Beamforming Mesh Deployment

TBA
Department of Electrical Engineering, Southern Methodist University, Dallas, TX

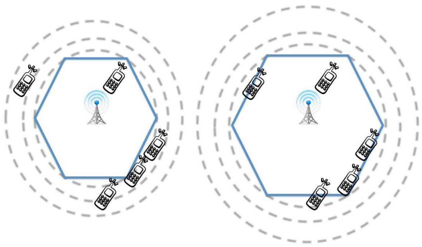

Fig. 1. Communication Range of Access Points

***Abstract*—Beamforming**

I. Problem Formulation

The objective of the mesh network deployment is to minimize the number of deployed mesh nodes with the constraint of full coverage of the target area and connectivity to the Internet. In this section we first describe the the motivation of frequency agility, then we introduce the deployment constraints, which the QoS requirements of the vendors and clients. Moreover, we discuss the frequency agility application impacts on a single access point and networks in dense and sparse areas. Further, we formulate the deployment problem as a graph-theoretic model with the QoS constraints an operational wireless mesh network must satisfy.

A. Motivation

Wireless propagation is the behavior of the signal loss characteristics when wireless signals are transmitted through the wireless medium. The strength of the received signal depends on both the line-of-sight path (or lack thereof) and multiple other paths that result from reflection, diffraction, and scattering from obstacles [1]. The widely-used Friis equation characterizes the received signal power P_r in terms of transmit power P_t, transmitter gain G_t, receiver gain G_r, wavelength λ of the carrier frequency, distance R from transmitter to receiver, and path loss exponent n according to [2]:

$$P_r = P_t + G_t + G_r + 10n \log_{10} \left(\frac{\lambda}{4\pi R} \right) \tag{1}$$

Here, n varies according to the aforementioned environmental factors with the value of two to five in typical outdoor settings [3]. Through the propagation model, in the same environment with a constant path-loss exponent n, lower frequency white space bands offer not only more bandwidth, but also large communication range, which could potentially be used to reduce the number of access points.

Thus, access point with white space bands radios could expand coverage region and increase a single access point capacity. However, at the same time, multiband radios application also increase the interference range which reduce the re-use ability in the network. To further employ these technologies reducing the number of access points, the trade off between more coverage area and interference has to be optimized. In this work, we focus on this problem. Before starting design a network, we introduce the network service constraints which are forced to be followed to satisfy the clients in the deployment.

Typically, the deployment of wireless access networks is subject to coverage and capacity constraints for a target area. Coverage is defined with respect to the ability of clients to connect to access points within their service area. We use a coverage constraint ratio of 95% in this work for a target area [4]. Capacity is defined with respect to the ability of a network to serve the traffic demand of clients. Spatial reuse allows improved capacity, but increases the cost of deploying a network by increasing the total number of access points required. Hence, for densely populated areas the greatest level of spatial reuse is often desired which could be offered through an expensive new access point working in higher frequency. In contrast, sparsely-populated rural areas have lower traffic demand per unit area. Thus, aggregating this demand with lower-frequency, white space bands could be highly effective in reducing the total number of access points required to achieve similar coverage and capacity constraints. Moreover, since less TV channels tend to be occupied in sparsely populated areas [5], a larger number of white space bands can be leveraged in these areas.

Under these constraints, the performance of the technology varies from dense populated area to sparse area. In dense populated area, more traffic demands from unit area, which request more spacial reuse from higher frequency. In [6], the channel occupancy varies with population density. With a proper sweep schedule, more time spent for the dense part could compensate the capacity occupied by other devices. In sparse areas, few user generate low level traffic demand, with less benefit for the service. Under these conditions, an access point with lower frequency would be an affordable option. We will model these factors as parameters in a link graph and continue to analyze their influence in wireless network deployment.

B. Model and Problem Formulation

As opposed to previous works such as [4], [7], [8], we focus on heterogeneous multiband access point selection for wireless access networks which jointly employ white space bands and WiFi bands. Through white space and WiFi bands frequency agility, an access point performance could be improve by the coverage area and throughput.

We assume the service vendor has a limited number of spectrum resources and wireless radios have similar configuration, such as transmit power, gains. Each radio on an access point operates with a classic protocol model [9]. Then we can further analyze the performance of access point under different traffic demand distribution according to the capacity and coverage constraint.

