Towards Dynamic Wireless Capacity Management for the Masses

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Abstract. In this paper we speculate that, with the technological elements already in place, an automated dynamic management of the RF spectrum in urban residential settings will soon be possible. Dense urban environments are increasingly facing RF spectrum congestion, in particular in the ISM bands. The Internet of Things is only expected to add to the pressures. In this work we outline an architecture that will analyze and resolve spectrum congestion. We are motivated by the adaptive and modifiable nature of existing protocols, inspired by existing capacity planning and channel allocation schemes from cellular networks, and emboldened by the synergies possible via software–defined radios. The cloud computing infrastructure can be leveraged to perform most compute-intensive tasks required towards this goal. We are encouraged that the approach is viable by the relatively static, in the local sense, topology that most residential networks exhibit. To be able to support a wide range of device capabilities we consider the possibility of using a mix of techniques, ranging from advanced physical layer, to special MAC coordination, to higher-layer protocol operations to indirectly influence the operation of legacy equipment.

Keywords: RF spectrum congestion · Urban environments · Wireless capacity planning · Channel allocation · Software-defined radios · Cloud computing · Medium access control

1 Introduction

Today's landscape of wireless networks in residential and, in many cases, in enterprise settings, is characterized by diversity and elevated expectations of efficiency and flexibility. It is now commonplace for wireless networks of various technologies to co-exist in the same space. Conceived and deployed separately from each other, the deployed networks result in a challenging operating environment. The cross-technology interference (CTI) gets further compounded by interference originating from non-communicating devices that exist in abundance in today's environments (microwave ovens, lighting equipment, electrical motors, etc.). The combined impact is poor performance which is only expected to get worse as two technological trends continue: (a) ever-increasing density of deployments, such as the ones heralded for supporting the Internet of Things (IoT),

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and (b) ever-decreasing operating power, meant to extend autonomy for battery-powered devices but at the same time jeopardizing the possibility for error-free reception in dense environments, because of poor Signal-to-Noise+Interference (SINR) at the receivers.

Yet, all of today's wireless networks interface, in one way or another, to the Internet, i.e., to a wired infrastructure. We speculate that this common denominator, i.e., the access to a common wired backbone network, and hence to services residing there, might be sufficient to improve the performance of co-existing wireless networks via a dynamic capacity management. Residential network deployments lack any capacity planning, which is a characteristic available only to a limited degree in some high-end enterprise networking products [9]. The spectrum utilization of the ISM bands is continuously changing with new technologies added every day making a dynamic wireless capacity management service among heterogeneous devices a necessity. This dynamic spectrum management application aims to improve the capacity of the wireless network, to efficiently and fairly share the spectrum and to support high Quality of Service (QoS).

At a very high level of abstraction, spectrum sensing and decision making algorithms can run on the cloud, which can then inform the local user equipment of actions to take. An example is the control of multiple access points (APs) in a neighborhood, subject to the channels and power used by other APs, as well as the existence of interference in certain geographical areas. We are motivated by the fact that a modicum of adaptivity and modifiability already exists in legacy protocols, such as 802.11, and an increasing number of access points exhibit "smart" software-controlled behavior. For example, the cloud-based control could inform the APs which channels, and what power, each should use.

We are inspired by the traditional cellular capacity and resource allocation schemes [16] but we speculate how, instead of being an exceptional one-time design, it is a continuous control and refinement process, in particular given the dynamics of the residential wireless environment. The overall proposed architecture is shown in Fig. 1. We separate the role of the wireless network elements as being access points (APs), clients (C) if they depend on APs, and peers (P) if they are autonomously operating. We note that AP refers to any element that has to function in a coordinating role for a wireless network to operate, i.e., it is not restricted to 802.11 APs. A role of interferer (I) is also noted but it is an abstract representation of a non-communicating source of interference. APs (and some Ps) may be connected to the wired infrastructure. A second dimension is whether they are legacy devices (superscript l), configurable by control at higher-layer protocol (superscript h), and configurable based on control of the physical layer (superscript p). A p device is assumed to be at least as capable as an h, but additionally it sports high-end programmable physical interfaces, as is the case with software-defined-radio (SDR). Clearly, "smart" devices (h and p) have to work around the fact that l devices and I are inflexible to control actions. The most challenging aspect of the architecture, not captured by Fig. 1 is that the sets of devices are dynamically added/removed and their traffic demands can change over time. The task of h and p devices is both to collect

