Chapter 10

Channel Assignment in Wireless Mobile Ad hoc Networks

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Contents

Due to the tremendous growth of the mobile ad hoc networks (MANETs), the efficient use of the scarce bandwidth allocated to the wireless communications is mandatory. In current wireless networks, a fixed spectrum assignment strategy is used to regulate the radio systems. In this strategy, the whole radio spectrum is subdivided into a fixed number of radio ranges, each exclusively assigned to a specific user. Such a spectrum assignment strategy leads to an undesirable condition under which some systems use only a small portion of the allocated spectrum while the others have very serious spectrum insufficiency. In addition to the current inefficient channel division policies, the channel interferences caused by the unconstrained simultaneous transmissions are the main origin of the problems with the radio spectrum assignment techniques. Cognitive radio is a highly potential technology to address the spectrum scarcity challenges in wireless ad hoc networks. This technology is the future trend of the MANETs in the field of radio spectrum management. The aim of a channel assignment scheme is to assign a minimum number of channels to the radio nodes in such a way that no interference happens. Although a MANET does not have the infrastructure of the base stations, the channel assignment in these networks can be efficiently conducted in a way very similar to that in infrastructure-based cellular systems, specifically when the network is clustered. This chapter aims to exhibit the current status of the channel assignment in MANET and the problems of the existing techniques by providing an in-depth survey of the most recent channel assignment protocols designed and developed for mobile wireless ad hoc networks. In this chapter, depending on the nature of ad hoc environments, the channel assignment schemes are generally categorized as contention-free and contention-based channel assignment schemes. Contention-free schemes are further subdivided into fixed and on-demand channel assignment (ODCA) schemes as the ad hoc networks require. This chapter summarizes the key design issues, objectives, and performances of each category and argues that due to the explosive growth of using mobile devices and ad hoc networks and the scarceness of the channel bandwidth in ad hoc networks, cognitive radios and intelligent bandwidth allocation schemes are the future trends of the MANET researchers to design efficient radio channel assignment protocols.

10.1 Introduction

Dynamic network topology changes; network mobility; severe constraints on network resources such as communication channel bandwidth, processing power, and battery life; and the lack of a fixed infrastructure or centralized administration are the major challenging issues from which the ad hoc networking protocols suffer, while the traditional networking does not consider them. In spite of the essential differences between the traditional and wireless mobile ad hoc networking, the channel assignment schemes reported in literature show that the protocols tailored for wired or cellular networks are also employed in MANET environments. In current wireless networks, the radio spectrum is partitioned into a fixed number of radios each of the same range or the channel bandwidth is evenly allocated to different users. This significantly degrades the channel utilization and network performance since different users have different requirements and so need different portions of the channel. Recent advances in wireless communication technology have provided an opportunity to develop a new approach of intelligent or cognitive radios in which the radio frequency spectrum can be adaptively distributed among the users proportional to their needs. In other words, the cognitive radio is an emergent paradigm to address the spectrum allocation strategy issues in wireless networks in which the wireless nodes are capable of changing their transmission or reception parameters to communicate efficiently without interference. A cognitive radio system supports a very dynamic medium access control (MAC) layer adaptation based on the active monitoring of available channel bandwidth. The following are the main functions of a cognitive radio [1]:

1. Exploring the unused ranges of the radio spectrum and sharing them with the other users avoiding interference and collision.
2. Selecting the best available spectrum to meet the system constraints and user requirements.
3. Supporting the user connection requests even if it exchanges the frequency of operation.
4. Providing the fair collision-free spectrum scheduling method.

However, cognitive radio is still in the very early stage of the research and development, and certainly will be the future trend of wireless ad hoc networking [1,2].

In wireless ad hoc networks, bandwidth is a scarce resource. The tremendous growth of wireless ad hoc networks requires an efficient use of the scarce bandwidth (radio spectrum) allocated to the wireless communications. However, the main difficulty against the efficient use of the bandwidth arises from interferences, caused by unconstrained simultaneous transmissions, which result in damaged communications that need to be retransmitted, leading to a higher cost of the service. Indeed, the aim of channel assignment is to assign a required number of channels to each host such that efficient bandwidth utilization is provided and interference effects are minimized. Two sorts of interferences must be avoided by an effective channel assignment algorithm. The first one occurs when a host simultaneously transmits and receives signals over the same channel, and the second one occurs when a node simultaneously receives more than one signal over the same channel. To prevent the first group of interferences, two hosts can be assigned the same channel if and only if none of them is within the transmission range of the other. Similarly, to prevent the second group of interferences, two hosts can be assigned the same channel if and only if by no means another host is located in the intersection of their transmission ranges. Interferences can be eliminated (or at least reduced) by means of suitable channel assignment schemes. Indeed, co-channel interference caused by channel reuse is one of the most critical factors on the overall system capacity in wireless networks. Channel assignment schemes partition the given bandwidth into a set of disjoint channels that can be used simultaneously by the hosts while maintaining acceptable radio signals. The purpose of channel assignment algorithms is to assign the channels to the hosts in such a way that the co-channel reuse distance and channel separation constraints are verified as well as the difference between the highest and lowest channels assigned is kept as small as possible. By taking advantage of the physical characteristics of the radio environment, the same channel can be reused by two or more hosts at the same time without interferences (co-channel stations), provided that the hosts are spaced sufficiently apart. The minimum distance at which co-channels can be reused with no interferences is called co-channel reuse distance. The interference phenomena may be so strong that even different channels used at near hosts may interfere if the channels are too close [3]. Figure 10.1 illustratively represents the concepts of the co-channel and co-channel reuse distance.

The conflict-free channel assignment problem is equivalent to the vertex coloring of a special class of geometric graphs, which is an NP-hard problem in graph theory. The conflict-free channel assignment problem seeks an assignment of the fewest channels to a given set of radio nodes with specified transmission ranges without any interference. It is a classic and fundamental problem in wireless ad hoc networks. It is shown that the channel assignment problem is NP-hard even if all the nodes are located in a plane and have the same transmission radii [3]. Since perfect filters are not available, interference between the close frequencies is a serious problem, which can be handled either by adding guard frequencies between adjacent channels or by imposing channel

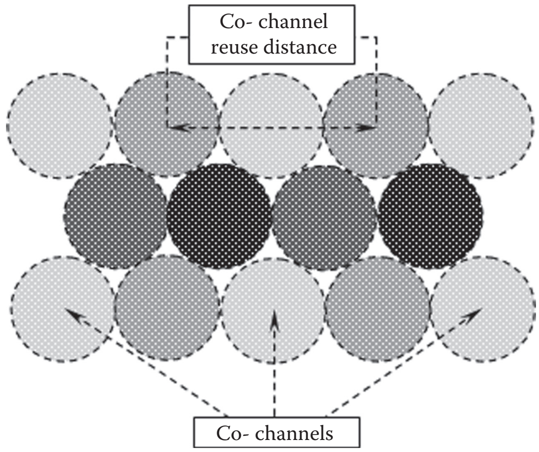

Figure 10.1 Co-channel and co-channel reuse distance.

separation. In the latter approach, the channels assigned to the near hosts must be separated by a gap on the radio spectrum—counted in a certain number of channels—which is inversely proportional to the distance between the hosts [4].

Roughly speaking, channel assignment schemes in wireless ad hoc networks are generally classified into fixed assignment, on-demand assignment, and contention-access algorithms. In fixed assignment, as the name implies, the channels are nominally assigned to the hosts in advance according to the predetermined estimated traffic intensity. In fixed assignment approach, the further transmission requirements are not taken into consideration. In on-demand assignment, channels are dynamically assigned as the calls arrive. Therefore, on-demand assignment is also called dynamic channel assignment. The dynamic channel assignment schemes schedule the channel access based on the demand of the hosts for packet transmission. The latter approach makes ad hoc environments more efficient, particularly if the traffic distribution is unknown or changes with time. On the contrary, the on-demand assignment algorithms are generally time-consuming and require more complex control. In both fixed and on-demand (dynamic) channel assignment algorithms, the MAC algorithms are collision-free. Various extensions or combinations of the above two schemes have been discussed in the literature. These channel assignment schemes are also referred to as contention-free approaches, since the hosts do not compete to seize the channel. The third class of the channel assignment algorithms comprises contention-access (or random access) algorithms, in which the hosts contend for channel access, and the hosts that lose it try again later. Since the collisions are not prohibited by the contention-access algorithms, they require a method for detecting and recovering the collisions. The fixed channel assignment (FCA) approach is the simplest off-line allocation scheme that outperforms the other schemes under uniform and heavy traffic loads. Furthermore, FCA problems can serve as bounds for the performance of the other schemes. For these reasons, FCA schemes constitute a significant research subject for the operations research, artificial intelligence, and mobile communication fields [3]. Frequency division multiple access (FDMA) [5], code division multiple access (CDMA) [6], and time division multiple access (TDMA) [7] schemes are some fixed assignment MAC layer protocols. Among the controlled access MAC protocols, TDMA is the most commonly used in wireless ad hoc networks. Combinations of FDMA and CDMA schemes with TDMA have been also proposed for ad hoc networks in the literature [8]. Polling [9], trunking [10], and reservation

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[11] are some well-known MAC layer protocols for supporting on-demand assignment approach. ALOHA [12] and carrier sense multiple access (CSMA) [13] are two famous medium access protocols proposed for wireless ad hoc networks.

This chapter presents a new classification of the channel assignment schemes for MANET, in which the allocation strategies are classified in two main categories: contention-free and contention-based channel assignment schemes. This chapter studies and compares the most recent effective schemes of each category, with the emphasis on the key design issues, objectives, performances, and costs. The rest of this chapter is organized as follows. The channel assignment problem is defined in Section 10.2. Section 10.3 presents a new classification of the channel assignment schemes and gives an in-depth overview of the well-known channel allocation strategies based on the proposed classification. Section 10.4 concludes the paper.

10.2 Channel Assignment Problem

In wireless communication systems, the radio spectrum is a limited resource. However, the efficient use of available channels has been shown to improve the system capacity. The role of a channel assignment scheme is to allocate channels to the users in such a way as to minimize call blocking or call dropping probabilities and also to maximize the quality of service (QoS). The channel assignment problem is an NP-hard problem that can be modeled as an appropriate bandwidth multicoloring problem. The channel assignment problem aims at finding an assignment of the fewest channels to a given set of radio nodes with specified transmission ranges without any interference. An efficient channel assignment scheme in a multihop ad hoc network should not only guarantee successful data transmissions without any interference but also enhance the channel spatial reuse to maximize the system throughput. In this section, the channel assignment problem in ad hoc networks is described in detail.

Definition 1.1: A wireless ad hoc network can be modeled as an undirected graph $G < V, E >$, where the vertex set V represents the individual hosts and an edge connects two hosts if the corresponding hosts are within the transmission range of each other.

