Chapter 2
Mesh Enabling Technology

2.1 IEEE 802.11 and Its Amendments

Ease of deployment and affordable cost are two main reasons behind the increasing popularity of wireless mesh networks. Compared to other alternatives of wireless access networks such as cellular networks, wireless mesh networks can potentially provide carrier-grade Internet services at a lower capital expenditure (CAPEX) and operational expenditure (OPEX). IEEE 802.11 technology has been the key in enabling low-cost wireless multi-hoping due to its support of ad-hoc networking. Because of this reason, many current wireless mesh network deployments are based on IEEE 802.11 standards. This by no means restricts the applicability of WMNs to other standards; but cheaper cost, flexibility and higher availability of 802.11 hardware and software are the factors that have most motivated the growth.

IEEE 802.11 a/b/g are most commonly used wireless technology standards for mesh networking. Since 802.11 a and g standards can provide higher data rates (upto 54 Mbps), they have become more popular in recent WMN deployments. A typical two-tier mesh network consists of an *access* tier and a *backhaul* tier. The access tier provides connectivity between mesh routing nodes and their clients, while the backhaul tier consists of interconnections among the mesh routers. In order to avoid interference between the two tiers, the access tier typically operates in 802.11 b/g mode while the backhaul tier operates in 802.11 a mode. This mitigates the inter-tier interference because 802.11 a uses the 5 GHz ISM band and 802.11 b/g use 2.4 GHz.

Even though most of the WMN deployments use IEEE 802.11 a/b/g standards, an additional amendment is proposed in the form of IEEE 802.11s standard. The motivation behind the design and development of 802.11s is that the a/b/g standards were not designed for multi-hop communications. Although the 802.11 a/b/g have been reasonably well leveraged for mesh, they were originally designed to operate in infrastructure WLANs. In order to address the issues of coordinated medium access, 802.11s proposes *Mesh Deterministic Access* (MDA), built on the idea that contention for access to the medium should be separated as much as possible from the actual medium utilization. We will discuss IEEE 802.11s MAC in more detail in a later chapter. The major difference between 802.11s and the other 802.11 standards is

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how mesh nodes access the medium. Functionality of other layers in 802.11s remain more or less similar; e.g. 802.11s uses similar PHY layer as a/g for carrying the traffic.

2.2 Multiple Input Multiple Output (MIMO) Based IEEE 802.11

The performance gains of utilizing multiple antennas in wireless networks have been long explained by seminal works of Foschini and Gans (1998), Telatar (1999). The systems in which multiple antennas are used at the wireless receiver and transmitter are referred to as Multiple-Input Multiple-Output (MIMO) (Fig. 2.1), as opposed to systems where receiver and transmitter each have a single antenna—Single-Input Single-Output (SISO). MIMO technology has been employed in many current mobile standards such as LTE, WiMAX and 802.11n.

MIMO technology can increase the throughput of a wireless channel, but (more importantly for our present context), it can improve the consistency and predictability of the channel, as we describe below. For this reason, it is an important technology for service continuity issues. Here, we restrict out attention to the IEEE 802.11n standard due to its applicability in wireless mesh networks. We also discuss multi-hop WiMAX networks in the Sect. 2.3.

Foschini and Gans (1998) and Telatar (1999) showed for the first time that capacity increases linearly when an additional pair of antennas are added at link end-points. This is an especially important result since the capacity gain is achieved even when