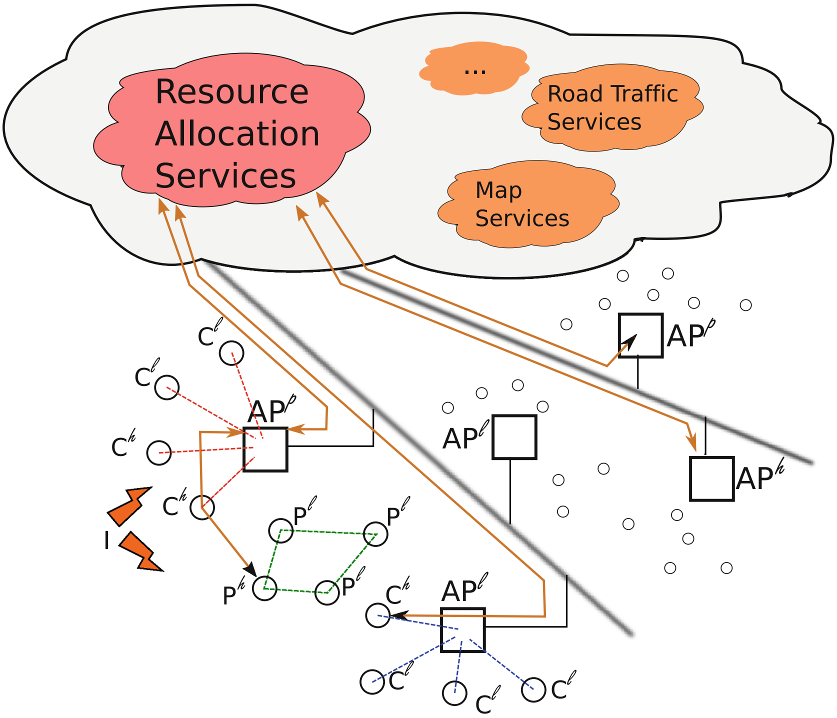

Fig. 1. Example layout: bidirectional brown arrows capture the measurement and control data flows. All the network elements in the lower left (under the left line representing the wired network) can be assumed to be within range of each other. Dashed colored lines indicate associations (AP with clients, or peers among them). (Color figure online)

measurements and to respond to control decisions. Early approaches with similar intent e.g., monitoring and diagnosis, have already been proposed [30]. Current efforts in the direction of IEEE 1900 and 802.11af integrate aspects of spectrum sensing as well. One notable challenge is how such systems will handle legacy and external (non-communication) interference sources.

This paper is structured as a survey of fields that come together under the same ambitious plan. Subsequent sections indicate the general system characteristics (Sect. 2), and new opportunities available because of recent technological advances (Sect. 3). We then provide a more thorough review of related work (Sects. 4 and 5), honing down eventually to a few works that open the possibilities we described in the previous paragraphs. The final, concluding, section is a compilation of open research opportunities that can be immediately pursued.

2 System Characteristics

A number of characteristics are evident in urban wireless networks; some arising from regulatory and device capability considerations and others from their typical use scenarios.

1. **Prevalence of ISM bands:** Despite the considerable attention paid to cognitive wireless networks [1], the immediately pressing needs for wireless co-existence of multiple devices is in ISM bands. In ISM bands, where exists no distinction between primary and secondary users, thus creating more options for network control. A test case for ISM band co-existence is the co-existence in the 2.4 GHz ISM band, where one of the main concerns, given their prevalence, is the performance attained by 802.11 devices. Nevertheless, several sub-GHz ISM devices [6] exist and are extensively used in IoT applications, especially exploring the ability to reach longer distance yet operating at very low power. Additionally, the 5 GHz ISM band, while not yet crowded, will eventually become crowded as well. We therefore argue that *RF co-existence in the ISM bands is of immediate concern.*
2. **Cross-technology interference:** Secondly, wireless communication standards are typically conceived, designed, and implemented, independently of other wireless protocols. For example, what constitutes a “channel” for one protocol can be completely different from what is a channel in another one, or for what the power and timing relation between transmissions might be. The exception is the purposeful backward compatibility when a standard evolves, albeit still the entire family of protocols for one standard tends to ignore other protocol families. Interestingly, the ISM bands have given the opportunity for completely proprietary protocols to emerge as well. We use the term cross-technology interference (CTI), as adopted by Hithnawi et al. [12] to express the impact the operation of the protocol has, seen as “interference”, on another protocol operating in the same location.
3. **Manifestations of interference:** Generally, the RF front-end and the associated signal processing chain, is highly specialized to (and in this sense efficient for) the needs of the particular protocol. We will call such RF designs “monolithic” as opposed to flexible Software Defined Radio (SDR) designs, even though some degree of agility is still possible in monolithic designs (channel selection, transmit power control, etc.). Correspondingly, the impact of another protocol’s transmissions manifest themselves as interference leading to either a poor Signal to Noise-plus-Interference (SINR) figure, or simply as indication that the medium is busy, i.e., when Clear Channel Assessment (CCA) is being attempted. From the viewpoint of a legacy, monolithic, RF design, there exists no real difference between a source of interference due to another protocol’s operation or from non-communication entities (microwave ovens, fluorescent light ballasts, internal combustion engine sparking, etc.).
4. **Predictability of user behavior:** While the user population is diverse, the per-individual, and the per-household behavior is remarkably consistent [26]. Today’s residential users’ traffic is dominated, in terms of data volume,