Definition 1.2: The demand vector $\Psi = \{\psi_i \mid v_i \in V\}$ is a function Ψ: $V \rightarrow \bullet$, where ψ_i is the required number of connections that must be simultaneously supported for host H_i.

Definition 1.3: The channel separation vector $\Lambda = \{\lambda_{ij} \mid \forall e_{i,j} \in E\}$ is a function Λ: $E \rightarrow \bullet$, where $\lambda_{i,j}$ denotes the minimum (valid) distance between the channels assigned to host H_i and H_j to avoid interference.

Definition 1.4: The channel assignment problem can be formally modeled by a quintuple $< G, \Psi, \Lambda, \mathbb{C}, \mathbb{F} >$, where $G \langle V, E \rangle$ denotes an undirected graph representing the wireless ad hoc network topology whose vertices in V correspond to the hosts and edges in E correspond to the pairs of hosts that can hear each other's transmission; $\Psi = \{\psi_i \mid v_i \in V\}$ denotes the demand vector associated with the vertex set V; $\Lambda = \{\lambda_{i,j} \mid \forall e_{i,j} \in E\}$ denotes the channel separation vector (or weight constraints) imposed to the edges of graph G; and $\mathbb{C}$ denotes the channel set. The channel assignment problem is to find a function $\mathbb{F}$: $V \rightarrow 2^{\mathbb{C}}$ from the vertex set to the channel set such that

$$|\mathbb{F}(v_i)| = \psi_i \text{ for all } v_i \in V,$$
$$\mathbb{F}(v_i) \cap \mathbb{F}(v_j) = \varnothing \text{ for all } e_{(i,j)} \in E, \text{ and}$$
$$|c_i - c_j| \geq \lambda_{i,j} \text{ for all } e_{(i,j)} \in E,\ c_i \in \mathbb{F}(v_i), \text{ and } c_j \in \mathbb{F}(v_j).$$

From the above definition, it can be seen that the channel assignment problem can be modeled as an appropriate bandwidth multicoloring problem. Each channel assignment algorithm aims at finding an assignment function $\mathbb{F}$. A channel assignment algorithm is optimal if it minimizes the number of channels assigned to the hosts.

10.3 Channel Assignment Schemes

Optimal channel assignment in an arbitrary wireless ad hoc backbone is an NP-hard problem (similar to the graph coloring problem). An optimal channel assignment algorithm looks for finding an allocation strategy that maximizes the channel reuse without violating the constraints. Such an optimal channel strategy minimizes the blocking rate. The constraints of the channel assignment can be classified into three categories: first, the channel constraint that specifies the number of available channels (frequencies) in the radio spectrum. This constraint is imposed by the national and international regulations; second, the traffic constraint that specifies the minimum number of frequencies required by each host; and third, the interference constraint that is further classified as the co-channel constraint and the adjacent channel constraint. The co-channel constraint states that the same channel cannot be assigned to certain pairs of wireless hosts simultaneously, and the adjacent channel constraint states that the adjacent channels in the frequency domain cannot be assigned to the adjacent wireless hosts at the same time. As described earlier, the existing channel assignment schemes in the literature are mostly heuristic based. These schemes can be classified as the contention-free (FCA schemes, ODCA schemes) and contention-based channel assignment schemes. Figure 10.2 shows the classification of channel assignment schemes presented in this chapter. In the remaining of this chapter, the above-mentioned classification of the channel assignment schemes is described in more detail and the existing channel assignment schemes are briefly discussed in each class.

10.3.1 Fixed Channel Assignment Schemes

The FCA approach is the simplest off-line channel allocation scheme in which the channels are assigned to the hosts either permanently or for a long time interval. In an FCA strategy, each host is allocated a predetermined set of channels. These schemes do not consider the further variations in communication requirements. This makes the fixed assignment schemes often the easiest to implement, but also the most inflexible in response to the changing network conditions.

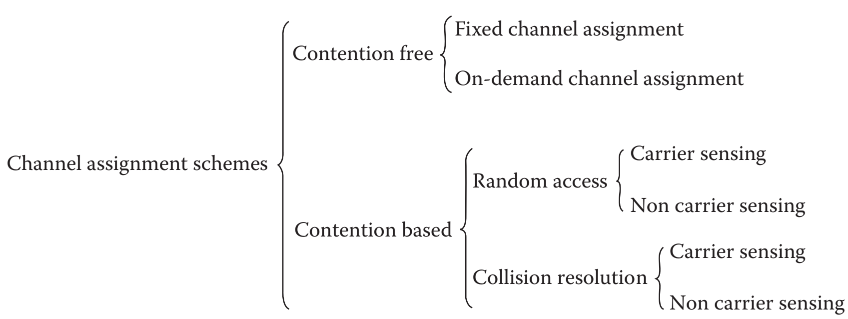

Figure 10.2 Classification of channel assignment schemes.

This characteristic is a large disadvantage for wireless ad hoc networks due to their ad hoc, self-organizing, and self-maintaining nature. Therefore, FCA schemes are rarely proposed for ad hoc networks. FCA protocols assure the hosts that their transmitting messages will not collide with the messages from the other hosts. That is, in FCA schemes the MAC algorithms are collision-free. TDMA, FDMA, and CDMA are typical protocols that belong to this class of channel assignment schemes. The following is a brief review of the most popular FCA protocols in the MAC layer.

10.3.1.1 Time Division Multiple Access

In the TDMA scheme, a single channel is time-shared. That is, the use of the channel is divided among several hosts by allowing each host to access the channel periodically, but only for a small period of time referred to as time slot. A set of such periodically repeating time slots is known as the TDMA frame. During a time slot, the entire bandwidth is available and then the host must relinquish the channel. A given host may be assigned more than one time slot in each frame. Since the channel is available only to one of the hosts at a (fraction of) time, TDMA is a collision-free scheme. Difficulties with TDMA largely center on the problem of synchronizing a number of independent hosts. To cope with this problem a perfect synchronization between the hosts is required, and a guard band (or guard interval) is proposed as a solution to relieve the impact of synchronization errors, clock drift during the slot, and differences in propagation delay between the hosts. Indeed, a guard band is a period of time during which the channel is assigned to no host. Due to the small size of the time slots, guard bands results in a significant overhead for the system [14]. Although the TDMA scheme is essentially a half-duplex mechanism in which only one of the two communicating hosts is able to transmit at a time, the small duration of the time slots gives the illusion of a two-way simultaneous communication. Among the controlled access MAC protocols, TDMA is the most commonly used in wireless ad hoc networks. Figure 10.3 shows the structure of a TDMA scheme.

In [14], a dynamic TDMA frame length expansion and recovery method called dynamic frame length channel assignment (DFLCA) was proposed. The proposed method, taking advantage of the channel spatial reuse concept, efficiently utilizes the channel bandwidth by assigning the unused slots to the new nodes as well as enlarging the frame length when the number of slots in the frame is insufficient to support the nodes. DFLCA controls the expansion and recovery of unassigned time slots by dynamically changing the frame length according to the traffic load and the number of mobile nodes in the contention area. For this purpose, the nodes are allowed to release the unused slots and shrink their channel tables when the frame is inefficient. An adaptive time slot

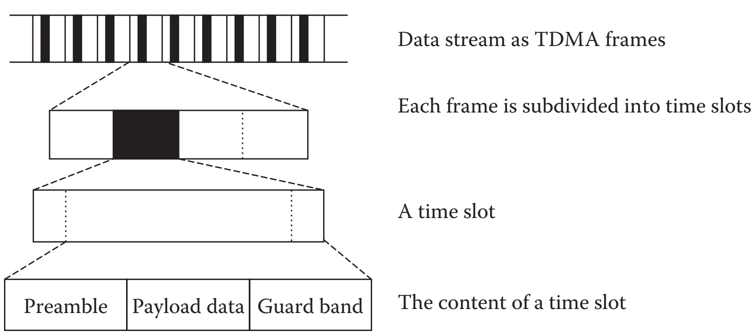

Figure 10.3 A simple structure of a TDMA scheme.

assignment algorithm was proposed in [15] for variable bandwidth switching systems. Kim and Kim [15] claim that the amount of change between the consecutive switching configurations is small, and so it is unnecessary to schedule all traffic for each configuration. The adaptive time slot assignment algorithm proposed in [15] employs such an idea and reduces the computational burden of finding switching configurations. Mo and Chew [16] proposed a new TDMA scheme in which the time slot duration is not fixed and vary with time for each user. In this method, the time slot duration is independently adjusted for each user proportional to its transmission requirements. In [16], it is shown that the proposed variable frame length TDMA scheme improves the bandwidth utilization. Xin et al. [17] proposed a simple and efficient time allocation scheme called MES-ESRPT for delay-sensitive VBR traffic in accordance with IEEE 802.15.3 standard. In this scheme, the coordinator allocates one MCTA (management channel time allocation) for each stream, which is the process of communication at the end of superframe. During the MCTA period, each transmitter should report the fragment number of the first and remainder MAC service data unit to the coordinator. In the next superframe, the coordinator allocates the channel time based on these by a shortest remaining processing time technique.

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Akbari Torkestani and Meybodi [1] proposed a cognitive radio for clustered wireless MANETs based on learning automata. In this method, the wireless hosts are grouped into clusters and each cluster head takes the responsibility of a collision-free channel access scheduling within the cluster. That is, Akbari Torkestani and Meybodi [1] design an adaptive TDMA scheme for slot assignment in each cluster of a clustered ad hoc network. To do this, each cluster head is equipped with a learning automaton whose action set includes an action for each of its cluster members. At each stage, cluster head randomly chooses one of its actions according to its action probability vector. Then, the cluster member corresponding to the selected action is permitted to transmit its packets during the current time slot. If the selected member has a packet to transmit, the cluster head rewards the selected action and penalizes it otherwise. As the proposed algorithm proceeds, the probability of choosing a given host converges to the proportion of time it has a packet to transmit. This probability specifies that the fraction of TDMA frame must be assigned to the host. Akbari Torkestani and Meybodi [1] argue that the proposed channel assignment scheme performs well under conditions that the input traffic parameters are unknown and time variable.

10.3.1.2 Frequency Division Multiple Access

In an FDMA scheme, the available spectrum is divided into a number of equal frequency channels, and one or more channel is assigned to each host for its own exclusive use. These frequency subchannels are sufficiently separated (via guard bands) to prevent co-channel interference. A significant portion of the effective channel bandwidth is usually wasted by the guard bands. FDMA is able to accommodate simultaneous packet transmissions (one on each subchannel) without collision. To receive packets from a particular sender, the destination host must be listening on the proper subchannel. Assigning frequencies for all potential users of the spectrum, when far fewer users will be present most of the time, leads to the poor spectrum utilization. These results in a significant fraction of the available spectrum will be unoccupied. While this is a minor or nonexistent problem for some services such as broadcasting that occupy the assigned frequencies almost continuously, it is a significant problem for other services, such as public safety communications that seldom require use of their frequencies. The FDMA scheme is shown in Figure 10.4.

