AP communication is needed as part of channel assignment, and 7) whether a scheme is scalable (i.e., whether a solution exists for relatively large networks). According to Table I, all the static schemes rely on a centralized control, while the adaptive schemes reside on both centrally managed and uncoordinated deployments. The solutions for the static schemes are usually executed only once, so that their complexity is of little concern. When the planning is done, the channels are established for long term use. Most schemes consider non-overlapping channels while the new trend tries to utilize both non-overlapping channels and overlapping ones [35]. Due to high computational complexity, most schemes resort to heuristic solutions. While the early schemes view interference only from the AP's point of view, recent schemes try to model interference also from clients' perspectives. As can be expected, all the channel assignment schemes in the uncoordinated environments are scalable due to their distributed execution whereas those in the centrally managed environments are not because of their privileged centralized control.

In addition, the comparison among relevant schemes in terms of performance is highlighted as follows. Recently, it has been reported that the fully distributed *Channel Hopping* approach [1] outperforms LCCS [26] in terms of fairness (measured by Jain's index) and throughput by 42% and 30%, respectively. Its performance is however comparable to the fully centralized *CFAssign-Rac* approach [13]. Further, CFRacAssign [13] is shown to outperform both the weighted coloring (Hminmax/Hsum) [31] and LCCS [26] approaches in terms of application-level throughput and percentage of MAC collisions. The weighted coloring (Hminmax/Hsum) [31] in turn outperforms LCCS [26] in terms of throughput. It is also reported that the measurement-based *Local-Coord* algorithm [14] gives higher average throughput than the CFRacAssign [13], with the price in signaling overhead to pay. Compared to the classical cellular results, the optimal channel assignment obtained from the *MinMax* approach [27] is also shown to match that for the cellular network with a frequency reuse factor of three for small networks. However, only suboptimal assignment is obtained when the proposed scheme is applied to large networks ($\geq$ 111 APs). Similar results are also reported in [28], [30], where the overall network throughput is also shown to improve over that of the random channel assignment by 65%. Compared to the random channel assignment scheme, the *Vertex Coloring* approach [24], [25], [12] is shown to give higher UDP/TCP aggregate network throughput, especially when the number of APs increases. The *Coverage-Oriented* approach [22] is also shown to outperform a random channel assignment scheme and sequential network planning approaches such as [16], [17], in terms of radio coverage and average throughput. In [32], the *Pick-Rand and Pick-First* approach is shown to outperform the worst-case channel assignment scheme, in which all APs are assigned the same channel, in terms of total interference by a factor of four. In [20], the *Patching* algorithm slightly improves overall throughput over both the ILP-based [18] and traditional [17] approaches in terms of fairness (Jain's index) and throughput. Further, it has been shown that [33] improves over [18] in terms of load distribution and interference reduction (as much as 4%).

VIII. Current Practice in Channel Assignment

Current practice in channel assignment for infrastructure-based 802.11 networks is still far behind current research described through several schemes in Sections V and VI. Most Cisco AP products, for example, still employ LCCS in

TABLE I
SUMMARY OF CHANNEL ASSIGNMENT SCHEMES IN 802.11 WLAN

	Nature		Deploy.		Channel		Solution		Interf.				
Schemes	Static	adaptive	Uncoordinated	Centrally Managed	Overlap.	Nonoverlap.	Heuristic	ILP	AP	Client	IAPP	Scalable?	References
Traditional	x			x		x	x		x		no	no	[16]
Priority-Map	x			x		x	x		x		no	no	[19]
MinMax	x		x			x	x		x		no	no	[27]
ILP-based	x			x		x		x	x		no	no	[18]
Patching	x			x		x	x			x	no	no	[20]
Cov.-oriented	x			x	x		x			x	no	no	[22]
Local-Coord		x		x		x	x		x	x	yes	no	[14]
Global-Coord		x		x		x	x		x	x	yes	no	[14]
No-Coord		x		x		x	x		x	x	no	no	[14]
MinMax II		x	x			x	x		x		no	no	[28], [30]
Conflict Set		x		x	x		x			x	yes	no	[13]
LCCS		x	x			x	x		x		no	yes	[26]
DSATUR		x	x		x		x		x		yes	yes	[12]
Hsum		x		x	x		x			x	yes	yes	[31]
Hminmax		x	x		x		x			x	yes	yes	[31]
Pick-Rand/Pick-1st		x	x		x		x		x		yes	yes	[32]
Pick-Rand/Pick-1st II		x	x		x			x	x		no	yes	[33]
Channel Hopping		x	x		x		x		x		no	yes	[1]

