FSMA - A Topology-Transparent Scheme for Opportunistic Spectrum Access

Hwee-Pink Tan*, Colman O'Sullivan† and Linda Doyle*†
*Center for Telecommunications Value-chain Research
†Department of Electronic Engineering
Trinity College, University of Dublin, Dublin 2, Ireland.
Email: {tanhp, cosull13 and ledoyle}@tcd.ie

Abstract— **With the advent of cognitive radio technology, new paradigms for spectrum access can achieve near-optimal spectrum utilization by letting users sense and utilize available spectrum opportunistically. Recently, graph-coloring models have been used to produce fair, efficient and optimal spectrum allocations for a given network topology. However, topology changes (e.g., due to user mobility) can incur significant signaling traffic to reallocate spectrum, consuming valuable resources. We propose a frequency-spread multiple access (FSMA) scheme that is topology-transparent, and numerical results suggest that it is suited for opportunistic spectrum access in a sparsely-connected, low-density mobile ad-hoc network.**

I. INTRODUCTION

In today's wireless networks, a *command and control* approach to spectrum management is deployed, where fixed spectrum slices are licensed to each wireless service / technology. However, recent studies [1] have shown that spectrum utilization is 6.5% (0.8%) and 78% (97%) of spectrum is unutilized in urban (rural) areas. This inefficient use of scarce wireless radio spectrum, along with a dramatic increase in the spectrum access for mobile services, have been the driving forces towards new spectrum management paradigms [2].

In the *licensed* model, an exclusive-use license is assigned which may be traded in secondary markets. The licensee is responsible for making all substantive choices as to how the spectrum is used. In contrast, under the *commons* model, (unlicensed) users share the spectrum according to a protocol e.g., spread-spectrum techniques developed for cellular networks. While a licensed user has a right for interference protection, any such right is implicit and a consequence of the protocol for an unlicensed user. A *mixed* regime that supports the *coexistence* of licensed and unlicensed users is enabled by the advent of cognitive radios (CR) [3], [4]. While licensed users have priority in spectrum access, unlicensed users can use available spectrum without interfering with licensed users through opportunistic access (overlay) or low power spread-spectrum techniques (underlay). This results in efficient spectrum usage and simplifies deployment of new applications, and hence a mixed regime is a promising candidate for dynamic spectrum access.

In this paper, we propose a topology-transparent scheme for opportunistic and cooperative spectrum access for CR-enabled unlicensed users that is simple to implement and provides fair spectrum utilization for a mixed spectrum regime. Our scheme is applicable in the presence of a central control entity and is also amenable to distributed implementation.

II. RELATED WORK

Cognitive radio is the key enabling technology for dynamic spectrum access. Each cognitive radio has the ability to sense the radio environment and determine the spectrum holes unused by licensed users. Each radio then *reconfigures* itself, e.g., in terms of transmission power [5], channel [6] or a combination of both [7], [8], to utilize the spectrum holes according to spectrum *access* schemes. While it is important to ensure fairness amongst all users, spectrum access schemes should also minimize the interference each user imposes on other users such that a maximum number of users can be supported for a given spectrum availability. Such schemes have to take into account many factors and are often hard to formulate.

Various research has emerged recently that assumes a *fixed* transmission power and constructs a spectrum (channel) allocation scheme using a color-sensitive graph coloring (GC) model [6], based on the channel assignment scheme proposed in [9]. We illustrate the mechanism of this scheme by considering a network with 3 users (nodes), {1, 2, 3} sharing 3 channels (colors), {A, B, C}. We define a simple (*spatial*) interference constraint, where two transmissions on the same channel conflict and fail if they are within a certain distance of each other (*re-use* distance). This distance typically corresponds to the transmission or sensing range of each user. By mapping each channel into a color, and taking into account the interference constraints, the channel assignment problem can be abstracted into a graph coloring model as illustrated in Fig. 1. A label on vertex (node) i (edge $i-j$) indicates channel(s) available to node i (unusable by nodes i and j simultaneously according to the interference constraint). Accordingly, a feasible allocation is given by {(1, A), (2, B), (3, C)}, where (i, J) indicates that node i is allocated channel J.