OFDMA (orthogonal frequency division multiple access) is a multiuser version of the popular orthogonal frequency division multiplexing (OFDM) digital modulation scheme. OFDM is a

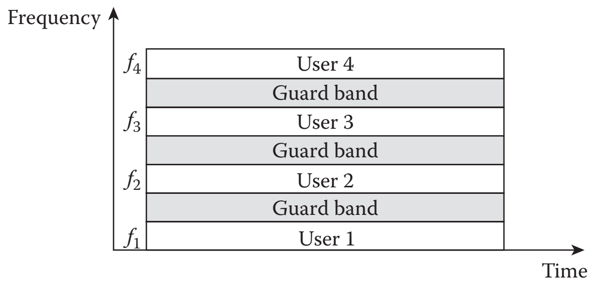

Figure 10.4 The FDMA scheme.

frequency division multiplexing scheme utilized as a digital multicarrier modulation method. In OFDM, the subcarrier frequencies are selected so that they are orthogonal to each other. By this, the cross talk between the subchannels does not occur and so intercarrier guard bands are not required. In this method, a large number of closely spaced orthogonal subcarriers are exploited to carry the data. OFDM divides the data into several data streams, each sending over a subcarrier. In OFDM, each subcarrier is modulated by using modulation. Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users. This allows simultaneous low data rate transmission from several users. Heikkinen and Hottinen [18] designed a distributed subchannel allocation scheme for an OFMDA system. To this end, they first showed that the centralized subchannel assignment problem in a two-hop multiuser relay network can be formulated as a three-dimensional assignment problem. The three-dimensional assignment problem is known to be NP-hard. Therefore, the centralized solutions perform well only in small-sized networks, and so the distributed subchannel allocation seems to be a promising approach. The distributed subchannel allocation was studied by using the noncooperative game theory. In the proposed scheme, a sequential greedy channel allocation mechanism (sequential game model) is used to select the first link that implies a good performance (without pricing) in a relay network relative to a per-hop optimal assignment. An auction-based game model is also used so as to do the per-hop optimal assignment, which imposes an additional updating price to the system. Therefore, there is a trade-off between efficiency and signaling costs in the proposed distributed resource allocation scheme [18]. A joint channel assignment, routing, and scheduling scheme called JARS was proposed in [19] for wireless ad hoc networks in which the nodes are equipped with multiple radios. JARS shows the benefits of integrating the routing, scheduling, and channel assignment procedures, which is achieved by using the multiple radios at each node to transmit and receive simultaneously on different orthogonal channels.

AU: Please confirm whether the edits made to the sentence "An auction-based game model…" convey the intended meaning.

San Jose-Revuelta [20] proposed a genetic algorithm-based heuristic to solve the frequency reuse problem in cellular radio communication systems. The proposed algorithm aims to minimize the required number of channels (or the minimum theoretical number of channels) to handle a certain number of connections. In this technique, the probabilities of mutation and crossover are on-line adjusted based on the diversity of the population. Huang et al. [21] proposed a new 802.11-like multichannel MAC protocol, called self-adjustable multichannel MAC (SAM-MAC). In the proposed scheme, one common channel and two half-duplex transceivers are used for each network node. Due to the overhead caused by the channel assignment process, the current 802.11-like schemes of the multichannel MAC are not able to efficiently use the available bandwidth of the multiple channels. On different channels, SAM-MAC uses a self-adjustment mechanism so as to do allocation and reallocation of the channels and to balance the traffic. Huang et al. [21] claim that due to less contention in common channel and smaller channel assignment overhead, their protocol has a higher throughput in comparison with the previous approaches.

10.3.1.3 Code Division Multiple Access

A CDMA is a spread spectrum multiple access scheme in which a transmitter spreads the information signal in a wide frequency band by using a spreading code. A receiver uses the same code to retrieve the received signal as well. This approach provides multiple accesses by allowing the simultaneous transmission by different nodes and is employed to reuse the bandwidth and to reduce the interferences. In the CDMA scheme, each group of nodes can be given a shared code. Many codes occupy the same channel, but only nodes associated with a particular code can understand each other. If the codes are orthogonal, or nearly so, so that any bit errors caused by co-channel interference can be handled by forward error correction, multiple nodes may occupy the same band. In the spread spectrum CDMA system, simultaneous transmissions can be isolated by using different spreading codes. Therefore, a unique code must be assigned to each transmitter and the receiver should be set to the same code as the designated transmitter. Assigning a unique code to each transmitter, which is called the code assignment problem, is a trivial problem if the network size is small. But when we employ the CDMA scheme in a large multihop ad hoc network, the code assignment becomes an intractable problem. It is impossible to assign a unique code to each transmitter or receiver since the number of available codes is limited. Therefore, the concept of the code spatial reuse seems to be promising. This means that two or more nonneighboring hosts can be assigned the same code if they are sufficiently separated. An interference-free code assignment problem is similar to the vertex coloring problem in which the neighboring nodes (hosts) are refrained from choosing the same colors (codes). Figure 10.5 provides a good comparison of TDMA, FDMA, and CDMA schemes.

10.3.1.4 Hybrid Multiple Access Scheme

The above-mentioned multiple access schemes can be combined in a single application to improve the network throughput. CDMA/TDMA [8,22], CDMA/FDMA [23], and FDMA/TDMA [24] are three possible hybrid multiple access schemes made of basic multiple access schemes. Among the hybrid multiple access schemes, CDMA/TDMA has received more attention. CDMA/TDMA is a combinational scheme in which the CDMA scheme is overlaid on top of the TDMA. It is a promising approach to solve the code assignment problem in wireless ad hoc networks [8,25]. In the CDMA/TDMA scheme, the networks must be initially partitioned into several groups

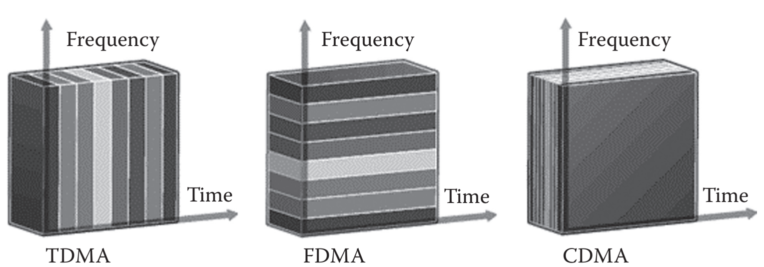

Figure 10.5 TDMA, FDMA, and CDMA schemes.

(clusters). In this scheme, the collision-free intracluster communications are organized by the cluster heads using a TDMA scheme, and a CDMA scheme is overlaid on the TDMA to organize the interference-free intercluster communications. A CDMA/TDMA scheme reduces the required number of codes to the number of clusters, which is significantly less than that of a CDMA scheme. To design a CDMA/TDMA scheme for clustered wireless ad hoc networks, we encounter the following three intricate problems. The first problem is dividing the network into a minimum number of nonoverlapping clusters. The second problem is to assign an interference-free code to each cluster considering the concept of the maximum code spatial reuse. That is, this problem is assigning the minimum number of codes to the clusters so that no two neighboring clusters are assigned the same codes. This problem is similar to the graph (vertex) coloring problem in graph theory, which is known to be NP-hard. In CDMA/TDMA networks, the TDMA scheme is used to schedule the intracluster communications. By this scheme, the code assigned to each cluster is divided into several time slots. The third problem we encounter is to assign a proper portion of the code (or TDMA frame) to each cluster member so that the maximum number of connections can be served during a TDMA frame.

Many studies have been carried out on the CDMA/TDMA scheme in cellular networks [26–29], while in ad hoc networks it has not received the attention it deserves. Gerla and Tsai [30] proposed an overlaid CDMA/TDMA channel access scheduling scheme for a clustered multihop wireless network. Gerla and Tsai [30] also proposed a distributed cluster formation algorithm. The cluster heads act as local coordinators to resolve channel scheduling, perform power measurement/control, maintain time division frame synchronization, and enhance the spatial reuse of time slots and codes. Using a CDMA scheme, an interference-free code is assigned to each cluster, and a TDMA scheme is used within the clusters. Richard and Gerla [31] also proposed a CDMA/TDMA-based scheme for multimedia support in a self-organizing multihop mobile network. They introduced a network architecture in which the nodes are organized into nonoverlapping clusters. In this method, the clusters are independently controlled and are dynamically reconfigured as the nodes move. In [31], an interference-free channel access scheduling method is proposed to handle the intercluster communications based on graph coloring problem. Due to the node clustering, the proposed method provides spatial reuse of the bandwidth. Furthermore, the bandwidth can be shared or reserved in a controlled fashion in each cluster. Wu [8] proposed a CDMA/TDMA structure for clustered wireless ad hoc networks. He designed a dynamic channel assignment algorithm called hybrid-DCA to make the best use of available channels by taking advantage of the spatial reuse concept. In this approach, the TDMA scheme is overlaid on top of the CDMA scheme to divide the bandwidth into smaller chunks. The proposed DCA algorithm forms the channel as a particular time slot of a particular code.

Akbari Torkestani and Meybodi [2] designed a learning automata-based dynamic frame length CDMA/TDMA scheme for clustered wireless ad hoc networks with unknown traffic parameters. In the proposed scheme, intracluster communications are scheduled by the cluster head using a TDMA scheme, and a CDMA scheme is overlaid on the TDMA to organize the interference-free intercluster communications. Therefore, to design the proposed scheme, the following three important problems were considered: cluster formation, code assignment (in CDMA scheme), and slot assignment (in TDMA scheme) problems. The authors proposed three learning automata-based algorithms to solve the addressed problems. By the proposed cluster formation algorithm, the network is partitioned into a number of clusters, each with a cluster head and a number of cluster members. Intercluster connections are handled by a CDMA scheme, in which an interference-free code must be assigned to each cluster. To do so, the authors proposed a code assignment algorithm based on the vertex coloring problem in which the neighboring clusters are refrained from choosing the same codes. Intracluster channel access scheduling is based on the TDMA scheme, and the cluster heads are responsible for the collision-free slot assignments within the clusters. In [2], after each cluster is assigned a code, the cluster head divides the code into time slots and assigns them to the cluster members. To optimally assign the time slots, the authors proposed a dynamic frame length slot assignment algorithm in which each cluster member receives a portion of TDMA frame proportional to its traffic load. By the proposed scheme, the authors claim that the following advantages can be achieved. This scheme organizes the channel access in groups and so can be effectively used in scalable multihop ad hoc networks. The number of required codes decreases to at most the number of groups, and exploiting the code spatial reuse concept, it can be minimized. In each group, using the TDMA scheme, a large number of connections can be served in a time-efficient manner. The experimental results show that the channel assignment scheme proposed in [2] significantly outperforms CS-DCA [25] and hybridDCA [8] in terms of number of clusters, code and channel spatial reuse, blocking rate, waiting time for packet transmission, control overhead, and throughput.