by video streaming of various compression qualities. Moreover, the network topology of residential wireless networks rarely changes drastically, and typically, only the location of a subset of the devices changes within the premises (e.g., smartphones and laptops). A residential network includes also a subset of IoT nodes and other low-power devices, such as Bluetooth Low Energy (BLE). While we cannot make a claim that the exact distance between devices is constant, the compartmentalization of devices within the premises of their corresponding owners suggests that the distances between nodes of the same residential unit remain bounded by a certain maximum distance.

Of the above characteristics, we note that items 1 to 3 present challenges, while item 4 provides also a glimmer of hope, in that making capacity management decisions can be helpful for an extended period of time, hopefully in the order of hours. Additionally, previous control actions can be repeated due to the predictable (diurnal, seasonal, etc.) user demands.

3 Technological Opportunities

We note the emergence of three technologies whose synergy could accelerate the deployment of dynamic wireless capacity management schemes.

1. **Spectrum sensing:** The emergence of SDRs has allowed the development of distributed spectrum analyzers [25], providing a comprehensive view of the spectrum use (including non-communication interference sources). We speculate that the features of SDRs will be integrated in APs in the near future. As such, the AP^p access points are assumed to be endowed with such capabilities, allowing them to switch between serving traffic, to, during idle periods, sample the background noise. A minimal form of spectrum sensing is also possible by legacy devices if access to Received Signal Strength Indicator (RSSI) values is supported. For example, almost all inexpensive sub-GHz RF transceivers allow RSSI values to be sampled, and this is a feature found in many P^l devices. Yet another, coarser and indirect indicator of spectrum condition, is the frame/packet error statistics collected by even the least flexible legacy devices (as interface statistics).
2. **Cloud processing:** The connectivity to the wired Internet by AP (as well as, indirectly, by C, and P) devices allows significant amounts of data collected by spectrum sensing to be shipped over for processing in the cloud. Trends and location-specific behavior of the interference and load demands can then be analyzed by computationally-intensive algorithms. In other words, the limited in-situ processing is overcome by off-site cloud-based processing. The idea of using the same cloud-based infrastructure to control the network has been an open research direction in 5G networks [27]. We augment this by (a) including sensing of the spectrum to ascertain the presence of multiple protocol device and sources of interference and (b) assume that legacy, l–type, devices cannot form part of the set of controllable devices, and hence it is up to the h and p devices to infer the behavior of co-located legacy devices.

3. **Web services:** While usually deployed as cloud-based application themselves, additional web-based services can assist in augmenting the decision making process. For example, WiFi Service Set Identifiers (SSIDs) mapped to geographic locations (such as wigle.net) or live traffic updates, provide, correspondingly, approximate information about the spatial separation of APs and a basis for anticipating residential data traffic load fluctuations. Moreover, persistent non-communication interference sources can be localized and their locations related to map coordinates [14]. While this does not imply a mitigation strategy, it can enable actions outside the automated network control. Another related example is a database service for area-specific white spaces demonstrated in SenseLess [24], geared towards non-ISM cognitive networks.