randomly searching for least congested channels at power-up or when the other parameters of radio interfaces are changed [36]. (The operations of LCCS are described in Section VI-A.) In LCCS, human intervention is still required in specifying which channels to ignore or search on. In other AP products, such automatic channel searching is not even available, and it is left to users or network administrators to manually assign channels to APs at the network planning phase or at later stages. Although recent products such as *Cisco WLAN Controllers* claim to use a more sophisticated method [37] in assigning channels to APs, which takes into account a variety of network dynamics such as AP received energy, noise, interference, channel utilization and client load, the centralized operations of the method however limit its applicability only to centrally managed networks. Detailed operations and implementation also are not available to public. Another sophisticated method described in Section V-B2 and reference [38] has also recently been illustrated to work well in practice, but, to the best of our knowledge, has not yet been implemented in real products. This method also suffers from its centralized operations. Being centralized, both of these methods are not applicable to uncoordinated networks in places such as residential neighborhoods, public hotspots, adjacent offices, etc. The recent trend in research then tends to focus on channel assignment schemes that work distributively across networks overseen by different network administrators, and that require less human intervention. More detail on this trend is given in the following section.

IX. CONCLUSION AND OPEN RESEARCH ISSUES

Channel assignment is one mechanism to improve the performance of WLANs. In this survey we have discussed several existing channel assignment schemes applicable to either centrally managed or uncoordinated environments. Several possible future research directions and open issues with regard to channel assignment in WLANs are outlined below:

- The research direction tends to shift toward adaptive channel assignment in uncoordinated environments, in which network dynamics is incorporated into the problem formulation. The following system parameters need to be considered: client locations, building layouts and AP locations, time fluctuation of traffic demand of wireless clients at various locations, and application QoS requirements. The challenge would be how to capture the network dynamics as much as possible while maintaining the complexity of implementation of channel assignment algorithm at a practical level. Furthermore, when WLANs are deployed in an uncoordinated fashion by different network administrators, the scalability of the implementation of channel assignment algorithms becomes even a more important issue. In such scenarios, a channel assignment scheme of choice should be cooperative and scalable enough to orchestrate channel switching across the entire network without creating significant interference to the neighbors. Being aware of the neighboring networks located in different administrative domains, the scheme should also be able to interact and exchange necessary information (network topology, channels in use, the number of clients, etc.) with its neighbors in order to allocate appropriate channels to the APs.
- Continually monitoring the network dynamics, say on a daily basis, at a particular location may lead to a discovery of traffic pattern. Channel assignment can then be performed at a particular location during a particular period of time based on the prediction (or self-learning experience) as well as the application requirements.
- The schemes discussed in this survey assume either uplink or downlink traffic. To be more realistic, traffic in both directions should be considered. This is reasonable as peer-to-peer communications become more popular.

- Implementation issues with regard to channel switching should be considered. With current hardware, the time required to switch a channel at an AP ranges from 100 us to 20 ms [1]. As an AP switches to operate on another channel, its associated clients should then be notified and/or handed over properly to another AP within this time limit. Ongoing communications, especially delay-sensitive applications, should be interrupted as least as possible. The concepts of hard and soft handoffs as employed in cellular networks could be developed. Also, for feasible implementation, installing any new channel assignment strategy in a network should result only in a driver update at APs, but not major hardware changes.
- Additionally, all the schemes discussed thus far assume fixed transmit power. In practice, this may not be the case since transmit power may vary with channel conditions and application QoS requirements (e.g., data rates). Joint optimization of channel assignment and power control, and cross-layer designs [39] may lead to more efficient utilization of radio channels. With the growing demand for multimedia contents in WLANs, channel assignment that takes power control into consideration is an interesting avenue for research.

REFERENCES

[1] A.Mishra and V. Shrivastava, D. Agrawal, S. Banerjee, and S. Ganguly, "Distributed Channel Management in Uncoordinated Wireless Environments," in *Proc. International Conference on Mobile Computing and Networking*, pp. 170–181, 2006.

[2] Y. Bejerano, S. Han, and L. Li, "Fairness and Load Balancing in Wireless LANs Using Association Control," in *Proc. ACM Mobicom*, 2004.

[3] A. Akella, G. Judd, S. Seshan, and P. Steenkiste, "Self-Management in Chaotic Wireless Deployments," in *Proc. ACM Mobicom*, 2005.

[4] B. Alawieh, Y. Zhang, C. Assi, and H. Mouftah, "Improving Spatial Reuse in Multihop Wireless Networks - A Survey," *IEEE Commun. Surveys Tutorials*, vol. 11, no. 3, 2009.