Jovanovic and Djordjevic [32] proposed a hybrid multiple access scheme called TFMAC in which the timing feature of TDMA is combined with the multiple channels of FDMA. TFMAC comes from time frequency MAC that exploits the existence of multiple channels and the ability of transceivers to switch between them quickly to increase network throughput. In order to provide conflict-free communication for data packets, TFMAC divides time into a fixed number of time slots and allows each node to use different frequencies within different time slots to send data packets to its neighbors. The slot assignment is accomplished in a distributed way through exchange of a limited number of control messages during the contention slot at the beginning of each time frame. Trifonov et al. [23] proposed a hybrid CDMA/FDMA scheme for 3G mobile communications. The proposed scheme uses a novel adaptive coding approach. In this method, the transmission bandwidth is subdivided into a number of subbands, each allocated to a group of users (FDMA), which transmit in a CDMA fashion. The proposed method exploits an efficient adaptive subband allocation (ASBA) approach. The ASBA has been shown to provide a significant gain in the uncoded system performance as compared with the usual fixed frequency mapping, based on the interleaving of the carriers assigned to different user groups.

As noted earlier, the FCA problem models the task of assigning radio spectrum to a set of hosts on a permanent basis. The formulation of this problem as a combinatorial optimization problem in the beginning of the 1980s led a number of computer scientists and operations research scientists to try and find optimal solutions. Heuristic methods are capable of finding near-optimal solutions in a reasonable computational cost to such a time-consuming problem. An overview of the most basic heuristics for fixed-channel assignment in the literature is the subject of the study in the remaining of this section. Li et al. [33] proposed an evolutionary-dynamic TDMA slot assignment protocol for ad hoc networks. In this slot management method, the frame length and transmission schedule are dynamically updated according to the topology density of network and bandwidth requirement. This protocol allows the transmitter to reserve one or more unscheduled slots from the set of unassigned slots. San Jose-Revuelta [34] proposed a new genetic algorithm with good convergence properties and remarkable low computational load to solve the channel reuse problem. The proposed method tunes up the probabilities of mutation and crossover on the basis of the analysis of the individuals' fitness entropy. The proposed algorithm aims at obtaining a conflict-free channel assignment in such a way that the resulting bandwidth is close to the minimum channel span required for the whole network. Vidyarthi et al. [35] developed an evolutionary strategy that optimizes the channel assignment. The proposed evolutionary strategy approach uses an efficient problem representation as well as an appropriate fitness function. In this approach, a novel way of generating the initial population is proposed that generates a possibly better initial parent. The new method of generating the initial population reduces the number of channels reassignments and therefore yields a faster running time. Smith and Palaniswami [36] apply the neural networks for minimizing the co-channel interference in FCA approaches. They first introduce a new nonlinear integer programming representation to formulate the FCA problem. Then, they propose two different neural networks for solving this problem. The first is an improved Hopfield neural network that resolves the issues of infeasibility and poor solution quality which have plagued the reputation of the Hopfield network. The second approach is a new self-organizing neural network that is able to solve the FCA problem and many other practical optimization problems due to its generalizing ability. Perez et al. [37] proposed a fuzzy-based interference canceller for CDMA schemes. The proposed interference canceller exploits a fuzzy filter to remove the interference signal from the received one.

10.3.2 On-Demand Channel Assignment Schemes

The economic viability of a wireless service is often a strong function of how efficiently it uses the available spectrum [38]. Spectral efficiency, in turn, is greatly affected by the employed channel access method. As mentioned earlier, FCA protocols cannot efficiently allocate the available channels. ODCA protocols attempt to improve on the channel inefficiencies of FCA schemes by reassigning the unused channels to the users, if they need. In ODCA schemes, the channels are not preallocated to any user and dynamically assigned as the calls arrive. Therefore, ODCA is also called DCA. DCA schemes attempt to optimize the system performance by adapting to the traffic variations. Unlike the fixed assignment, in ODCA schemes all the channels can be used by all users as long as the co-channel constraints are satisfied. The benefit of dynamic assignment is the ability to switch an interface to any channel, thereby offering the potential to use many channels with few interfaces. Furthermore, in ODCA schemes, the MCA algorithms are collision-free. However, it should be noted that the ODCA algorithms are generally time-consuming and require more complex control. In the rest of this section, we review the well-known ODCA algorithms proposed in the literature.

10.3.2.1 Polling Scheme

The polling is an ODCA scheme in which a centralized controller queries the hosts, in a cyclic predetermined order, whether they have data to transmit or not. Due to the recent advances in communication systems, some other variations of the polling scheme have also been considered. These variations deal with noncyclic allocation policies, which include random, Markovian, or, more generally, nondeterministic allocation policies. In a polling scheme, controller polls (one by one) the hosts to give them an opportunity to access the medium. The hosts that have no packet to be transmitted (or do not need the channel access) decline, and the other hosts begin the packet transmission upon receiving the query. In polling scheme, the centralized controller is responsible for coordinating the transmissions, and so polling is a collision-free scheme. In this scheme, the entire bandwidth is available for the host that is permitted to transmit data. Although in realistic scenarios, traffic load of the different hosts is not the same, the major drawback of the basic polling scheme is to give the same importance (or equal access to the channel) to all hosts. A prioritized polling system may provide better results. Furthermore, the polling scheme suffers from the substantial overhead caused by the large number of messages generated by the controller to query the communicating hosts. As mentioned earlier, polling is based on a centralized control system. Therefore, in ad hoc networks, due to the lack of fixed infrastructures and centralized administrations, polling cannot be a practical channel assignment policy. Clustering the ad hoc networks in which the network is subdivided into several nonoverlapping groups is a promising approach to solve the above-mentioned problem. In clustered multihop ad hoc networks, the cluster head assumes the role of a centralized controller.

Polling systems have been extensively studied for the last three decades because of the applicability to the computer networks and communication systems. Grillo [39] provided a survey on applications of polling scheme in communication systems. Wang et al. [40] proposed an efficient distributed scheduling algorithm based on a prioritized polling policy for multihop wireless networks. The proposed algorithm maximizes the spatial and time reuse with an interference-based network model. Lye and Seah [41] also studied a priority-based random polling scheme. A QoS supportive adaptive polling scheme was proposed by Lagkas et al. [42] for wireless networks. In this scheme, an access point polls the wireless nodes in order to grant them permission to transmit. The polled node sends its data directly to the destination node. The proposed polling scheme is based on an adaptive algorithm by which the active nodes are polled with a higher probability. This results in a higher throughput and lower packet delays. Yang and Liu [43] also proposed a QoS support bandwidth polling scheme called BBP. In this scheme, to allocate a proper portion of bandwidth to each node, a coordinator defines a framing structure of time slots. A coordinator is allowed to poll a node more than once, and this causes it to allocate a proper number of slots (or a proper bandwidth portion) to each active node. However, in ad hoc networks, due to the lack of centralized coordination, the polling scheme has not received the attention it deserves. Dimitriadis and Pavlidou [44] proposed a polling access scheme for clustered multihop ad hoc networks called two-hop polling (2HP). 2HP is a revised version of the polling scheme tailored for the clustered environments. The authors claim that by this scheme it is possible to utilize intercluster links (distributed gateways) without adding much to the complexity of polling. 2HP changes the medium access by giving more liberty to the non-cluster-head hosts. In clustered networks, the hosts that belong to the different clusters must communicate through the cluster heads. This results in many potent links between the hosts not to be used. In the proposed scheme, the members of the neighboring clusters can directly communicate by the intercluster connections they have in between. Tseng and Chen [45] proposed a priority-based polling scheme with reservation for QoS guarantee in wireless ad hoc networks. The proposed scheme combines the priority-based and randomly addressed polling schemes to guarantee QoS constraints.

10.3.2.2 Reservation Method

The basic idea behind the reservation-based schemes is to set some time slots for carrying reservation messages. Figure 10.6 shows a reservation-based channel access scheme. As the name suggests, reservation methods require a controller device to reserve a communication channel prior to transmission. In this method, the time is subdivided into superframes and each superframe is then further divided into a reservation period and a data-transmission period. The reservation period is also divided into frames, with one frame assigned to each host in the network. During the reservation time frame, the host transmits a code word, indicating whether or not it has message traffic to send, and the number of data transmission slots it requires. All the other hosts do the same in turn. When the controller receives the reservation request, it computes a transmission schedule and announces the schedule to the hosts. At the end of the reservation period, all hosts know which hosts will be transmitting during the data-transmission period. This method avoids the collisions since each host sends only in its assigned time slot. This form of reservation-based methods is not

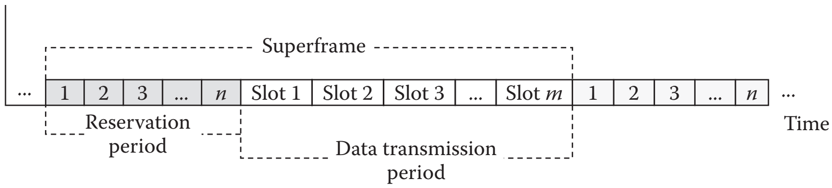

Figure 10.6 A reservation-based channel access scheme.

fair, since there are a finite number of available data-transmission slots and hosts request them in a preferred order. Therefore, the initial hosts (in predefined order) are always able to transmit, while the last ones find slots available only if the other hosts have left some for them. One way to solve this problem is to define an aging value for each host in its reservation code word, which indicates how long it has been waiting for transmission. In this method, each message is assigned a priority on the basis of its aging value. The messages with higher priorities are then selected for transmission during the data-transmission period.

Goodman et al. [11] presented a reservation method called PRMA that uses the concept of packet reservation. PRMA is a reservation protocol with features of TDMA and ALOHA. In PRMA, a star network is assumed. Time is divided into frames, each of which has many numbered slots. The network controller transmits an acknowledgment message at the end of each slot, which identifies that slot as being "reserved" or "unavailable." When a host has message traffic, it uses the ALOHA protocol to contend for an available slot. When the controller successfully receives the message, it replies with a "reserved" acknowledgment message, indicating receipt and indicating that the host has reserved that slot for future frames. The host now has an assigned slot in the frame (similar to TDMA), and so the transmission is collision-free in that slot in all future frames since the other neighboring hosts also detect the acknowledgment message. When the host has completed its traffic, the slot reservation is released by the simple expedient of not transmitting in it. The network controller then transmits an "available" acknowledgment message at the end of the slot.