The above scheme is highly channel efficient (since it is collision-free) and optimal (minimum number of channels required for a given number of nodes, or maximum number of nodes supported for a given number of channels) for the case where the available spectrum is accessible by all nodes

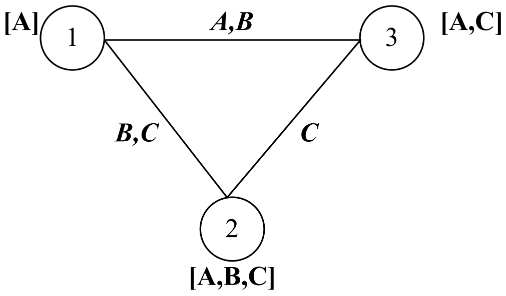


Fig. 1. A color-sensitive graph coloring model for allocating 3 channels, {A, B, C} amongst 3 users, {1,2,3} (represented by vertices). Label on vertex *i* (edge *i*–*j*) indicates spectrum available to node *i* (unusable by nodes *i* and *j* simultaneously).

[9]. However, a major drawback of the scheme for mobile ad-hoc networks is that the interference constraints depend on the *detailed* topology of the network. Node mobility induces topology changes and labels on vertices and edges have to be refreshed accordingly and a new graph constructed before a new channel allocation can be formulated. This necessitates the exchange of signaling messages which consumes valuable spectrum and introduces substantial latency.

To combat the topology-dependence in resource allocation schemes, time-spread multiple access (TSMA) protocols have been initiated in [10], where each node is assigned a unique code that deterministically specifies the time slots in which each node can transmit. Despite the possibility of collisions, each node is *guaranteed* a successful transmission to every neighboring node (within its re-use distance) within each time frame (cycle). Since the transmission schedule for every node is constructed according to a given maximum number of nodes, N and maximum node degree, Δ, no scheduling updates are needed when topology changes, as long as they are within the bounds of (N, Δ). Hence, TSMA combines the topology-independence of contention-based schemes (such as ALOHA) with the guaranteed delivery of time-division multiple access (TDMA) classes of protocols. We extend this topology-transparent property to the frequency domain and propose a frequency-spread multiple access (FSMA) spectrum allocation scheme for CR-enabled users.

III. FSMA: A TOPOLOGY-TRANSPARENT SPECTRUM ALLOCATION SCHEME

A. System Model

We consider CR-enabled unlicensed users with *fixed* transmission power dispersed throughout a geographical region and self-configured to form a mobile ad-hoc network, where the network topology changes *frequently* due to user mobility. This network co-exists with licensed users such that each unlicensed user senses and opportunistically utilizes the available spectrum unused by licensed users subject to spatial interference constraints defined previously.

Without loss of generality, we assume that the spectrum band is channelized in the frequency domain, where the basic resource unit is a *channel* of bandwidth b Hz. This corresponds to the bandwidth requirement of each user to meet its Quality of Service (QoS) needs, assumed to be the same (one channel) for all users (*homogeneous* users). Although the spectrum available for unlicensed users is usually both time and location-dependent (as it depends on the usage of licensed users), we assume that it is (a) *static* during spectrum assignment and (b) location-independent so that it is commonly available to *all* users.

Finally, as with most proposed spectrum assignment schemes, each user has access to a perfectly synchronized and dedicated (interference-free) Common Signalling Control Channel (CSCC). By exchanging signaling messages on the CSCC, each user can compute the parameters required by the channel assignment scheme.

B. Description of FSMA scheme

We recall that N is the maximum number of nodes in the network and Δ is the maximum node degree (or the number of *interferers* per user), where we assume that a user i interferes with another user j when both users are within each other's re-use distance and transmit in the same channel.