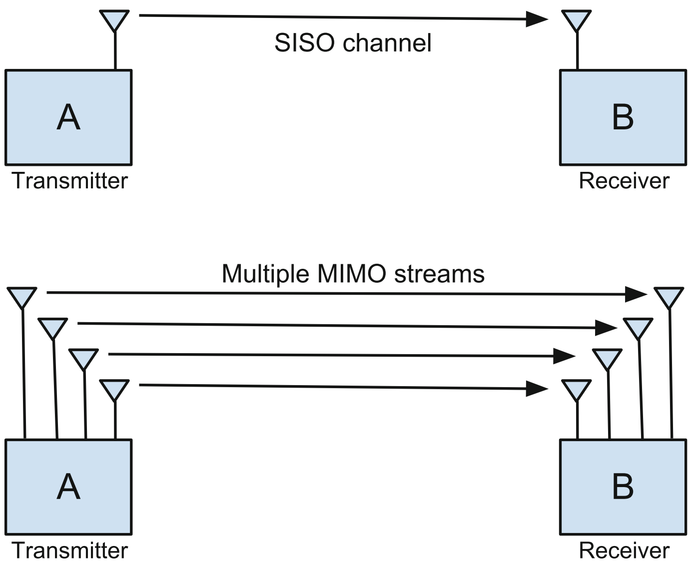

Fig. 2.1 SISO and MIMO: a transmitter and receiver can communicate with a single antenna pair, or with multiple antenna pairs constituting a MIMO link

both receiver and transmitter are tuned on the same channel; thus it represents a more effective utilization on the same spectrum, not the use of additional antennas to access additional spectrum. The gain is attributed to the creation of independent spatial paths between pairs of antennas, which allows significantly more information to be exchanged at the same time. Previously 802.11a/g have also employed multiple antennas for capacity gain. This is different from latter MIMO systems such as 802.11n; in the former, the best signal out of multiple antennas is chosen, while the latter allows parallel processing of data from all antennas. The theoretical achievable throughput of 802.11n is 600 Mbps as opposed to 54 Mbps attainable in 802.11a/g. As shown by Halperin et al. (2010), the increase is due to multiple antennas, increase in channel width, and link layer frame aggregation. The increase of data rate using multiple antennas can be leveraged by the backhaul links of wireless mesh networks, which typically experience stable high traffic demand.

Similar to 802.11a/g, 802.11n uses Orthogonal Frequency Division Multiplexing (OFDM). When operating in non-HT (High Throughput) mode, a A 20 MHz channel is divided into 56 subcarriers (out of which 52 subcarriers are usable) when operating in High Throughput (HT) mode, or 52 subcarriers (48 usable) when operating in non-HT mode.[1] Similarly, a 40 MHz channel is divided into 114 subcarriers where 108 carriers can be used for transmission. This is shown in Fig. 2.2. The spectral mask of a 40 MHz channel is shown in Fig. 2.3. Using this spectral mask, the 5.4 GHz U-NII band can be divided into 5 orthogonal channels (Fig. 2.4). Due to the larger spread, multiple orthogonal channels of 40 MHz can not be obtained in 2.4 GHz spectrum where 802.11g devices are largely located (Fig. 2.5). We will see later how their coexistence can create prohibitive throughput decrements in 802.11n links. Due to this reason, the 2.4 GHz spectrum is largely unsuitable for 802.11n operations.

There are multiple reasons behind performance increase of 802.11n as compared to 802.11a/g. First, 40 MHz channels provide higher link throughput. 802.11n is also effective in combating multi-path fading (Judd et al. 2008), because such fading effects are largely frequency specific, and when sufficient redundancy is added in subcarrier information, it is possible to decode the information even if multiple consecutive subcarriers are affected due to multi-path fading. Since such techniques are already employed in 802.11a/g, the added advantage of 802.11n comes due to multiple antennas that can allow spatial diversity. Details of gains due to spatial diversity and frame aggregation are listed in the next subsection.

Table 2.1 lists the data rates achievable by the 802.11n standard. Modulation and Coding Scheme (MCS) is a number derived based on combinations of modulation, coding rate, guard period size, channel width and number of spatial streams. The guard period is the time between two consecutive transmissions of symbols, necessary in order to adjust for delayed receptions due to multi-path effects. Finally, a number of spatial streams is established in each case, between that number of antenna pairs in parallel.

[1] Some subcarriers are used as pilots for dynamic calibration, and are not usable for data transmission.