Hou and Papavassiliou [46] presented a dynamic channel reservation scheme to provide the QoS guarantees in wireless mobile networks. Providing QoS is one of the most critical issues in MANETs. QoS is considered in routing, channel access and call admission control, resource reservation, and mobility management in MANET. Due to frequent topology changes and formation of dynamic connections, improvement of QoS through minimizing the interferences and collisions is a challenging issue in mobile ad hoc networking [47]. The proposed method in [46] is based on a concept called influence curve. The concept of influence curve is defined on the basis of the handoff probabilities [46] and directional factors [46]. The basic idea behind this scheme is that besides the requirements in the current cell, a mobile node exerts some influence on the channel allocation process within the neighboring cells. In [46], it is shown that due to the handoffs, traffics in the various cells are not necessarily independent of each other. That is, when a call enters a cell, not only it does need to consume a channel in the current cell, but the channels of the neighboring cells are probably also affected by this call. Such an influence is greatly related to the moving pattern of the node and can be calculated statistically. Through simulation experiments, the authors show that the proposed reservation scheme outperforms traditional channel reservation methods and can effectively adapt to the real-time network conditions.

Menache and Shimkin [48] presented a distributed channel access control mechanism in which a reservation scheme is applied to efficiently use the shared medium. The proposed technique adopts the virtual carrier sense mechanism of 802.11 (CSMA scheme will be discussed later in this chapter). That is, the channel access scheme proposed in [48] is a carrier sense reservation method. In this scheme, as a mobile station gets ready to transmit data, it first sends an RTS (request to send) control packet including the source, destination, and requested duration of the data transmission period. Then, the base station responds the RTS by sending back a CTS (clear to send) control packet with the same information as above.

10.3.2.3 Trunking

Trunking is a multiple access scheme that dynamically assigns the available logical channels to the communication requests. The earliest trunked systems were wired telephone systems, in which multiple lines between points were installed and calls were routed to a line with available capacity. This greatly increased the reliability of the network, since a single line outage would be unlikely to result in a loss of service, and also improved infrastructure economy, since any peaks in call volume could be rerouted over other, less busy, lines, and every line did not have to be designed for the peak call volume requested over that route. The first wireless systems to employ trunking methods (other than the microwave systems employed by the telephone system itself) were FDMA land-mobile radio (LMR) systems. These systems employed repeaters to provide communication links among mobile devices, normally organized into groups, and between mobile devices and wireline infrastructure such as telephone interconnect. Devices on LMR systems typically have very low average data throughput, but very high peak throughput—the worst-case scenario for channel efficiency using FDMA. To install an FDMA trunking system, the system operator amasses a collection of 5–40 FDMA frequency pairs (inbound/outbound) by using a repeater for each of them. One repeater is designated the control channel, while the others are used for message traffic. When not engaged in sending or receiving message traffic, network devices monitor the outbound control channel. When a device has a message for a particular group, it sends the request on the inbound control channel. The trunking system identifies an available repeater (channel) and transmits a command on the outbound control channel for all devices in the requested group to change to the available channel, where the requesting device transmits and the rest of the group receives [10]. Since a much larger number of users can be served with the existing spectrum allocation, this scheme greatly improves the economics of LMR. In the United States, FDMA trunking has since been expanded into the Associated Public Safety Communications Officials Project 25 Advanced Narrowband Digital Communications standard [49]. Trunking principles can also be applied to TDMA systems. The terrestrial trunked radio (formerly the trans-European trunked radio) (TETRA) standard [50] employs TDMA with four slots per frame. The control frame is the last frame in a series of 18 consecutive frames, called a TETRA "multiframe." Operation is analogous to FDMA trunked systems; mobile devices monitor the (outbound) control frame transmitted by the base station and are assigned communication resources, in the form of identified slots in identified frames, to communicate. TETRA is designed to transmit both voice and data as separate services; the use of TDMA engenders great flexibility in channel access for this purpose, since voice services can be assigned frequent, repetitive slots, while data transfers can be assigned larger blocks of time and interrupted for the more latency-critical voice transmissions.

Lima et al. [51] proposed two adaptive genetic algorithms called GALC and GASC for dynamic channel assignment in mobile communication systems. GALC locks in the channel assigned throughout the call holding time, and GASC switch the assigned call from a channel to another one during the call holding time. The proposed algorithms aim at minimizing the blocking probability of new calls and the dropping probability of handoff calls in channelized systems. To improve the efficiency and the convergence speed of algorithms, a number of mechanisms are added to the canonical genetic algorithm. These mechanisms are adaptive parameters, random immigrants, a greedy policy, a reservoir to assist the initial population, a truncation selection scheme, and a three-point crossover. Wang et al. [52] proposed a genetic channel assignment algorithm to minimize the effects of interferences where the number of available channels is substantially less than the minimum number of channels required for interference-free assignment. The proposed channel assignment algorithm takes advantage of genetic algorithms to minimize the interference between the calls while demands for channels are satisfied. Vidyarthi et al. [35] also proposed an evolutionary channel assignment algorithm that exploits a new method for generating the initial population to reduce the number of channel reassignments.

Tseng et al. [53] considered the channel assignment problem in a MANET that has access to multiple channels. They proposed a new location-aware channel assignment algorithm called GRID-B, which exploits the concept of channel borrowing. Several channel borrowing strategies are proposed to dynamically assign the available channels to the mobile hosts to improve the channel reuse and to resolve the unbalanced traffic loads. The proposed protocols assign channels to mobile hosts based on the location information of mobile hosts that might be available from the positioning device. Wu and Yang [54] proposed a novel channel assignment scheme for improving the channel reuse efficiency. The authors believe that by overhearing the control packets of one-hop neighbors, a host can easily know the channel condition within the range of two-hop neighbors and so can select a suitable transmitting/receiving data channel to form the better reuse pattern. To enhance the probability of forming channel reuse pattern, they propose a back-off counter adjustment scheme such that a host with more channel information can transmit control packets earlier than those with less channel information. Gong et al. [55] presented three distributed channel assignment protocols for multichannel MANETs. They first proposed a new channel assignment protocol called CA-AODV, in which a channel assignment algorithm is combined with the AODV routing protocol. Then, they also presented two extensions to the CA-AODV protocol, namely, the enhanced 2-hop CA-AODV (E2-CA-AODV) protocol and the enhanced k-hop CA-AODV (Ek-CA-AODV) protocol. The proposed protocols combine channel assignment with distributed on-demand routing. In these protocols, the available channels are only assigned to the active nodes. They are shown to require fewer channels and exhibit lower communication, computation, and storage complexity, compared with existing approaches.

Wu et al. [56] proposed a protocol that assigns channels dynamically in an on-demand style. This protocol, called DCA, requires one dedicated channel for control messages and other channels are for data transmission. Each host has two transceivers so that it can listen on both the control channel and the traffic channel simultaneously. DCA follows an "on-demand" style to assign channels to mobile hosts and does not require clock synchronization. This kind of scheme does not perform well when the number of channels is large because all the negotiations are fulfilled on the control channel and too much contention will cause the saturation problem over the control channel. Sallent et al. [57] presented an integrated framework for heterogeneous wireless networks in order to design efficient dynamic and decentralized spectrum and radio management schemes. The proposed framework is defined as a layered model in which the radio resource allocation and spectrum management mechanisms are identified at both the intraoperator and interoperator levels. Such a framework needs to be strongly supported by the multiple radio access technologies and flexible spectrum capabilities. Therefore, it can be fully accomplished solely based on intelligent and cognitive radio as the new generation of radio technology [57]. Sallent et al. [57] propose an on-demand cognitive pilot channel called CPC to enable the radio for decision making and decentralized operation at the mobile terminal side. The authors show the superiority of the proposed on-demand CPC over the broadcast CPC in terms of the delay to retrieve the information.

10.3.3 Contention-Based Channel Assignment Schemes

As we have seen, ODCA protocols can improve the channel efficiency of FCA protocols. However, most ODCA schemes require a centralized coordinator to assign the channels. In many networks, for example, wireless ad hoc networks, such a controller does not exist. Multihop ad hoc networks, in which the network architecture (and even the order of the network) is not known *a priori*, are another difficult application for both FCA and ODCA schemes. To make matters worse, many types of multihop ad hoc networks generate traffic patterns that have a low average message rate, but a high peak rate, a difficult type of traffic pattern for a channel access protocol to support. The solution to this dilemma is the third class of channel assignment schemes: contention (random)-based channel assignment schemes. In these protocols, the hosts contend (compete) among each other for channel access; the hosts that lose access to the channel merely try again later. Contention-based channel access strategies require no coordination among the nodes accessing the channel. They do not exercise any control to determine which communicating node can access the medium next. In these protocols, the colliding nodes back off for a random duration of time before again attempting to access the channel. Furthermore, these strategies do not assign any predictable or scheduled time for any node to transmit. All backlogged nodes must contend to access the transmission medium. If only one neighbor tries its luck, the packet goes through the channel. If two or more neighbors try their luck, these have to compete with each other, and in unlucky cases, for example, due to hidden-terminal situations, a collision might occur, wasting energy of both transmitter and receiver. Collision occurs when more than one node attempts to transmit simultaneously. To deal with collisions, the protocol must include a mechanism to detect collisions and a scheme to schedule colliding packets for subsequent retransmissions. Contention-based protocols were first developed for long radio links and for satellite communications. The ALOHA protocol, also referred to as pure ALOHA, was one of the first such media access protocols. ALOHA simply allows nodes to transmit whenever they have data to transmit. Efforts to improve the performance of pure ALOHA lead to the development of several schemes, including slotted ALOHA, CSMA, carrier sense multiple access with collision detection (CSMA/CD), and carrier sense multiple access with collision avoidance (CSMA/CA). The following is an overview of the contention-based channel assignment schemes.

10.3.3.1 Random Access

ALOHA [12] is the simplest type of contention-based channel access schemes developed to regulate access to a shared transmission medium among uncoordinated contending hosts. The ALOHA communication system was part of a wireless time-sharing system used to connect a mainframe computer near Honolulu with remote users on other Hawaiian islands. Channel access in pure ALOHA is completely asynchronous and independent of the current activity on the transmission medium. A host is simply allowed to transmit data whenever it is ready to do so. Upon completing the data transmission, the communicating node listens for a period of time equal to the longest possible round-trip propagation time on the network. This is typically the time it takes for the signal to travel between the two most distant nodes in the network. If the node receives an acknowledgment for data transmitted before this period of time elapses, the transmission is considered successful. The acknowledgment is issued by the receiver after it determines the correctness of the data received by examining the error check sum. In the absence of an acknowledgment, however, the communicating host assumes that the data are lost due to errors caused by noise on the communication channel or because of collision and retransmits the data. If the number of transmission attempts exceeds a specified threshold, the host refrains from retransmitting the data and reports a fatal error. ALOHA is a simple protocol that requires no central control, thereby allowing nodes to be added and removed easily. Furthermore, under light-load conditions, hosts can gain access to the channel within short periods of time. The main drawback of ALOHA, however, is the sever network performance degradation as the number of collisions rapidly increases due to increased load. Assuming that message generation follows Poisson statistics, it can be shown that the ALOHA system becomes unstable (i.e., the number of retransmissions grows without bound) when the fraction of time the channel is utilized exceeds $1/2e \approx 0.184$. To improve the performance of pure ALOHA, slotted ALOHA [58] was proposed. As shown in Figure 10.7, in pure ALOHA protocol, each node starts transmitting the data upon its frame gets ready. Such a random access protocol may cause collision. Boxes indicate the frames, and dotted boxes show the frames which have collided.