Given (N, Δ), the FSMA scheme assigns a unique polynomial of degree k over the finite Galois field $\mathbf{GF}(q)$ to each node, where q is the power of a prime number. Overlap of channel allocations (and hence possible collisions) corresponds to common roots of the polynomial associated to different nodes. To guarantee at least one collision-free channel per node, the FSMA mechanism relies on an appropriate choice of q and k to ensure that a channel cannot be covered by up to Δ^2 nodes. The non-covering condition can be expressed as [10]

$$q \geq k\Delta + 1.$$

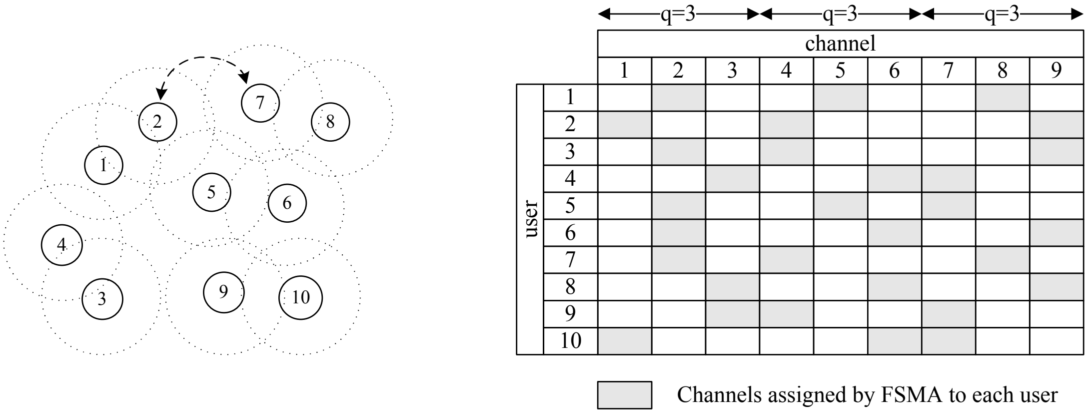
On the other hand, polynomials must be uniquely assigned to each node, so that the following condition must hold as well:

$$q^{k+1} \geq N.$$

The resulting spectrum allocation schedule comprises a total of q^2 channels, where each node is assigned exactly one channel per interval of q channels. Hence, based on *limited* topology information (N, Δ), the FSMA assignment schedule requires $L = q^2$ channels to guarantee a collision-free channel to each user, where a *smaller* $\frac{L}{N}$ indicates better *allocation efficiency*. Hence, even when topology changes (within the bounds of (N, Δ)), the same guarantee can be achieved with the FSMA assignment, demonstrating its *topology-transparency*.

C. Illustration of FSMA scheme

We illustrate the mechanism of FSMA for a network with (N,Δ) = (10,1) and detailed topology as shown in the LHS of Fig. 2. According to our spatial interference model, any pair of users located within each other's re-use distance (defined by the dotted circles) cannot transmit in the same channel without interfering each other. An example of a spectrum assignment



user	1	2	3	4	5	6	7	8	9
1		▨			▨			▨	
2	▨			▨					▨
3		▨		▨					▨
4			▨			▨	▨		
5		▨			▨		▨		
6		▨				▨			▨
7		▨		▨				▨	
8			▨			▨			▨
9			▨	▨			▨		
10	▨					▨	▨		

▨ Channels assigned by FSMA to each user

Fig. 2. (LHS) An example of a network topology with (N,Δ) = (10,1) and (RHS) the corresponding FSMA schedule (q=3).

schedule constructed by FSMA (q=3 and $q^2 = 9$ channels) is given in the RHS of Fig. 2.

According to Fig. 2, although each user is assigned q channels, the channels that are collision-free (at least one) cannot be pre-determined. Hence, each user may transmit initially on each of the assigned channels in turn before tuning in to the one(s) that permit collision-free transmission.