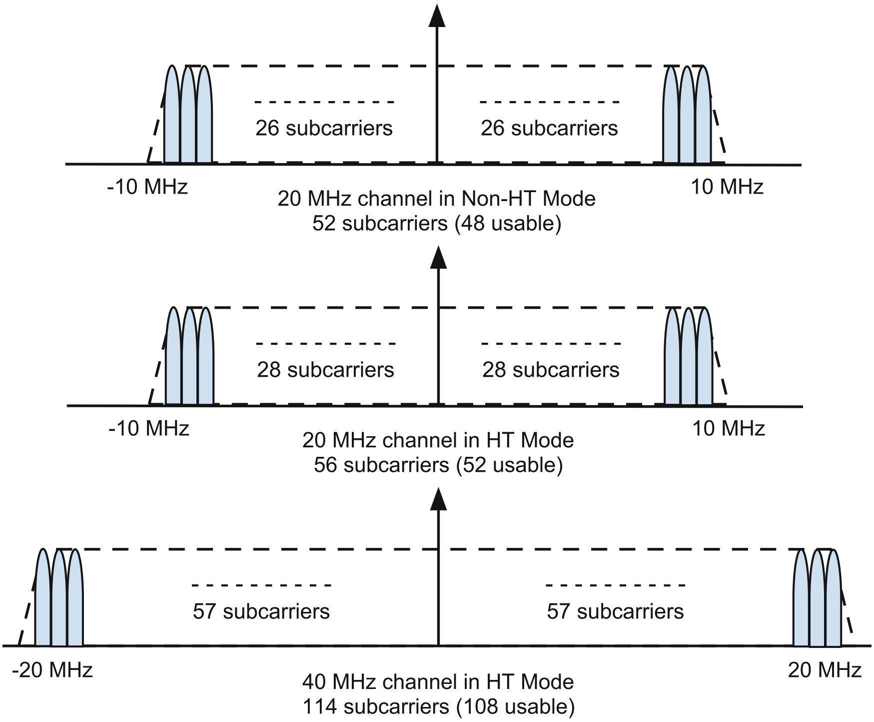

Fig. 2.2 Increased number of subcarriers allows larger and more reliable information exchange in 802.11n

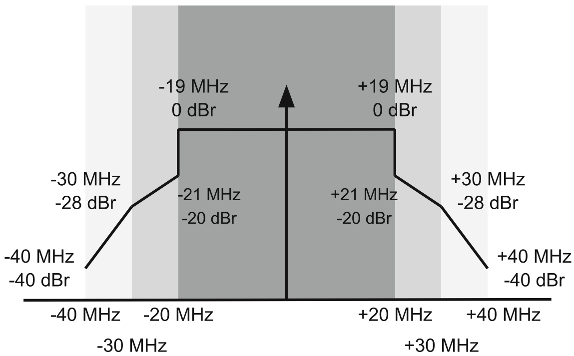

Fig. 2.3 Spectral mask of 40 MHz channel allowed in 802.11n

2.2.1 Spatial Diversity

A set of techniques are applied to the receiver and transmitter in order to leverage the multiple signals received by multiple antennas.

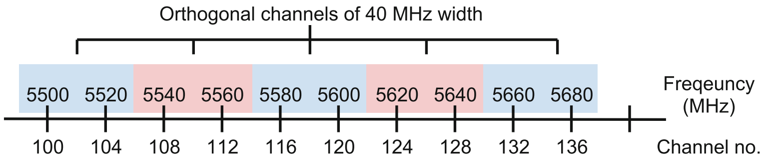

Fig. 2.4 U-NII Spectrum band (5.450–5.725 GHz) divided into 5 channels of 40 MHz

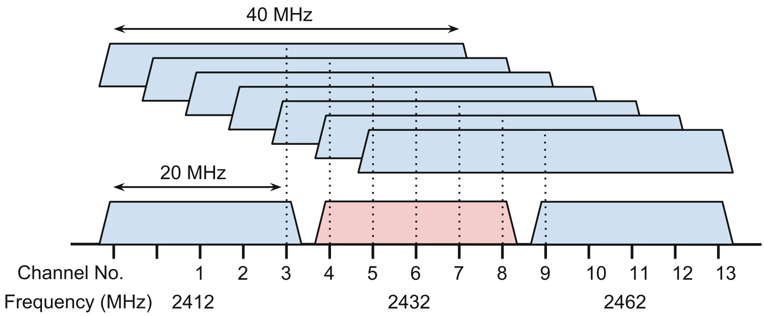

Fig. 2.5 40 MHz channels are not suitable for 2.4 GHz band

2.2.1.1 Receiver Diversity

In order to understand receiver diversity, let us first consider a sample two-node network shown in Fig. 2.6. In the network, both nodes are equipped with 3 antennas. Node A (transmitter) only uses one antenna to transmit the signal. Node B (receiver) uses all three antennas to receive the transmitted signal. Receiver diversity techniques are used to combine the received signals of each antenna in order to constructively determine the transmitted information. Following Halperin et al. (2010), we discuss two methods of receiver diversity.