Slotted ALOHA introduces the synchronized transmission time slots similar to TDMA. In this approach, nodes can transmit only at the beginning of a time slot. The introduction of time slots doubles the throughput as compared with the pure ALOHA scheme, with the cost of necessary time synchronization. In this scheme, all communication nodes are synchronized and all packets have the same length. Furthermore, the communication channel is divided into uniform time slots whose duration is equal to the transmission time of a data packet. Contrary to pure ALOHA, transmission can occur only at a slot boundary. Consequently, collision can occur only in the beginning of a slot, and colliding packets overlap totally in time. Limiting channel access to slot boundaries results in a significant decrease in the length of collision intervals, resulting in increased utilization of the underlying communication channel. Slotted or nonslotted, the ALOHA protocol is quite simple and is often used as a part of more complex medium-access methods such as PRMA proposed by Goodman et al. [11], which is a packet-reservation multiple access protocol with features of TDMA and ALOHA. Despite this performance improvement, however, pure and slotted ALOHA remain inefficient under moderate to heavy load conditions. In communication networks where the propagation delay is much shorter than the transmission time of a data packet, nodes can become aware almost immediately of an ongoing packet transmission. This observation led to the development of a new class of medium access schemes, whereby before a transmission is attempted, a host that has a packet to transmit first senses the carrier by listening to the channel. Carrier sensing forms the basis of the CSMA schemes. The CSMA-based schemes further reduce the possibility of packet collisions and improve the throughput. Figure 10.8 shows the slotted ALOHA protocol for a sample network including five nodes. Boxes show the frame, and dotted boxes indicate the frames that are collided.

CSMA [13] algorithms attempt to improve upon the relatively poor channel capacity of ALOHA by obliging the hosts to sense the channel for any ongoing activity prior to transmission.

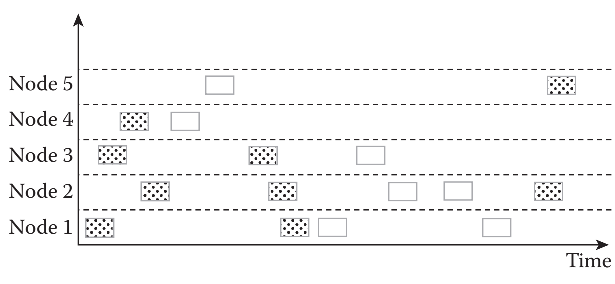

Figure 10.7 Pure ALOHA protocol.

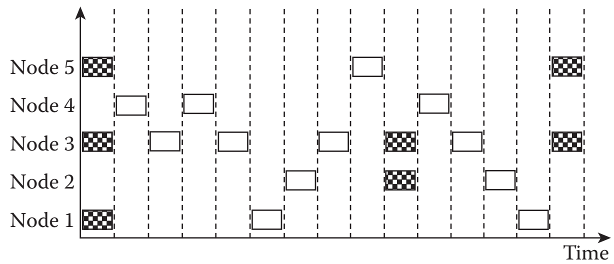

Figure 10.8 Slotted ALOHA protocol.

In a CSMA system, the hosts can be in three possible states: transmitting, idle, or listening. When the propagation delay is small compared to the packet transmission time, the throughput of the CSMA system is significantly better than that of ALOHA. CSMA protocols can be divided into two categories—nonpersistent CSMA and persistent CSMA—depending on the strategy used to acquire a free channel and the strategy used to wait for a busy channel to become free. In nonpersistent CSMA protocol, when a node becomes ready to transmit a packet, it first senses the carrier to determine whether another transmission is in progress. If the channel is idle, the node transmits its packet immediately and waits for an acknowledgment. In setting the acknowledgment timeout value, the node must take into account the round-trip propagation delay and the fact that the receiving node must also contend for the channel to transmit the acknowledgment. In the absence of an acknowledgment, before a timeout occurs, the sending node assumes that the data packet is lost due to collision or noise interference. The node schedules the packet for retransmission. If the channel is busy, the transmitting node "backs off" for a random period of time after which it senses the channel again. Depending on the status of the channel, the station transmits its packet if the channel is idle or enters the back-off mode if the channel is busy. This process is repeated until the data packet is transmitted successfully.

The nonpersistent CSMA protocol minimizes the interference between packet transmissions as it requires the hosts that find the channel busy to reschedule their transmissions randomly. The major drawback of the nonpersistent CSMA scheme, however, results from the fact that a channel may become idle during the back-off time of a contending host. The unnecessary waste of channel capacity can reduce significantly the overall network throughput. The need to address the shortcomings of nonpersistent CSMA led to the development of a class of p-persistent CSMA schemes. These schemes differ in the algorithm they use to acquire a free channel. The *1-persistent* scheme never allows the channel to remain idle if a node is ready to transmit. Based on this scheme, a node ready to transmit a data packet first senses the channel. If the channel is free, the node transmits its message immediately. If the channel is busy, however, the node persistently continues to listen until the channel becomes idle. Transmission is attempted immediately after the channel is sensed idle. The p-persistent algorithm represents a compromise between the nonpersistent and 1-persistent schemes. Based on this algorithm, a node that senses the channel idle transmits its packet with probability p. With probability $(1 - p)$, the node waits for a specific period of time before attempting to transmit the packet again. At the end of the waiting period, the node senses the channel again. If the channel is busy, the node continues to listen until the channel becomes idle. When the channel becomes idle, the node repeats the foregoing p-persistent channel acquisition algorithm. This process continues until the data packet is transmitted successfully. The optimal value of p for maximum throughput depends on the offered traffic rate. A drawback to all CSMA protocols is the so-called hidden terminal problem. Nonpersistent and persistent (1-persistent and *p*-persistent) CSMAs belong to the category of CSMA protocols with collision detection.

Pathmasuntharam et al. [59] identified a new type of exposed terminal problem, known as the critically exposed terminal problem, which causes severe throughput degradation in ad hoc networks. They proposed two possible methods: via scheduling and channel assignment to solve this problem with further elaboration of the latter scheme. They also analyzed the proper method of channel assignment and worked out the minimal channel assignment required to eliminate the critically exposed terminal problem. They suggest use of certain clustering approach to achieve the minimal assignment.

10.3.3.2 Collision Resolution

Busy tone is the first solution for the hidden-terminal problem in CSMA proposed by Tobagi and Kleinrock [60]. This solution rests on the realization that the hidden-terminal problem, and frame collisions in general, occurs at the receiving device while the CSMA algorithm is being performed at the transmitting device. The busy-tone solution requires each network device receiving a frame to simultaneously transmit a "busy tone" on another signaling channel, indicating that its receiver is busy. Devices desiring to transmit are required to check for the presence of busy tones prior to transmission. If present, they delay transmission since the channel (at the receiving device, where it matters) is busy.

Karn [61] proposed another influential single-channel solution to the hidden-terminal problem of CSMA, called CSMA/CA. CSMA/CA is also called MACA. The MACA protocol introduces the use of two control messages that can (in principle) solve the hidden and exposed terminal problems. The control messages are called RTS and CTS. The essence of the scheme is that when a node wishes to send a message, it issues an RTS packet to its intended recipient. If the recipient is able to receive the packet, it issues a CTS packet. When the sender receives the CTS, it begins to transmit the packet. When a nearby node hears an RTS addressed to another node, it inhibits its own transmission for a while, waiting for a CTS response. If a CTS is not heard, the node can begin its data transmission. If a CTS is received, regardless of whether or not an RTS is heard before, a node inhibits its own transmission for a sufficient time to allow the corresponding data communication to complete. Figure 10.9 illustrates the function of the CSMA/CA MAC layer protocol.

CSMA/CD is a modification of pure CSMA. CSMA/CD is used to improve the performance of CSMA by terminating the simultaneous transmissions upon detection of a collision. The CSMA/CD protocol is generally composed of a carrier sensing scheme and a collision detection algorithm. CSMA/CD can be described as follows: If some node has a data for transmitting, it initially assembles the data frame. Then, it checks to see if the channel is busy or not. If so, the transmitting node waits for a random time interval and tries again. Otherwise, if the channel is idle, it starts transmitting the data. During the transmission of the data frame, transmitting node checks for a collision. If no collision occurs, it continues sending the data until the frame is thoroughly transmitted. Upon detecting a collision, it terminates the current transmission and calls the collision recovery procedure. This procedure sends the jam signal to inform the other transmitting nodes that there has been a collision, waits for a random (back-off) period, and initiates a new transmission. In this mechanism, by waiting for a random period of time before retransmission, the probability of the second collision on retransmission significantly decreases. This is because the choice probability of the same random time by different nodes is negligible. The function of CSMA/CD is illustrated in Figure 10.10.

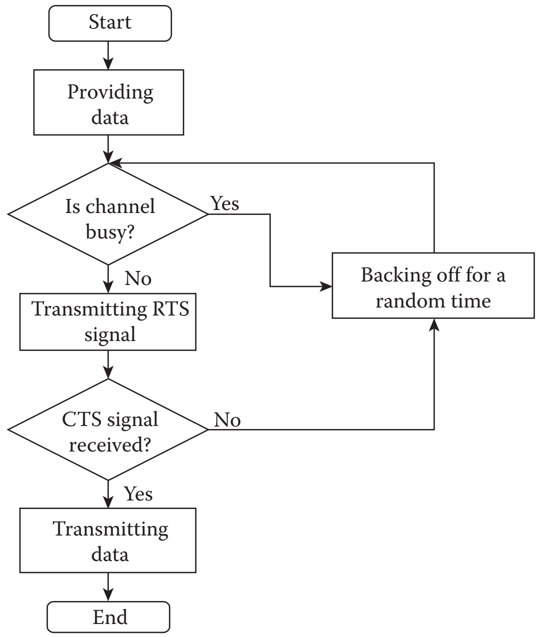

Figure 10.9 CSMA/CA MAC layer protocol.