4 Related Work: Resource Allocation

The literature on wireless resource management is vast. We note, for example, the channel assignment literature for cellular networks, e.g., [16] as relevant, but one that follows the cellular network model of operation, i.e., single (or few) providers, no outside interferers, known locations (hence one-time, or infrequent, computation of allocation plans), etc. We need to abandon these assumptions in order to capture the essence of residential ISM, and in particular dense urban, environments. A starting point can thus be seen in the channel allocation schemes specific to WiFi, such as those surveyed by Chieochan et al. [8], which take into account the characteristic irregularities of AP coverage and the variety of traffic and QoS demands in different areas. They study schemes aimed for centrally managed environments where interference constitutes the metric of interest (which translates to a capacity measure) as well as schemes for uncoordinated environments.

The control of APs suggests a need for an Inter-AP Protocol (IAPP), a protocol essential for the cooperation and communication between APs of the l and h variety. Mahonen et al. have described a scheme using the IAPP protocol [21]. The channel allocation is expressed as a classical vertex coloring approach, DSATUR, where APs are modeled as vertices of an interference graph. The ingredient of their scheme which we consider essential in a cloud-supported allocation system is the fact that their proposal for channel allocation is dynamic and cooperative. Every new station that arrives within range automatically becomes part of the interference graph. APs detect other APs by means of hearing their beacons and construct vectors of information consisting of AP MAC addresses, signal-to-noise ratios, and received signal strength [8,21]. After the identification of their neighbours, the APs can share their knowledge with other APs in the network and the procedure can be repeated whenever the topology changes.

The lessons learned from 802.11 can be transformed to a broader class of wireless networks. The underlying coloring problems, and any other heavily computational optimization problems, can be relegated to the cloud. Additionally, there are a number of extensions, that could allow the easier transformation of 802.11 schemes to more general ones. First, the AP-centric view has been exchanged for a client-/peer-specific view. For example, Mishra et al. [22], introduce load balancing into the channel assignment scheme where interference is examined from the clients' point of view and it is claimed that even hidden (from the APs view) interference is captured and accounted for. A client is considered to suffer from channel conflict in two cases. In the first, the interference seen by a client comes from APs located within a communication range of the client of interest and in the second from APs or wireless clients (in neighboring BSSs), located within a one-hop distance of the AP-client link of interest [8,22]. Their client-centric algorithm called CFAssign-RaC is based on conflict set coloring. In this algorithm, the goal is to distribute the clients to APs in a way that the conflict is minimized while the load is balanced.

Following on similar logic, Chen et al. [7] present, among other algorithms, Local-Coord. Local-Coord coordinates the APs in a network aiming to minimize the interference as seen by both APs and wireless clients. This is work that uses in-situ, real time interference power measurements at clients and/or APs, on all the frequency channels. Local-Coord promises increased throughputs and mitigation of interference by performing frequency allocation irrespective of network topology, AP activity level, number of APs, rogue interferers, or available channels. The weighted interference constitutes the cost function in this approach and it is applied for every BSS. Metrics like the average traffic volume and average RSSI of the clients within a BSS can be used as weights, thus guiding the protocol to tolerate different metrics accordingly. Correspondingly, a proposed global coordination scheme, Global-Coord, applied centrally, performs overall coordination and spectrum allocation of a network only if a new channel assignment results in lower co-channel weighted interference.

Leung and Kim propose MinMax [20], focusing on interactions among APs and aiming to minimize the maximum effective channel utilization at the network's bottleneck AP, so that its throughput is improved and the overall network escapes congestion. The effective channel utilization is defined as the time a channel assigned to an AP is used for transmission, or is sensed busy because of interference from its co-channel neighbors. More specifically, initially random channel assignment is performed to all the APs in the network. Next, the bottleneck AP's interfering neighbors channels are readjusted so that the effective channel utilization of the bottleneck AP is minimized [8,20].

Yu et al. propose a dynamic radio resource management scheme in [31], where again the maximum effective channel utilization at the network's bottleneck AP, is to be minimized but without interactions among APs. In their work, the channel utilization is determined by a real-time algorithm that estimates the number of active stations from an AP's point of view. The real time consideration of active stations before each channel assignment, as well as a post channel assignment QoS check reinforces the dynamic nature of this approach. However, this scheme does not scale to large networks [8].