1. Strongest-signal-only (SSO): The antenna that receives the strongest signal will be considered for frame reception. The method is simple and is in fact helpful in reliability since it provides a choice of potentially better signal. On the other hand, the received signals at the other antennas are simply wasted.
2. Maximal Ratio Combining (MRC): Signals are superimposed with each other such that they are in the same phase. This allows constructive addition of the signals, which is likely to be better than the SSO signal. Further, before addition of the signals, they can be weighted using their SNR values to avoid the impact of noise from weaker signals on MRC. Most of the current 802.11n implementations use MRC for receiver diversity.

Halperin et al. (2010) present results regarding the performance of different receiver diversity methods when a 1×3 topology similar to Fig. 2.6 is implemented using commodity hardware in indoor environment. As can be expected, their results verify that the signals received by individual antennas suffer multipath fading in certain subcarriers. On the other hand, when MRC is used, the resultant signal strength

Table 2.1 Achievable 802.11n data rates using various modulations, coding rates, number of spatial streams and guard intervals

MCS index	Type	Coding rate	Spatial streams	Data rate (Mbps) with 20 MHz CH		Data rate (Mbps) with 40 MHz CH	
				800 ns	400 ns (SGI)	800 ns	400 ns (SGI)
0	BPSK	1/2	1	6.50	7.20	13.50	15.00
1	QPSK	1/2	1	13.00	14.40	27.00	30.00
2	QPSK	3/4	1	19.50	21.70	40.50	45.00
3	16-QAM	1/2	1	26.00	28.90	54.00	60.00
4	16-QAM	3/4	1	39.00	43.30	81.00	90.00
5	64-QAM	2/3	1	52.00	57.80	108.00	120.00
6	64-QAM	3/4	1	58.50	65.00	121.50	135.00
7	64-QAM	5/6	1	65.00	72.20	135.00	150.00
8	BPSK	1/2	2	13.00	14.40	27.00	30.00
9	QPSK	1/2	2	26.00	28.90	54.00	60.00
10	QPSK	3/4	2	39.00	43.30	81.00	90.00
11	16-QAM	1/2	2	52.00	57.80	108.00	120.00
12	16-QAM	3/4	2	78.00	86.70	162.00	180.00
13	64-QAM	2/3	2	104.00	115.60	216.00	240.00
14	64-QAM	3/4	2	117.00	130.00	243.00	270.00
15	64-QAM	5/6	2	130.00	144.40	270.00	300.00
16	BPSK	1/2	3	19.50	21.70	40.50	45.00
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31	64-QAM	5/6	4	260.00	288.90	540.00	600.00

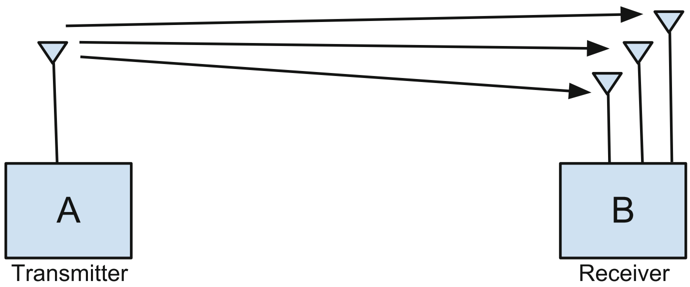

Fig. 2.6 An example 1 × 3 MIMO link

is much higher due to their constructive addition. Their results also demonstrate that MRC with only two antennas already shows large improvements, but MRC with three antennas shows an even further, though smaller, improvement.

Fig. 2.7 A 3×1 MIMO link

2.2.1.2 Transmit Diversity

Similar to receiver diversity, transmit diversity techniques apply to cases where there are multiple antennas at the transmitting node and a single antenna at the receiving node, such as the 3×1 case in Fig. 2.7. There are two widely used methods of transmit diversity.