Consider user 1 that is assigned channels 2, 5 and 8 while user 2 is assigned channels 1, 4 and 9. Since this pair of users are assigned distinct channel sets and only interfere with each other and not any other user, they can transmit in any of the assigned channels. However, if users 2 and 7 switch locations (see LHS of Fig. 2), then users 1, 7, 2, 8 can transmit in channel 5, 4, $\{1{,}4\}$, $\{3{,}6\}$ respectively collision-free - demonstrating the topology-transparency of the FSMA channel assignment constructed solely on *limited* topology information, (N, Δ).

On the other hand, the GC approach that uses *detailed* topology information requires only 2 channels to guarantee collision-free transmission (e.g., assigning channel 1(2) to odd (even)-indexed users). However, if users 2 and 7 switch locations (as above), the spectrum assignment for users 1, 2, 7 and 8 will have to be refreshed for collision-free transmissions, incurring overhead due to signaling messages as well as latency. Hence, compared with FSMA, the allocation efficiency of GC is traded off with its topology-dependence.

Remark 1: It is worthwhile noting that, if the only topology information available is N, then a simple FDMA scheme that assigns a *unique* channel to each user would require N channels to guarantee collision-free transmission. For the network in the LHS of Fig. 2, by availing to the additional topology information, Δ, an improvement in allocation efficiency is achieved with the FSMA scheme ($\frac{L_{FSMA}}{N}= 0.9$ and $\frac{L_{FDMA}}{N}$=1), which may not be true for all topologies. If allocation efficiency is the only consideration, then FSMA should be considered over FDMA only if $q^2 < N$. In general, CR-enabled unlicensed users should have the option to select the assignment scheme that suits.

IV. PERFORMANCE EVALUATION

We generate a network comprising N nodes distributed randomly over a geographic area of 1x1. We vary the transmission range, R $\in$ [0.05, 0.95] to obtain topologies with different maximum node degree, Δ, while ensuring that the network remains *connected* (i.e., minimum node degree > 0).

A. Allocation Efficiency

We first evaluate the performance of the FSMA and GC spectrum assignment schemes in terms of the allocation efficiency, $\frac{L_{FSMA}}{N}$ and $\frac{L_{GC}}{N}$ respectively. The allocation efficiency is plotted as a function of N for various values of R in Fig. 3. We note that the results are *averaged* over a set of 10 network topologies generated for each (N, R).

As expected, the (optimal) GC approach is significantly more allocation-efficient than our proposed FSMA scheme. In both cases, as the network becomes more *connected* (i.e., as R increases for a given N), more channels are required to guarantee collision-free channels to users since the interference range (re-use distance) is increased. However, for a given R, the FSMA (GC) scheme becomes less (more) efficient as the network congestion increases (increasing N).

Next, we plot the allocation efficiency of each scheme for a network of N=200 as a function of Δ by varying R. The results are shown in the LHS of Fig. 4, alongside the performance obtained with FDMA ($\frac{L_{FDMA}}{N}$=1 independent of Δ). We note that FSMA can achieve better allocation efficiency than FDMA when the network is *sparsely* connected.

B. Performance sensitivity to topology changes

Next, we evaluate the performance sensitivity of GC to topology changes. We generate an initial topology with N=200 and R=0.3 and assign channels using GC according to this topology. We induce topology changes by swapping the locations of j randomly selected pairs of users within the bounds of (N, Δ) of the initial topology. For each value of j, we average the proportion of users assigned interference-free channels