An added degree of freedom arises from power management. Power management of APs accounting for traffic load distribution and spectrum allocation is proposed in [11] by considering the notion of a "bottleneck" AP in a network and suggest its transmission power readjustment (reduction) takes place together with channel assignment in order to reduce the total interference over the network. The power reduction only applies to beacon packets and not data packets, so that clients that cannot longer be supported turn to another less congested AP. In this work, the total data rate required by an AP's clients over the AP's available bandwidth forms the, so–called, congestion indicator [8,11]. Their proposed optimization algorithm is claimed to be able to redistribute the load in a network, reduce the AP congestion and finally perform spectrum allocation so that the interference is minimized.

Concluding, we also note that whereas the coloring-based channel allocation problem is a useful abstraction, there has been evidence that a potential overlap of the allocated channels (hence abandoning a strict vertex coloring interpretation) is not as harmful as suggested by most of the literature, while it is almost unavoidable in high density network deployments anyway. Specifically, Mishra et al. [23], by explicitly modelling an interference factor (I-factor), derive capacity improvements. We conjecture a similar model, which explicitly accounts for interference factors, may be the way of the future, in particular if the I-factor is defined for cross-technology interference as well. Moreover, in certain instances, accepting interference as unavoidable, may be the only available strategy, e.g., with l-type network elements.

5 Related Work: Characterizing and (Re-)Acting

5.1 Channel Characterization

A crucial element towards performing dynamic capacity management in the face of changing conditions, such as interference, is the collection of suitable measurements. We can collectively call the various facets of this problem as the Channel State Information (CSI) problem, but recognize that, in the same network, different devices can acquire completely different types of CSI metrics, from fine-grained to coarse-grained and for different bandwidths. Our tacit assumption is that similar measurements along with the user behavior predictability imply that similar actions need to be taken on a regular, e.g., daily, basis.

A type of detection that can be performed with p type devices using simple measurements is energy-based signal detection [19] which involves a low computational overhead but generally performs poorly in low SINR environments. Cyclostationarity [10], on the other hand, has been a potent technique but at a high computational cost. Clearly, if the sampled channel data can be shipped quickly and in large volumes to a cloud-based detection algorithm, cyclostationarity computation is a viable option. Nevertheless, cyclostationarity is not exhibited by non-communication (hence not modulated) interference sources. There, a form of feature detection can be used instead. An example are on-line classification mechanisms of interference such as the ones proposed by Boers et al. [4].

Inspired by Boers et al.'s work [3] and in [4,5], where they explore and characterize noise and interference patterns found on 256 frequencies in an indoor urban environment's 900 MHz ISM and non-ISM bands, as well as based on our previous work in [29] where we studied whether the agreement of the same interference patterns on the class of a channel, can be linked to the cross correlation statistic, we envision the next step to be the exploration of the whole spectrum in the ISM band for further characterization of noise and interference patterns.

We anticipate that the perceived interference is location-specific. Indeed, the cross-correlation results of the time series [29] is suggesting that nearby nodes are experiencing similar interference. Seen differently, it is not necessary that all nodes in an area, e.g., not all APs, have to be p-type devices since very similar measurements would end up being collected. However, it is still not known how dense should the spatial sampling be to derive reliable channel state metrics for the various areas of the network. We note that similarities exist with the case of sampling strategies for optimal monitoring [18] as they express the situations where limited sampling resources are to handle a large network. Yet another, natural facet of the same problem is how high the sampling rate should be and how to convey the sampled data for processing in the cloud. Our early results show that wavelet compression of the sampled time series may produce significant data volume savings [28].

5.2 Interference Reaction/Mitigation

Current strategies to handle interference include *interference alignment* which is a transmission strategy relying on the coordination of multiple transmitters so that their mutual interference aligns at the receivers, and promises to improve the network's throughput [2]. Such techniques set as their objective to approximate the maximum degrees of freedom, also known as the channel's maximum multiplexing gain. Nevertheless, there are still open issues that need to be considered, such as realistic propagation environments, and the role of channel state information at the transmitter, and most importantly for our approach, the practicality of interference alignment in large networks [2].

Krishnamachari and Varanasi [17] study systems characterized by multi-user interference channels with single or multiple antennas at each node and develop an interference alignment scheme where there is no global channel knowledge in the network, but where each receiver knows its channels from all the transmitters and broadcasts a quantized version of it to all the other terminals, at a rate that scales sufficiently fast with the power constraint on the nodes. The quantized channel estimates are treated as being perfect and it is shown that they are indeed sufficient to attain the same sum degrees of freedom as the interference alignment implementation utilizing perfect channel state information at all the nodes. Significant is also the observation by Jafar [13], that statistical knowledge of channel autocorrelation structure alone is sufficient for interference alignment and, to this end, an alternative to CSI.