A network deployment should ideally provide network capacity equal to the demand of the service area to maintain the capacity constraint. The demand of a service area could be calculated as the summation of individual demands all over the service area $D_a = \sum_{p \in P} D_p$. Since household demand for Internet has been previously characterized [10], D_a could represent the population distribution f and service area k as $D_a = \sum_{f \in F, k \in K} \bar{D_p} * f * k$. The capacity constraint could be represented with access points set M according to:

$$\sum_{m \in M} C_r^m \geq \sum_{f \in F, k \in K} \bar{D_p} * f * k \tag{2}$$

At the same time, the wireless network must additionally satisfy the coverage constraint in the service area where the access points provide connectivity for client devices. Generally, a coverage of 95% is acceptable for wireless access networks [4]. The object of this work is to find the best possible number of access points so that the network has good connectivity and enough capacity to satisfy the traffic demands.

Under the capacity and coverage constraints, the service area of an access point is limited by the propagation range and access point capacity. The radius of service area r_s could be represented as:

$$r_s = min\{r_p, r_c\} \tag{3}$$

r_p represents the propagation range of the access point, r_c is the capacity range of a radio in the access point. A simple example is when the traffic demand is distributed uniform in a circle, from Eq. 2 the capacity range r_c could be noted as $r_c = \sqrt{k/\pi}$. Moreover, the propagation range and capacity rang could be determined by the environment, traffic distribution and power control [4]. These parameters could be pre-detected from existing measurements, census and public or private database. When a target area is given, we could model the traffic demand, access points and potential connectivity links as a graph according to the parameters from database.

Thus, the target area with pre-defined parameters could be modeled as a connectivity graph with vertexes represented as the centralized traffic demand of a certain area and potential access points locations. The edges note the links between the locations. Oppose to previous works, [4], [7], [11], [12] we formulate the input connectivity graph as a graph $G = (V, E, F)$, where centralized traffic demand, access points location candidates and links from a type of access point defined by its frequency form a unified connectivity graph.

The vertexes in the modeled input graph represent a set C of separated target area with traffic demands. The set C consists of physical coordinates representing target areas where client coverage is desired, analogous to the area to be covered in a geometric formulation and the traffic amount need to be served. And also the set of potential access points M is a second part of the vertexes in the modeled graph. The potential locations of access points are assumed known through the infrastructure conditions. The vertex set of the input connectivity graph is the union of potential access points and centralized traffic demand locations as $V = C \cup M$.

The access points types set F is defined by the working frequency band It is a set of different combination of frequency. The set E int the graph is the physical link under protocol model between two vertexes according to the access point type.

The output of the problem is expected to be an graph $G' = (V', E', F')$ which marks the access points and chosen frequency. In the output graph, V' includes the chosen access points set M' and served traffic demand location set C'. The set F' tells the chosen access point type of each M'. The connectivity and capacity constraints could be defined by the output graph G', as shown in 4 and 5

$$\frac{\sum Number\{C'\}}{\sum Number\{C\}} \geq \theta_{coverage} \tag{4}$$

$\theta_{coverage}$ is the desired level of coverage for the target area. C' is the served traffic demand location of the target area.

$$C'_n \geq C_n \cdot \theta_{capacity}, C'_n \in C', C_n \in C \tag{5}$$

$\theta_{capacity}$ is the percentage of satisfied traffic demand for the target area, which also include the fairness request in the equation.

The output of the graph could be optimized in several aspects. From the view of vendors, the number of access points would be the primary concern $Min\{Number\{M'\}\}$. Through the vendors monthly income from flow charge, maximize the served traffic demand would be the objective $Max\{\sum C'\}$.

To optimize these parameters,

II. Related Work

There are significant challenges in wireless mesh network deployment, such as user priorities, user behaviors, long term throughput estimation, selfish clients, interference and energy efficiency, etc. [13] These challenges are distributed under the topics of channel assignment, cognitive radio, protocol design, etc. [13], [14] Previous works have recognize the impact of interference in wireless mesh network deployment is the key issue [11], [12], [15]. To overcome the challenges, a lot of works have been done to optimize the deployment in increasing throughput, minimize resource, reducing interference, etc. [12], [16], [17] Many works have studied the network deployment problem in multihop wireless networks [13], [18]–[20]. In addition, multiple radios have been used to improve the routing in multi-channel scenarios [12], [21]. Both static and dynamic network deployments have been discussed in previous works under the 802.11 WiFi scenario [16], [22], [23]. However, all of the aforementioned works have not considered propagation differences of the diverse frequency bands of white space and WiFi, which we show are critical improving the performance of mesh networks. Frequency agility in multiband scenario brings more traffic capacity to wireless network deployment as well as more complexity of resolving the interference issues.