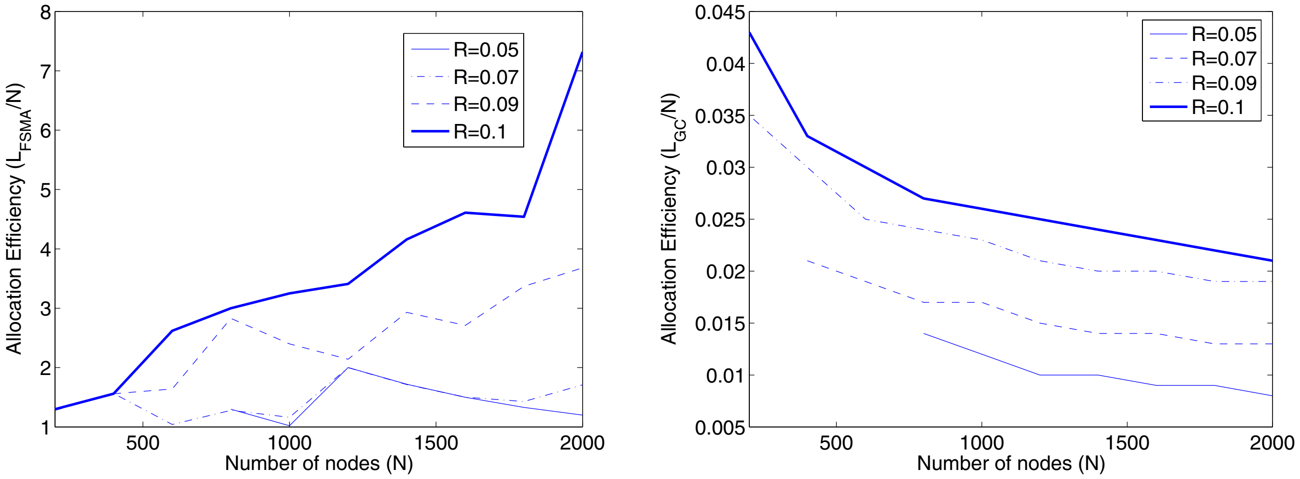


Fig. 3. Allocation efficiency vs number of nodes for the (left) FSMA and (right) GC schemes for various transmission ranges, *R*.

over 10 sets of initial topologies, and the results are plotted in the RHS of Fig. 4.

We observe that while FSMA guarantees collision-free channel(s) to each user regardless of the induced topology changes, the likelihood of maintaining such a guarantee with the GC scheme reduces quadratically as the level of topology change is increased.

V. DISCUSSION

A. Implementation issues for FSMA

According to Section III-B, FSMA assigns channels to each user using *limited* network topology information specified by (N, Δ). We assume that each user device is preloaded with reasonable values of (N, Δ) and is indexed by an identifier i chosen randomly in $[1, N]$. We can define a set-up phase prior to each data transmission phase, where each user broadcasts its identifier on the CSCC and re-computes it if more than one user shares the same identifier. Each user computes the unique polynomial according to its identifier based on the FSMA protocol, which determines its channel assignment. In addition, to ensure that the current network topology satisfies (N, Δ), these parameters are refreshed during the set-up phase.

Although each user is guaranteed at least one collision-free channel, a change in topology due to node mobility may result in collision on the selected channel. In this case, the affected user can simply re-select a collision-free channel(s) amongst the assigned channel set without the need to refresh the spectrum allocation for the whole network as needed in the GC scheme.

B. Performance enhancements for FSMA and GC

Since the introduction of TSMA in [10], a variant of the original scheme that maximizes the network throughput has been presented in [11]. A (recursive) generalization of the scheme in [10] has been presented in [12]. It has also been shown in [13] that the throughput of topology-transparent scheduling schemes can be enhanced by transmitting (with a given probability) in slots that are not assigned for transmission. These enhancements may be extended in the frequency domain to study performance tradeoffs for the FSMA protocol. In addition, if we express Δ in terms of N [15], the asymptotic performance of FSMA in terms of network capacity can be improved with user mobility [16]. Finally, it has been shown in [14] that all the schemes in this family can be represented by orthogonal arrays. This relaxes the constraint that q has to be a power of a prime number, and can result in a more allocation-efficient channel assignment.