Another philosophy is that of embracing and exploiting interference. For example, Katti et al. [15] show that by combining physical-layer and network-layer information, network capacity can be increased. Their analog network coding scheme actually encourages strategically picked senders to interfere. Instead of forwarding packets, it suggests that routers forward the interfering signals, so that the destination leverages network-level information to cancel the interference and recover the signal destined to it. On a different tangent of embracing interference is the work by Boers et al. [3] which essentially proposes a MAC coordination scheme that takes into consideration the temporal behavior of interference patterns and aims to steer transmissions around them. Their approach simulates a pattern-aware MAC (PA-MAC) and their results include improved packet reception rates in both single and multi-hop environments at the cost of increased latency.

6 Conclusions and Research Directions

Given the reviewed literature, we identify a relative lack of work and, hence, a need to address the following technical issues:

- developing techniques to determine when, and for how long, nodes can take time away from their "regular business" of handling traffic and instead sensing the spectrum, i.e., a form of scheduling the spectrum analysis tasks with minimal impact on the regular operation of the networks,
- developing techniques that allow spectrum sensing data acquired from different nodes to be temporally aligned correctly and referenced back to natural time, despite the lack of strongly synchronized clocks,
- developing tools that will allow us to quickly identify correlations in interference patterns, both for determining the origin of the interference, and for guiding nodes to follow similar mitigation strategies,
- developing simple metrics and models for quantifying the CTI over a broad set of protocols, such that they can be used to capture "cost" metrics useful to resource management optimization decisions.

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References

1. Akyildiz, I.F., Lee, W.Y., Vuran, M.C., Mohanty, S.: Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey. Comput. Netw. **50**(13), 2127–2159 (2006)
2. Ayach, O.E., Peters, S.W., Heath, R.W.: The practical challenges of interference alignment. IEEE Wirel. Commun. **20**(1), 35–42 (2013)
3. Boers, N.M., Nikolaidis, I., Gburzynski, P.: Impulsive interference avoidance in dense wireless sensor networks. In: Li, X.-Y., Papavassiliou, S., Ruehrup, S. (eds.) ADHOC-NOW 2012. LNCS, vol. 7363, pp. 167–180. Springer Berlin Heidelberg, Berlin, Heidelberg (2012). doi:10.1007/978-3-642-31638-8_13
4. Boers, N.M., Nikolaidis, I., Gburzynski, P.: Sampling and classifying interference patterns in a wireless sensor network. ACM Trans. Sen. Netw. **9**(1), 2:1–2:19 (2012)