In wireless network deployment, reduce the interference is the key issue. Previous work [24] involve the inter-network interference in multiband scenario, but did not offer the solution of intra-network interference. As a new designed wireless network, intra-network interference is more important for performance estimation. Previous work focus on WiFi wireless networks proposed several methods to reduce the interference targeting on multiple metrics. [4], [11], [25] focus on reducing the gateway mesh nodes. [12], [16] try to reduce the overall interference in the worst case of traffic independent scenario. [15], [26] improve the performance in throughput. However, these works fails to involve the traffic demands of clients in their solutions. [4], [27] consider the QoS requirements in the WiFi network design. Our work also consider the traffic demands from the client as part of our network design to satisfy both customers and vendors.

The wireless network deployment problem has been proved as a NP-hard problem [8]. Several works introduce relaxed linear program formulation to find the optimization of multihop wireless networks [11], [12], [28]. Also, game theory methods is another option to solve the problem [29], [30]. Social network analysis is also popular in wireless network design [31]. In contrast, we formulate the multiband scenario problem as a graph model similar to [4] for approaching.

To be used effectively, white space bands must ensure that available TV bands exist but no interference exists between microphones and other devices [32]. White space bands availability has to be known in prior of network deployment. TV channels freed by FCC are fairly static in their channel assignment, databases have been used to account for white space channel availability (e.g., Microsoft's White Space Database [5]). In fact, Google has even visualized the licensed white space channels in US cities with an API for research and commercial use [33]. In contrast, we study the performance of mesh networks with a varying number of available white space channels at varying population densities, assuming such white space databases and mechanisms are in place. As FCC release these bands for research, many methods have been proposed to employ these frequency bands. [32] introduce WiFi like white space link implementation on USRP and link protocols. [34] discuss the point to point communication in multiband scenario. In [28], white space band application is discussed in cognitive radio network for reducing maintenance cost. In [35], the white space is proposed to increase the data rates through spectrum allocation. In contrast, we focus on reducing the deployment cost with customer constraints in mesh nodes number.

REFERENCES

[1] J. B. Andersen, T. S. Rappaport, and S. Yoshida, "Propagation measurements and models for wireless communications channels," *IEEE Communications Magazine*, vol. 33, no. 1, pp. 42–49, 1995.

[2] H. T. Friis, "A note on a simple transmission formula," vol. 34, no. 5, pp. 254–256, May 1946.

[3] T. Rappaport, *Wireless Communications, Principles & Practice.* Prentice Hall, 1996.

[4] J. Robinson, M. Singh, R. Swaminathan, and E. Knightly, "Deploying mesh nodes under non-uniform propagation," in *IEEE INFOCOM*, 2010.

[5] "Microsoft research white space database," http://whitespaces.cloudapp.net/Default.aspx, 2013.

[6] P. Cui, H. Liu, D. Rajan, and J. Camp, "A measurement study of white spaces across diverse population densities."

[7] A. A. Franklin and C. S. R. Murthy, "Node placement algorithm for deployment of two-tier wireless mesh networks," in *Global Telecommunications Conference, 2007. GLOBECOM'07. IEEE.* IEEE, 2007, pp. 4823–4827.

[8] W. Si, S. Selvakennedy, and A. Y. Zomaya, "An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks," *Journal of Parallel and Distributed Computing*, vol. 70, no. 5, pp. 505–524, 2010.

[9] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. on Information Theory*, vol. 46, no. 2, pp. 388–404, 2000.

[10] G. Rosston, S. Savage, and D. Waldman, "Household demand for broadband internet service," *Communications of the ACM*, vol. 54, no. 2, pp. 29–31, 2011.

[11] J. Tang, G. Xue, and W. Zhang, "Interference-aware topology control and QoS routing in multi-channel wireless mesh networks," in *ACM MobiHoc*, 2005.

[12] R. E. Irwin, A. B. MacKenzie, and L. A. DaSilva, "Resource-minimized channel assignment for multi-transceiver cognitive radio networks," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 3, pp. 442–450, 2013.