[5] A. Vasan, R. Ramjee, and T. Woo, "Echos: Enhanced Capacity 802.11 Hotspots," in *Proc. IEEE Infocom*, 2005.

[6] "IEEE Standard for Information Technology-Telecommunications and Information Exchange between Systems-Local and Metropolitan Area Networks-specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE STD 802.11-2007 (Revision of IEEE Std 802.11-1999)*, pp. C1–1184, June 12 2007.

[7] "Supplement to IEEE Standard for Information Technology Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-Speed Physical Layer in the 5 GHz Band," *IEEE STD 802.11a-1999*, 1999.

[8] "List of WLANs Channels," *http://en.wikipedia.org/wiki/List_of_WLAN_channels*, Available Online.

[9] I. Katzela and M. Naghshineh, "Channel Assignment Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey," *IEEE Personal Commun.*, June 1996, pp. 10-31.

[10] S. Pack, J. Choi, T. Kwon, and Y. Choi, "Fast-Handoff Support in IEEE 802.11 Wireless Networks," *IEEE Commun. Surveys Tutorials*, vol. 9, no. 1, pp. 2-12, 2007.

[11] W. K. Hale, "Frequency Assignment: Theory and Applications", in *Proc. IEEE*, Vol. 68, pp. 1497–1514, 1980.

[12] P. Mahonen, J. Riihijarvi, and M. Petrova, "Automatic Channel Allocation for Small Wireless Local Area Networks using Graph Colouring Algorithm Approach," in *Proc. IEEE Int. Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 536–539, Sept. 2004.

[13] A. Mishra, V. Brik, S. Banerjee, A. Srinivasan, and W. Arbaugh, "A Client-driven Approach for Channel Management in Wireless LANs," in *Proc. 25th IEEE International Conference on Computer Communications (INFOCOM'06)*, 2006.

[14] J. K. Chen, G. D. Veciana, and T. S. Rappaport, "Improved Measurement-based Frequency Allocation Algorithms for Wireless Networks," in *Proc. IEEE GLOBECOM'07*, Washington, DC, USA, Nov. 2007.

[15] M. Gast, 802.11 Wireless Networks: The Definitive Guide O'Reilly, Farnham, 2nd ed., 2005.

[16] A. Hills, "Large-Scale Wireless LAN Design," *IEEE Commun. Mag.*, vol. 39, no. 11, pp. 98–107, November 2001.

[17] R. C. Rodrigues, G. R. Mateus, and A. A. F. Loureiro, "On the Design and Capcacity Planning of a Wireless Local Area Network," in *Proc. IEEE/IFIP Network Operations and Management Symposium*, 2000.

[18] Y. Lee, K. Kim, and Y. Choi, "Optimization of AP Placement and Channel Assignment in Wireless LANs," in *Proc. 27th Annual IEEE Conf. Local Computer Networks*, pp. 831–836, Nov. 2002.

[19] P. Wertz, M. Sauter, F. Landstorfer, G. Wolfle, and R. Hoppe, "Automatic Optimization Algorithms for the Planning of Wireless Local Area Networks," in *Proc. IEEE Vehicular Technology Conference*, vol. 4, pp. 3010–3014, Sep. 2004.

[20] X. Ling and K. L. Yeung, "Joint Access Point Placement and Channel Assignment for 802.11 Wireless LANs," in *Proc. IEEE WCNC'05*, 2005.

[21] G. Bianchi, "Performance Analysis of IEEE 802.11 Distributed Coordination Function," *IEEE J. Sel. Areas Commun.*, vol. 18, pp. 535–547, Mar. 2000.

[22] A. Eisenblatter, H. F. Geerdes, and I. Siomina, "Integrated Access Point Placement and Channel Assignment for Wireless LANs in an Indoor Office Environment," in *Proc. 8th IEEE Intl. Symposium on a World of Wireless, Mobile and Multimedia Networks*, June 2007.

[23] "Official IEEE 802.11 Working Group Project Timelines: IN-PROCESS Standards, Amendments, and Recommended Practices," *http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm*, Available Online.

[24] J. Riihijarvi, M. Petrova, and P. Mahonen, "Frequency Allocation for WLANs using Graph Colouring Techniques," in *Proc. 2nd Annual Conference on Wireless On-demand Network Systems and Services 2005*, pp. 19–21, Jan. 2005.

[25] J. Riihijarvi, M. Petrova, and P. Mahonen, J. A. Barbosa, "Performance Evaluation of Automatic Channel Assignment Mechanism for IEEE 802.11 Based on Graph Coloring," in *Proc. 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1–5, Sept. 2006.