5. Boers, N., Nikolaidis, I., Gburzynski, P.: Patterns in the RSSI traces from an indoor urban environment. In: 2010 15th IEEE International Workshop on Computer Aided Modeling, Analysis and Design of Communication Links and Networks (CAMAD), pp. 61–65 (2010)
6. Centenaro, M., Vangelista, L., Zanella, A., Zorzi, M.: Long-range communications in unlicensed bands: the rising stars in the iot and smart city scenarios. CoRR abs/1510.00620 (2015). http://arxiv.org/abs/1510.00620
7. Chen, J.K., de Veciana, G., Rappaport, T.S.: Improved measurement-based frequency allocation algorithms for wireless networks. In: IEEE GLOBECOM 2007, pp. 4790–4795 (2007)
8. Chieochan, S., Hossain, E., Diamond, J.: Channel assignment schemes for infrastructure-based 802.11 WLANs: a survey. IEEE Commun. Surv. Tutorials **12**(1), 124–136 (2010)
9. Cisco: Radio resource management under unified wireless networks. Technical report 71113, Cisco Systems, May 2010
10. Gardner, W.A., Spooner, C.M.: Signal interception: performance advantages of cyclic-feature detectors. IEEE Trans. Commun. **40**(1), 149–159 (1992)
11. Haidar, M., Akl, R., Al-Rizzo, H., Chan, Y.: Channel assignment and load distribution in a power-managed WLAN. In: 2007 IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications, pp. 1–5, September 2007
12. Hithnawi, A., Li, S., Shafagh, H., Gross, J., Duquennoy, S.: Crosszig: combating cross-technology interference in low-power wireless networks. In: 2016 15th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), pp. 1–12, April 2016
13. Jafar, S.A.: Exploiting channel correlations - simple interference alignment schemes with no CSIT. In: GLOBECOM (2010)
14. Joshi, K., Hong, S., Katti, S.: Pinpoint: Localizing interfering radios. In: 10th USENIX Symposium on Networked Systems Design and Implementation (NSDI 2013), pp. 241–253. USENIX, Lombard, IL (2013)
15. Katti, S., Gollakota, S., Katabi, D.: Embracing wireless interference: analog network coding. Comput. Commun. Rev. **37**(4), 397–408 (2007)
16. Katzela, I., Naghshineh, M.: Channel assignment schemes for cellular mobile telecommunication systems: a comprehensive survey. IEEE Pers. Commun. **3**(3), 10–31 (1996)
17. Krishnamachari, R.T., Varanasi, M.K.: Interference alignment under limited feedback for MIMO interference channels. In: 2010 IEEE International Symposium on Information Theory, pp. 619–623, June 2010
18. Le, T., Szepesvári, C., Zheng, R.: Sequential learning for multi-channel wireless network monitoring with channel switching costs. IEEE Trans. Sig. Process. **62**(22), 5919–5929 (2014)
19. Lehtomäki, J.: Analysis of energy based signal detection. Ph.D. thesis, University of Oulu, Faculty of Technology, Department of Electrical and Information Engineering, Oulu, Finland, November 2005
20. Leung, K.K., Kim, B.J.: Frequency assignment for IEEE 802.11 wireless networks. In: 2003 IEEE 58th Vehicular Technology Conference, VTC 2003-Fall, vol. 3, pp. 1422–1426, October 2003
21. Mahonen, P., Riihijarvi, J., Petrova, M.: Automatic channel allocation for small wireless local area networks using graph colouring algorithm approach. In: PIMRC 2004, vol. 1, pp. 536–539, September 2004

22. Mishra, A., Brik, V., Banerjee, S., Srinivasan, A., Arbaugh, W.: A client-driven approach for channel management in wireless LANs. In: Proceedings of IEEE INFOCOM 2006, 25TH IEEE International Conference on Computer Communications, pp. 1–12, April 2006
23. Mishra, A., Shrivastava, V., Banerjee, S., Arbaugh, W.: Partially overlapped channels not considered harmful. SIGMETRICS Perform. Eval. Rev. **34**(1), 63–74 (2006)
24. Murty, R., Chandra, R., Moscibroda, T., Bahl, P.V.: SenseLess: a database-driven white spaces network. IEEE Trans. Mob. Comput. **11**(2), 189–203 (2012)
25. Naganawa, J., Kim, H., Saruwatari, S., Onaga, H., Morikawa, H.: Distributed spectrum sensing utilizing heterogeneous wireless devices and measurement equipment. In: 2011 IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), pp. 173–184, May 2011
26. Pefkianakis, I., Lundgren, H., Soule, A., Chandrashekar, J., Guyadec, P.L., Diot, C., May, M., Doorselaer, K.V., Oost, K.V.: Characterizing home wireless performance: the gateway view. In: 2015 IEEE Conference on Computer Communications (INFOCOM), pp. 2713–2731, April 2015
27. Rost, P., Bernardos, C.J., Domenico, A.D., Girolamo, M.D., Lalam, M., Maeder, A., Sabella, D., Wbben, D.: Cloud technologies for flexible 5G radio access networks. IEEE Comm. Mag. **52**(5), 68–76 (2014)
28. Vlachaki, A., Nikolaidis, I., Harms, J.: Wavelet-based analysis of interference in WSNs. In: 41st IEEE Conference on Local Computer Networks (LCN), November 2016 (to appear)
29. Vlachaki, A., Nikolaidis, I., Harms, J.J.: A study of channel classification agreement in urban wireless sensor network environments. In: Postolache, O., van Sinderen, M., Ali, F.H., Benavente-Peces, C. (eds.) SENSORNETS 2014, pp. 249–259. SciTePress (2014)
30. Yeo, J., Youssef, M., Agrawala, A.K.: A framework for wireless LAN monitoring and its applications. In: Proceedings of the 2004 ACM Workshop on Wireless Security, Philadelphia, PA, USA, 1 October 2004, pp. 70–79 (2004)
31. Yu, M., Luo, H., Leung, K.K.: A dynamic radio resource management technique for multiple APs in WLANs. IEEE Trans. Wirel. Commun. **5**(7), 1910–1919 (2006)