[13] E. Z. Tragos, S. Zeadally, A. G. Fragkiadakis, and V. A. Siris, "Spectrum assignment in cognitive radio networks: A comprehensive survey." *IEEE Communications Surveys and Tutorials*, vol. 15, no. 3, pp. 1108–1135, 2013.

[14] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Computer Networks*, vol. 50, no. 13, pp. 2127–2159, 2006.

[15] S. Chieochan and E. Hossain, "Channel assignment for throughput optimization in multichannel multiradio wireless mesh networks using network coding," *Mobile Computing, IEEE Transactions on*, vol. 12, no. 1, pp. 118–135, 2013.

[16] A. P. Subramanian, H. Gupta, S. R. Das, and J. Cao, "Minimum interference channel assignment in multiradio wireless mesh networks," *IEEE TMC*, vol. 7, no. 12, pp. 1459–1473, 2008.

[17] M. Doraghinejad, H. Nezamabadi-Pour, and A. Mahani, "Channel assignment in multi-radio wireless mesh networks using an improved gravitational search algorithm," *Journal of Network and Computer Applications*, vol. 38, pp. 163–171, 2014.

[18] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," *Wireless networks*, vol. 11, no. 4, pp. 471–487, 2005.

[19] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer networks*, vol. 47, no. 4, pp. 445–487, 2005.

[20] A. Raniwala, K. Gopalan, and T.-c. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM SIGMOBILE MCCR*, vol. 8, no. 2, pp. 50–65, 2004.

[21] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *ACM MobiCom*, 2004.

[22] X. Wu, J. Liu, and G. Chen, "Analysis of bottleneck delay and throughput in wireless mesh networks," in *IEEE MASS*, 2006.

[23] K. N. Ramachandran, E. M. Belding-Royer, K. C. Almeroth, and M. M. Buddhikot, "Interference-aware channel assignment in multi-radio wireless mesh networks." in *IEEE INFOCOM*, 2006.

[24] D. R. Pengfei Cui, Hui Liu and J. Camp, "A measurement study of white spaces across diverse population densities," *IEEE 10th WiNMeE*, 2014.

[25] B. He, B. Xie, and D. P. Agrawal, "Optimizing deployment of internet gateway in wireless mesh networks," *Computer Communications*, vol. 31, no. 7, pp. 1259–1275, 2008.

[26] X. Li, J. Wu, S. Lin, and X. Du, "Channel switching control policy for wireless mesh networks," *Journal of Parallel and Distributed Computing*, vol. 72, no. 10, pp. 1295–1305, 2012.

[27] Y. Long, H. Li, M. Pan, Y. Fang, and T. F. Wong, "A fair qos-aware resource-allocation scheme for multiradio multichannel networks," *Vehicular Technology, IEEE Transactions on*, vol. 62, no. 7, pp. 3349–3358, 2013.

[28] I. Filippini, E. Ekici, and M. Cesana, "A new outlook on routing in cognitive radio networks: minimum-maintenance-cost routing," *IEEE/ACM Transactions on Networking (TON)*, vol. 21, no. 5, pp. 1484–1498, 2013.

[29] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *IEEE INFOCOM*, 2005.

[30] B. Wang, Y. Wu, and K. Liu, "Game theory for cognitive radio networks: An overview," *Computer Networks*, vol. 54, no. 14, pp. 2537–2561, 2010.

[31] Y. Zhu, B. Xu, X. Shi, and Y. Wang, "A survey of social-based routing in delay tolerant networks: positive and negative social effects,"

Communications Surveys & Tutorials, IEEE, vol. 15, no. 1, pp. 387–401, 2013.

[32] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh, “White space networking with WiFi like connectivity,” *ACM SIGCOMM*, vol. 39, no. 4, pp. 27–38, 2009.

[33] “Google spectrum database,” http://goo.gl/NnIFXQ, 2013.

[34] P. Cui, H. Liu, J. He, O. Altintas, R. Vuyyuru, D. Rajan, and J. Camp, “Leveraging diverse propagation and context for multi-modal vehicular applications,” in *IEEE WiVeC*, 2013.

[35] S. Deb, V. Srinivasan, and R. Maheshwari, “Dynamic spectrum access in dtv whitespaces: design rules, architecture and algorithms,” in *Proceedings of the 15th annual international conference on Mobile computing and networking*. ACM, 2009, pp. 1–12.