[26] M. Achanta, "Method and Apparatus for Least Congested Channel Scan for Wireless Access Points," *US Patent No. 20060072602*, Apr. 2006.

[27] K. K. Leung and B.-J. Kim, "Frequency Assignment for IEEE 802.11 Wireless Networks," in *Proc. IEEE Vehicular Technology Conference*, vol. 3, pp. 1422–1426, Oct. 2003.

[28] M. Yu, H. Luo, and K. K. Leung, "A Dynamic Radio Resource Management Technique for Multiple APs in WLANs," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 1910-1919, July 2006.

[29] F. Cali, M. Conti, and E. Gregori, "Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit," *IEEE/ACM Trans. Netw.*, vol. 8, pp. 785-799, Dec. 2000.

[30] M. Yu and H. Luo, "An Adaptive Radio Resource Management Technique for APs in WLANs," in *Proc. IEEE International Conference on Networks (ICON'04)*, Nov. 2004.

[31] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted Coloring Based Channel Assignment for WLANs," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 9, no. 3, pp. 19–31, 2005.

[32] R. Akl and A. Arepally, "Dynamic Channel Assignment in IEEE 802.11 Networks," in *Proc. IEEE International Conference on Portable Information Devices (PORTABLE'07)*, 2007.

[33] M. Haidar, R. Akl, and H. Al-Rizzo, "Channel Assignment and Load Distribution in a Power-managed WLAN," in *Proc. IEEE PIMRC: 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, September 2007.

[34] H. Al-Rizzo, M. Haidar, R. Akl, and Y. Chan, "Enhanced Channel Assignment and Load Distribution in IEEE 802.11 WLANs, in *Proc. IEEE International Conference on Signal Processing and Communication*, November 2007.

[35] A. Mishra, V. Shrivastava, S. Banerjee, and W. Arbaugh, "Partially Overlapped Channels Not Considered Harmful," in *ACM SIGMETRICS Performance Evaluation Review*, vol.34, no.1, pp. 63-74, 2006.

[36] "Online Help for Cisco IOS Release 12.2(15)JA," *http://www.cisco.com/web/techdoc/wireless/access_points/online_help/eag/122-15.JA/1400br/h_ap_network-if_802-11_c.html*, Available Online.

[37] "Using Radio Resource Management to Deliver Secure and Reliable WLAN Services," *http://www.cisco.com/en/US/prod/collateral/wireless/ps6302/ps8322/ps6307/prod_white_paper0900aecd802c949b_ns736_Networking_Solutions_White_Paper.html*, Available Online.

[38] "Method and System for Client-Driven Channel Management in Wireless Communication Networks," *http://www.faqs.org/patents/app/-20080259883*, Available Online.

[39] F. Foukalas, V. Gazis and N. Alonistioti, "Cross-Layer Design Proposals for Wireless Mobile Networks: A Survey and Taxonomy," *IEEE Commun. Surveys Tutorials*, vol. 10, no. 1, pp. 70-85, 2008.

Surachai Chieochan received his B.S. degree in Electrical Engineering from Washington University in St.Louis, and his M.E. degree in Telecommunications from Asian Institute of Technology, Patumthani, Thailand in 2002 and 2006, respectively. He is currently a Ph.D. student in electrical and computer engineering at University of Manitoba. His research interest focuses mainly on radio resource management in wireless local area networks.

Ekram Hossain (S'98-M'01-SM'06) is currently an Associate Professor in the Department of Electrical and Computer Engineering at University of Manitoba, Winnipeg, Canada. Dr. Hossain's current research interests include design, analysis, and optimization of wireless communication networks and cognitive radio systems. He is a co-author/co-editor for the books "Dynamic Spectrum Access and Management in Cognitive Radio Networks" (Cambridge University Press, 2009), "Heterogeneous Wireless Access Networks" (Springer, 2008), "Introduction to Network Simulator NS2" (Springer, 2008), "Cognitive Wireless Communication Networks" (Springer, 2007), and "Wireless Mesh Networks: Architectures and Protocols" (Springer, 2007). Dr. Hossain serves as an Editor for the *IEEE Transactions on Mobile Computing*, the *IEEE Transactions on Wireless Communications*, *IEEE Wireless Communications*, and *IEEE Communications Surveys and Tutorials*. He is a registered Professional Engineer in the Province of Manitoba, Canada.

Jeffrey Diamond is a scientist and research program manager with TR*Labs*, a not-for-profit applied telecommunications research consortium. He received B.Sc. and M.Sc. degrees in physics and M.Sc. and Ph.D. degrees in operations research from the University of Manitoba, Canada. His research interests are in queuing theory and optimization applied to telecommunications and in methods for secure multiparty computations.