Local bargaining approaches have been proposed in [17] to adapt the topology-optimized GC allocation to topological changes. Essentially, users affected by mobility events self-organize into bargaining groups and adapt their spectrum assignment to approximate a new optimal assignment. Results from extensive simulations indicate that the proposed bargaining performs similarly to the GC solution but with significantly reduced algorithm complexity. It would be interesting to compare the performance of local bargaining with FSMA for a mobile ad-hoc network.

C. User and spectrum heterogeneity

In the current study, we assumed both user- and spectrum-homogeneity, i.e., all users have the same QoS demands and spectrum availability is spatially-invariant and static during spectrum allocation. In reality, users may be running different applications (e.g., video streaming vs web browsing) with different bandwidth requirements. Also, in a mixed spectrum regime, spectrum availability is usually both time and location-dependent due to the presence and activity of licensed users.

User heterogeneity may be addressed by the FSMA scheme by assigning j unique identifiers to a user with bandwidth requirement of j channels. In this way, the user will be assigned jq^2 channels amongst which at least j channels will be collision-free with high probability.

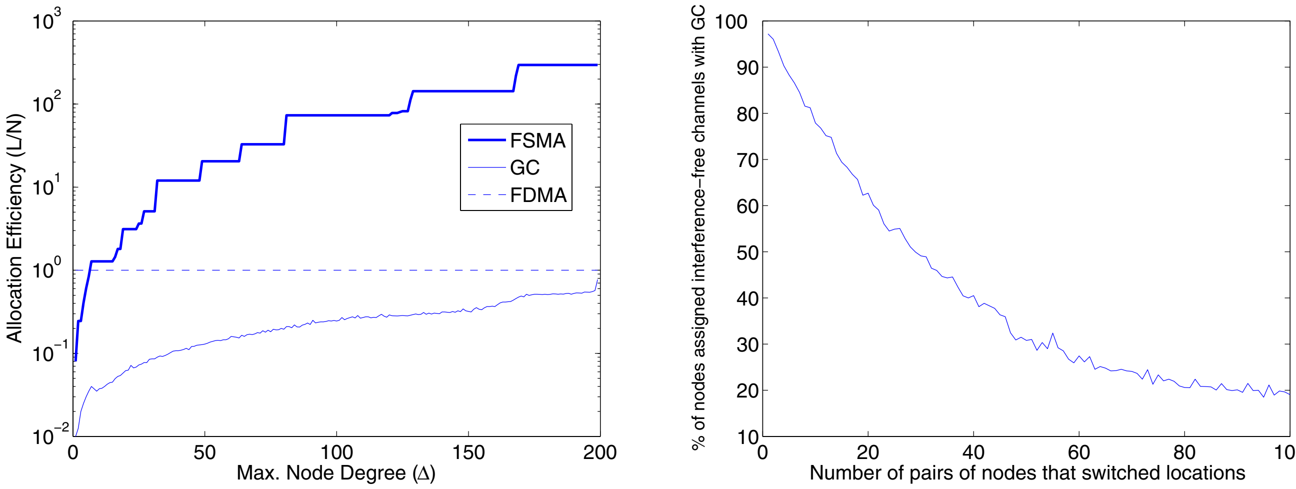


Fig. 4. (Left) Allocation efficiency vs maximum node degree for the FSMA and GC schemes and (right) Performance degradation for the GC scheme due to topology changes.

However, incorporating spectrum heterogeneity in the FSMA scheme is less straightforward. Although user *i* is guaranteed at least one collision-free channel, they may not be accessible by user *i* although the same channel(s) may be accessible by another user *j*. To reduce the resulting throughput degradation, users may periodically update their identifiers on the CSCC during the set-up phase if (a) they are non-unique (see Section V-A) or (b) no collision-free channel is detected due to spectrum heterogeneity.

VI. CONCLUSIONS

With the advent of cognitive radio (CR) technology, a mixed spectrum regime enables more efficient spectrum utilization by letting unlicensed users sense and utilize available spectrum opportunistically without interfering with licensed users. Recently, graph-coloring models have been used to produce a fair, efficient and optimal spectrum assignment. However, this assignment needs to be refreshed whenever topology changes, which can incur significant signaling traffic, consuming valuable resources.