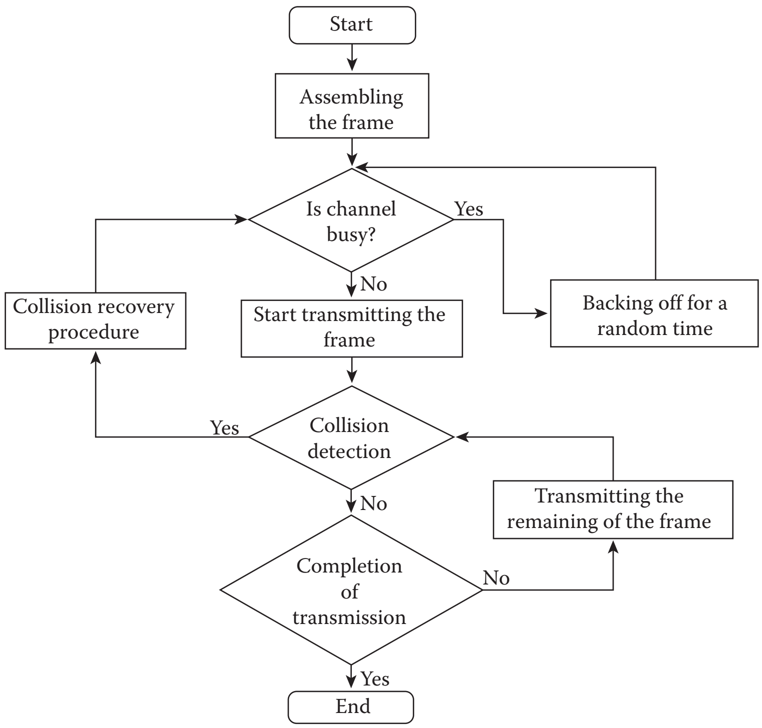

Figure 10.10 CSMA/CD MAC layer protocol.

MACA was very influential and led to many variants, including MACAW [62], floor acquisition multiple access (FAMA) [63], and the MAC methods used by wireless local area network standards such as IEEE 802.11 [64]. Most variants attempted to address identified weaknesses in MACA, such as the still-non-zero probability of frame collisions [65] and its back-off algorithm. MACA proposed the use of a simple binary exponential back-off, in which the back-off time is doubled after every collision and returned to the minimal value after a successful RTS/CTS exchange. This algorithm was shown [62] to be unfair in that over time one network device would "win" the channel and have a low back-off value (with frequent channel access), while all remaining network devices would have very large back-off values and be effectively frozen out of the network. MACA's back-off problem has been addressed in a number of ways; MACAW, for example, shares back-off values between network devices. The MACA and MACAW [61,62] protocols perform poorly since the time periods of RTS contentions can be very long. Several other protocols have been proposed that are based on RTS/CTS exchanges; they differ in the methods used to resolve the collisions of RTSs. FAMA proposed by Garcia-Luna-Aceves and Fullmer [66] is another MACA-based scheme that requires every transmitting station to acquire control of the floor (i.e., the wireless channel) before it actually sends any data packet. Unlike MACA or MACAW, FAMA requires that collision avoidance be performed at both the sender and receiver nodes. To "acquire the floor," the sending node sends out an RTS using either nonpersistent packet sensing or nonpersistent carrier sensing. The receiver responds with a CTS packet, which contains the address of the sending node. Any station overhearing this CTS packet knows about the station that has acquired the floor. The CTS packets are repeated long enough for the benefit of any hidden sender that did not register another sending node's RTS. The authors recommend the nonpersistent carrier sensing variant for ad hoc networks because it addresses the hidden-terminal problem effectively.

Nicopolitidis et al. [67] proposed a learning automata-based carrier-sense-assisted adaptive learning MAC protocol for wireless LANs, capable of operating efficiently in bursty traffic wireless networks with unreliable channel feedback. According to the proposed protocol, the mobile station that is granted the permission to transmit is selected by means of learning automata. At each station, the learning automaton takes into account the network feedback information in order to update the choice probability of each mobile station. The proposed protocol utilizes carrier sensing in order to reduce the collisions that are caused by different decisions at the various mobile stations due to the unreliable channel feedback.

10.4 Conclusion

Over the past few years, due to the rapid development of the ubiquitous computing techniques and proliferation of the mobile communication devices, the wireless mobile ad hoc networking has been experiencing exponential improvements. A MANET is a self-organizing and self-configuring multihop wireless network that can be instantly developed in situations where either a fixed infrastructure is unavailable or a fixed infrastructure is difficult to install. Because of many applications of ad hoc networks in personal area networking, military environments, civilian environments, medical and emergency operations, and so on, these networks received much attention from academic and industrial researchers during last years. Due to ease and speed of implementation and deployment of ad hoc networks in different situations as well as ease of joining the mobile hosts to these networks, the size of ad hoc network rapidly and incredibly grows. Therefore, the radio bandwidth is a scarce resource in wireless channels that must be economically assigned to the users. The channel assignment techniques are used to allocate a (minimum) required number of channels to the hosts in such a way that the interference effects are minimized and the available bandwidth can be effectively used. The conflict-free channel assignment problem can be modeled by the graph coloring problem of a special class of geometric graphs, which is an NP-hard problem. Therefore, the channel assignment problem is known to be NP-hard even if all the nodes are located in a plane and have the same radio transmission range. Two types of interferences might happen in a wireless ad hoc network. The former interference happens if a host decides to transmit and receive signals over the same channel simultaneously, and the second one takes place if a host receives more than one signal over the same channel at the same time. Since in wireless ad hoc networks the radio spectrum is a very limited resource, it must be profitably assigned to the radio nodes avoiding both interferences. Many studies have been carried out on channel assignment in wireless and cellular networks, while in ad hoc networks it has not received the attention it deserves. This chapter provided an in-depth survey of the most recent channel assignment schemes for wireless ad hoc networks. Depending on the nature of ad hoc networks, this chapter generally classified the channel assignment techniques into two main categories as contention-free and contention-based techniques. This chapter investigated and compared the well-known schemes of each category, with the emphasis on the key design issues, objectives, performances, and drawbacks. This chapter also discussed that because of bandwidth scarceness and rapid growth of using wireless mobile devices and ad hoc networks, cognitive radios and intelligent bandwidth allocation schemes are the promising approaches that are opening the new horizons to the researchers to design efficient radio channel assignment protocols.

References

1. J. Akbari Torkestani and M.R. Meybodi. A learning automata-based cognitive radio for clustered wireless ad-hoc networks. *Journal of Network and Systems Management*, vol. X, 2010, pp. XX–XX.
2. J. Akbari Torkestani and M.R. Meybodi. An efficient cluster-based CDMA/TDMA scheme for wireless mobile ad-hoc networks: a learning automata approach. *Journal of Network and Computer applications*, vol. 33, 2010, pp. 477–490.
3. A. Sen and M.L. Huson. A new model for scheduling packet radio networks. *ACM/Baltzer Journal Wireless Networks*, vol. 3, 1997, pp. 371–382.
4. C.-W. Yi. Maximum scan statistics and channel assignment problems in homogeneous wireless networks. *Theoretical Computer Science*, vol. 410, 2009, pp. 2223–2233.
5. A.M. Saleh. Inter-modulation analysis of FDMA satellite systems employing compensated and uncompensated TWTs. *IEEE Transactions on Communications*, vol. 30, no. 5, 1982, pp. 1233–1242.
6. W.C.Y. Lee. Overview of cellular CDMA. *IEEE Transactions on Vehicular Technology*, vol. 40, no. 2, 1991, pp. 291–302.
7. T. Sekimoto and J.G. Puente. A satellite time-division multiple-access experiment. *IEEE Transactions on Communications*, vol. 16, no. 4, 1968, pp. 581–588.
8. C.-M. Wu. Hybrid dynamic channel assignment in clustered wireless multihop CDMA/TDMA ad hoc networks. *Wireless Personal Communications*, vol. 42, 2007, pp. 85–105.
9. A. Capone, M. Gerla, and R. Kapoor. Efficient polling schemes for Bluetooth picocells. In *Proceeding of the IEEE International Conference on Communications (ICC2001), Finland*, vol. 7, 2001, pp. 1990–1994.
10. X. Chrapkowski and G. Grube. Mobile trunked radio system design and simulation. In *Proceedings of the IEEE Vehicular Technology Conference*, 1991, pp. 245–250.
11. D.J. Goodman, R.A. Valenzuela, K.T. Gayliard, and B. Ramamurthi. Packet reservation multiple-access for local wireless communications. *IEEE Transactions on Communications*, vol. 37, 1989, pp. 885–890.

AU: Provide the volume number as well as the page range in Ref. 1.

AU: Provide the initials for "Chrapkowski" in Ref. 10.

12. N. Abramson. The ALOHA system—another alternative for computer communications. In *Proceedings of the AFIPS Fall Joint Computer Conference*, vol. 37, 1970, pp. 281–285.
13. L. Kleinrock and F.A. Tobagi. Packet switching in radio channels. Part I:Carrier sense multiple-access modes and their throughput-delay characteristics. *IEEE Transactions on Communications*, vol. 23, no. 12, 1975, pp. 1400–1416.
14. M. Wu. Dynamic frame length channel assignment in wireless multihop ad hoc networks. *Journal of Computer Communications*, vol. 30, 2007, pp. 3832–3840.
15. S. Kim and J.I. Kim. An adaptive time slot assignment algorithm for variable bandwidth switching systems. *Computers & Operations Research*, vol. 27, 2000, pp. 423–435.
16. R. Mo and Y.H. Chew. System throughput analysis of rate adaptive TDMA system supporting two class services. *Wireless Networks*, vol. 11, 2005, pp. 687–695.
17. L. Xin, D. Qionghia, and W. Qiu-feng. Time allocation scheme in IEEE 802.15.3 TDMA mechanism. *Journal of Zhejiang University Science A*, vol. X, 2006, pp. 159–164.
18. T. Heikkinen and A. Hottinen. Distributed subchannel assignment in a two-hop network. *Computer Networks*, vol. X, 2010, pp. XX–XX.
19. X. Wang and J.J. Garcia-Luna-Aceves. Distributed joint channel assignment, routing and scheduling for wireless mesh networks. *Computer Communications*, vol. 31, 2008, pp. 1436–1446.
20. L.M. San Jose-Revuelta. A heuristic search technique for fixed frequency assignment in non-homogeneous demand systems. *Signal Processing*, vol. 88, 2008, pp. 1461–1476.
21. R. Huang, H. Zhai, C. Zhang, and Y. Fang. SAM-MAC: an efficient channel assignment scheme for multi-channel ad hoc networks. *Computer Networks*, vol. 52, 2008, pp. 1634–1646.
22. J.T. Wang. Throughput analysis for interference limited TDMA and TDMA/CDMA wireless ad hoc networks. *International Journal of Communication Systems*, vol. 22, 2009, pp. 365–372.
23. P. Trifonov, E. Costa, and A. Filippi. *Adaptive Coding in MC-CDMA/FDMA Systems with Adaptive Sub-Band Allocation*. XXXX: Kluwer Academic Publishers, 2003.
24. X. Horikawa and M. Hirono. A digital FDMA/TDMA microcell system for the next generation cordless telephones.In Proceedings of the Fourth Nordic Seminar on Digital Mobile Radio Communications, Oslo, 1990.
25. Y. Akaiwa and H. Andoh. Channel segregation—a self-organized dynamic channel allocation method: application to TDMA/FDMA microcellular system. *IEEE Journal of Selected Areas in Communications*, vol. 11, no. 6, 1993, pp. 949–954.
26. J. Perez-Romero, O. Sallent, and R. Agusti. On the optimum traffic allocation in heterogeneous CDMA/TDMA networks. *IEEE Transaction on Wireless Communications*, vol. 6, no. 9, 2007, pp. 3170–3174.
27. K. Navaie and H. Yanikomeroglu. Optimal downlink resource allocation for non-real time traffic in cellular CDMA/TDMA networks. *IEEE Communication Letters*, vol. 10, no. 4, 2006, pp. 278–280.
28. K. Navaie and H. Yanikomeroglu. Downlink joint base-station assignment and packet scheduling algorithm for cellular CDMA/TDMA networks. In *IEEE International Conference on Communications*, 2006, pp. 4339–4344.
29. R. Vannithamby and E.S. Sousa. An optimum rate/power allocation scheme for downlink in hybrid CDMA/TDMA cellular system. In *52nd IEEE Conference on Vehicular Technology*, 2000, pp. 1734–1738.
30. M. Gerla and J. Tsai. Multicluster, mobile, multimedia radio network. *ACM/Baltzer Journal on Wireless Networks*, vol. 1, no. 3, 1995, pp. 255–265.
31. C.R. Richard Lin and M. Gerla. Adaptive clustering for mobile wireless networks. *IEEE Journal of Selected Areas in Communications*, vol. 15, no. 7, 1997, pp. XX–XX.
32. M.D. Jovanovic and G.L. Djordjevic. TFMAC: multi-channel MAC protocol for wireless sensor networks. In *IEEE – Telsiks*, 2007, pp. 23–27.
33. W. Li, J.B. Wei, and S. Wang. An evolutionary-dynamic TDMA slot assignment protocol for ad hoc networks. *Wireless Communications and Networking Conference*, 2007, pp. 138–142.
34. L.M. San Jose-Revuelta. A new adaptive genetic algorithm for fixed channel assignment. *Information Sciences*, vol. 177, 2007, pp. 2655–2678.

AU: Provide the volume number in Ref. 17.

AU: Provide the volume number and the page range in Ref. 18.

AU: Provide the year of publication in Ref. 23.

AU: Provide the initials for “Horikawa” in Ref. 24.

AU: Provide the page range in Ref. 31.

35. G. Vidyarthi, A. Ngom, and I. Stojmenovic. A hybrid channel assignment approach using an efficient evolutionary strategy in wireless mobile networks. *IEEE Transactions on Vehicular Technology*, vol. 54, 2005, pp. 1887–1895.
36. K. Smith and M. Palaniswami. Static and dynamic channel assignment using neural networks. *IEEE Journal on Selected Areas in Communications*, vol. 15, no. 2, 1997, pp. 238–249.
37. A.I. Perez, J. Bas, and M.A. Lagunas. A neuro-fuzzy system for source location and tracking in wireless communications. In *Neuro-Fuzzy and Fuzzy-Neural Applications in Telecommunications*. XXXX: XXXX, 2005, pp. 119–148.
38. S. Bandyopadhyay and E.J. Coyle. An energy efficient hierarchical clustering algorithm for wireless sensor networks. In Proceedings of INFOCOM 2003, San Francisco, 2003.
39. X. Grillo. Polling mechanism models in communication systems—some application examples. In H. Takagi, ed., *Stochastic Analysis of Computer and Communication Systems*. XXXX: XXXX, 1990, pp. 659–698.
40. K. Wang, M.-G. Peng, and W.-B. Wang. Distributed scheduling based on polling policy with maximal spatial reuse in multi-hop WMNs. *The Journal of China Universities of Posts and Telecommunications*, vol. 14, 2007, pp. 22–27.
41. K. Lye and K. Seah. Random polling scheme with priority. *Electronics Letters*, vol. 28, 1992, pp. 1290–1291.
42. T.D. Lagkas, G.I. Papadimitriou, and A.S. Pomportsis. QAP: a QoS supportive adaptive polling protocol for wireless LANs. *Computer Communications*, vol. 29, 2006, pp. 618–633.
43. C. Yang and C.F. Liu. A bandwidth-based polling scheme for QoS support in Bluetooth. *Computer Communications*, vol. 27, 2004, pp. 1236–1247.
44. G. Dimitriadis and F.N. Pavlidou. Two-hop polling: an access scheme for clustered, multihop ad hoc networks. *International Journal of Wireless Information Networks*, vol. 10, no. 3, 2003, pp. 149–158.
45. C. Tseng and K.-C. Chen Priority polling with reservation wireless access protocol for multimedia ad hoc networks. In *Proceedings of Vehicular Technology Conference*, vol. 2, pp. 899–903, 2002.
46. J. Hou and S. Papavassiliou. A dynamic reservation-based call admission control algorithm for wireless networks using the concept of influence curve. *Telecommunication Systems*, vol. 22, no. 1–4, 2003, pp. 299–319.
47. K. Kim. A distributed channel assignment control for QoS support in mobile ad hoc networks. *Journal of Parallel and Distributed Computing*, vol. X, 2010, pp. XX–XX.
48. I. Menache and N. Shimkin. Reservation-based distributed medium access in wireless collision channels. In *Telecommunication Systems*. XXXX: Springer Publishing Company, 2010.
49. G.M. Stone and K. Bluitt. Advance digital communications system design considerations for law enforcement and internal security purposes. In *Proceedings of the IEEE 29th Annual International Carnahan Conference on Security Technology*, 1995, pp. 402–408.
50. European Telecommunication Standards Institute. Terrestrial trunked radio (TETRA), voice plus data (V + D). Part 2: Air Interface (AI). Document ETSI EN 300 392-2 V2.4.2 (2004-02). XXXX: European Telecommunication Standards Institute, 2004.
51. M.A.C. Lima, A.F.R. Araújo, and A.C. Cesar. Adaptive genetic algorithms for dynamic channel assignment in mobile cellular communication systems. *IEEE Transaction on Vehicular Technology*, vol. 56, no. 5, 2007, pp. 2685–2696.
52. L. Wang, S. Arunkumaar, and W. Gu. Genetic algorithms for optimal channel assignment in mobile communications. In *Proceedings of the 9th International Conference on Neural Information Processing (ICONIP'O2)*, vol. 3, 2002, pp. 1221–1225.
53. Y.C. Tseng, C.M. Chao, S.L. Wu, and J.P. Sheu. Dynamic channel allocation with location awareness for multi-hop mobile ad hoc networks. *Computer Communications*, vol. 25, 2002, pp. 676–688.
54. S.L. Wu and J.Y. Yang. A novel channel assignment scheme for improving channel reuse efficiency in multi-channel ad hoc wireless networks. *Computer Communications*, vol. 30, no. 17, 2007, pp. 3416–3424.
55. M.X. Gong, S.F. Midkiff, and S. Mao. On-demand routing and channel assignment in multi-channel mobile ad hoc networks. *Ad hoc Networks*, vol. 7, 2009, pp. 63–78.

AU: Provide the editor names, name of the publisher, as well as the place of publication in Ref. 37.

AU: Provide the initials for "Grillo," the name of the publisher, as well as the place of publication in Ref. 39.

AU: Provide the volume number as well as the page range in Ref. 47.

AU: Provide the place of publication in Ref. 48.

AU: Provide the place of publication in Ref. 50.

56. S. Wu, C. Lin, Y. Tseng, and J. Sheu. A new multi-channel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks. In Proceedings of ISPAN'00, USA, 2000.
57. O. Sallent, R. Agustí, J. Pérez-Romero, and L. Giupponi. Decentralized spectrum and radio resource management enabled by an on-demand cognitive pilot channel. *Annual Telecommunication*, vol. 63, 2008, pp. 281–294.
58. L.G. Roberts. ALOHA packet system with and without slots and capture. *Computer Communications Review*, vol. 5, no. 2, 1978, pp. 28–42.
59. J.S. Pathmasuntharam, A. Das, and A.K. Gupta. *Channel Assignment for Nullifying the Critically Exposed Node Problem in Ad hoc Wireless Networks*. XXXX: IEEE, 2004.
60. A. Tobagi and L. Kleinrock. Packet switching in radio channels. Part II: The hidden terminal problem in carrier sense multiple-access and the busy tone solution. *IEEE Transactions on Communications*, vol. COM-23, no. 12, 1975, pp. 1417–1433.
61. P. Karn. MACA—a new channel access method for packet radio. In *Proceedings of the ARRL/CRRL Amateur Radio 9th Computer Networking Conference*, 1990, pp. 134–140.
62. V. Bharghavan, A. Demers, S. Shenker, and L. Zhang. MACAW: a medium access protocol for wireless LANs. *ACM SIGCOMM Computer Communication Review*, vol. 24, no. 4, 1994, pp. 212–225.
63. L. Fullmer and J.J. Garcia-Luna-Aceves. Solutions to hidden terminal problems in wireless networks. *ACM SIGCOMM Computer Communications Review*, vol. 27, no. 4, 1997, pp. 39–49.
64. Institute of Electrical and Electronics Engineers, Inc. *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 Standard 802.11-1999 (ISO/IEC 8802-11: 1999)*. XXXX: IEEE Press, 1999.
65. S. Singh and C.S. Raghavendra. PAMAS—power aware multi-access protocol with signalling for ad hoc networks. *ACM SIGCOMM Computer Communication Review*, vol. 28, no. 3, 1998, pp. 5–26.
66. J.J. Garcia-Luna-Aceves and C. Fullmer. Floor acquisition multiple access (FAMA) in single-channel wireless networks. *ACM Mobile Networks and Application (MONET)*, vol. 4, no. X (Special Issue on Ad hoc Networks), 1999, pp. 157–174.
67. P. Nicopolitidis, G.I. Papadimitriou, M.S. Obaidat, and A.S. Pomportsis. Carrier-sense-assisted adaptive learning MAC protocols for distributed wireless LANs. *International Journal of Communication Systems*, vol. 18, 2005, pp. 657–669.

AU: Provide the place of publication in Ref. 59.

AU: Provide the place of publication in Ref. 64.

AU: Provide the issue number in Ref. 66.