Hence, we propose a frequency-spread multiple access (FSMA) scheme that constructs a channel assignment based solely on the maximum number of nodes, N and maximum node degree, Δ. This assignment guarantees each user at least one collision-free channel for any topology that satisfies (N, Δ), i.e., it is topology-transparent. Numerical results suggest that the FSMA scheme is suited for opportunistic spectrum access by CR-enabled unlicensed users deployed in a sparsely-connected, low density mobile ad-hoc network.

REFERENCES

[1] A. Petrin and P. G. Steffes, “Analysis and comparison of spectrum measurements performed in urban and rural areas to determine the total amount of spectrum usage,” *Proc. of the ISART*, March 2005.
[2] W. Lehr and J. Crowcroft, “Managing shared access to a spectrum commons,” *Proc. of the IEEE DySPAN*, pp. 420–444, November 2005.
[3] J. M. III, “Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio,” Ph.D. dissertation, KTH Royal Institute of Technology, 2000.
[4] S. Haykin, “Cognitive Radio: Brain-Empowered Wireless Communications,” *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, February 2005.
[5] J. Neel, J. Reed, and A. MacKenzie, “Cognitive radio network performance analysis,” *Cognitive Radio Technology*, August 2006.
[6] C. Peng, H. Zheng, and B. Zhao, “Utilization and fairness in spectrum assignment for opportunistic spectrum access,” *Mobile Networks and Applications*, vol. 11, no. 4, pp. 555–576, August 2006.
[7] N. C. Ericsson, S. Falahati, A. Ahlen, and A. Svensson, “Scheduling and Adaptive Transmission for the Downlink in 4G Systems,” *Proc. of the IEEE DySPAN*, pp. 251–258, November 2005.
[8] J. Bater, H. P. Tan, K. Brown, and L. Doyle, “A negotiated etiquette for dissimilar commons wireless systems,” *Submitted*, February 2007, available at http://www.cs.tcd.ie/HweePink.Tan/publications.html.
[9] S. Ramanathan, “A unified framework and algorithm for channel assignment in wireless networks,” *Wireless Networks*, vol. 5, no. 2, pp. 81–94, March 1999.
[10] I. Chlamtac and A. Farago, “Making transmission schedules immune to topology changes in multi-hop packet radio networks,” *IEEE/ACM Transactions on Networking*, vol. 2, no. 1, pp. 23–29, February 1994.
[11] J. H. Lu and V. O. K. Li, “An optimal topology-transparent scheduling method in multihop packet radio networks,” *IEEE/ACM Transactions on Networking*, vol. 6, no. 3, pp. 298–306, June 1998.
[12] I. Chlamtac, A. Farago, and H. Zhang, “Time-spread multiple access (TSMA) protocols for multihop mobile radio networks,” *IEEE/ACM Transactions on Networking*, vol. 5, no. 6, pp. 804–812, December 1997.
[13] K. Oikonomou and I. Stavrakakis, “Analysis of a probabilistic topology-unaware TDMA MAC policy for ad hoc networks,” *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 7, pp. 1286–1300, September 2004.
[14] V. R. Syrotiuk, C. J. Colbourn, and A. C. H. Ling, “Topology-transparent scheduling for MANETs using orthogonal arrays,” *Proc. of DIALM-POMC*, 2003.
[15] M. D. Penrose, *Random Geometric Graphs*. Oxford University Press, 2003.
[16] D. Miorandi, H. P. Tan, and M. Zorzi, “Ad hoc networks with topology-transparent scheduling schemes,” *Proc. of the WiOpt*, April 2006.
[17] L. Cao and H. Zheng, “Distributed spectrum allocation via local bargaining,” *Proc. of the IEEE SECON*, pp. 475–486, September 2005.