1. Transmit Beamforming: The technique can be considered an informed inverse of the MRC technique. In transmit beamforming, the transmitter precodes the signals sent from antennas such that their phase have an opportunity of constructive addition at the receiver antenna. As in MRC, the signals can be weighted using expected SNR of each independent spatial path. This technique requires prior knowledge of path quality, which in turn requires feedback from the receiver. 802.11n uses various control packets in order to notify the transmitter regarding the path statistics. Phased antenna arrays can also be used for beamforming in which phase delays are added via their physical orientation so that the resultant signals meet constructively at the receiver. Note that this is different from switched beamforming where out of many available antenna one or more are chosen at any given time in order to establish best spatial path.
2. Space-time Codes: The idea behind space-time codes is to achieve transmitter diversity by encoding information in both spatial and temporal domain. This is done by replicating the data stream, encoding it using space-time codes and sending them out over different antennas. The space-time codes (Goldsmith 2005; Oestges and Clerckx 2007; Tse and Viswanath 2005) ensure that they are orthogonal in terms of their mutual interference so that the receiver can construct a strong signal. Due to their simplicity, and no requirement of feedback, they are often adopted for 802.11n systems.

Both transmit and receive diversity techniques can be implemented, together, to yield advantages of both techniques. These techniques allow sending (or receiving) the same data stream across multiple antennas for an improved and robust communication. On the other hand, spatial-division multiplexing can be used to exchange independent data stream at each antenna pair.

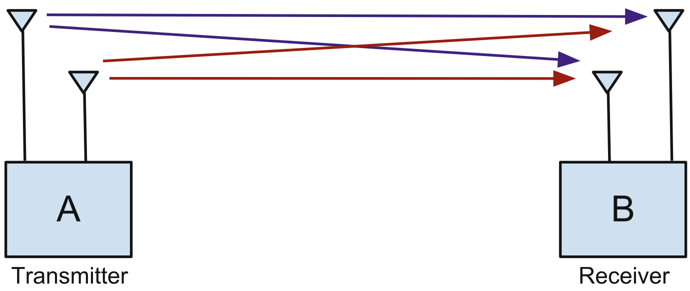

Fig. 2.8 Diversity techniques (receive and transmit) or spatial-division multiplexing can be used to yield greatest advantage of $N \times N$ MIMO system

Table 2.2 Theoretical achievable gains of using N antennas at end-points

	SISO	$1 \times N$ or $N \times 1$ diversity	$N \times N$ diversity	Multiplexing
Capacity	$B\,log_2(1+\rho)$	$B\,log_2(1+\rho N)$	$B\,log_2(1+\rho N^2)$	$BN\,log_2(1+\rho)$

2.2.2 Spatial-Division Multiplexing

Consider Fig. 2.8 in which there are N parallel stream between sender and receiver. These allows N independent spatial paths on which N different data streams can sent, and the receiver is able to receive these streams in parallel using dedicated RF chain processing. Foschini and Gans (1998), Halperin et al. (2010) outline the performance gains that can be achieved in systems with receiver diversity, transmit diversity and spatial-division multiplexing. These results are listed in Table 2.2.

In case of SISO systems, Shannon's theory gives us the capacity with B being the bandwidth of link. In a system with N antennas on receiver or transmitter side ($1 \times N$ or $N \times 1$ systems) the diversity techniques explained above can result into N times improvement in SNR. In the case of N antennas at each end, with diversity techniques implemented at both ends, a total of N^2 times increase of SNR can be achieved. In the case where spatial multiplexing is used to transmit N independent streams, the resultant benefit is N times the capacity that is achievable using a SISO system.

2.2.2.1 Experimental Evaluation of Throughput Gains of 802.11n

802.11n and inbuilt MIMO techniques have shown the potential of significant throughput increase when utilized in wireless mesh networks. Shrivastava et al. (2008) first presented a comprehensive experimental evaluation of 802.11n link by implementing them on a real testbed. They studied the impact of MIMO diversity, coexistence with other 802.11 networks, channel width and frame packet aggrega-

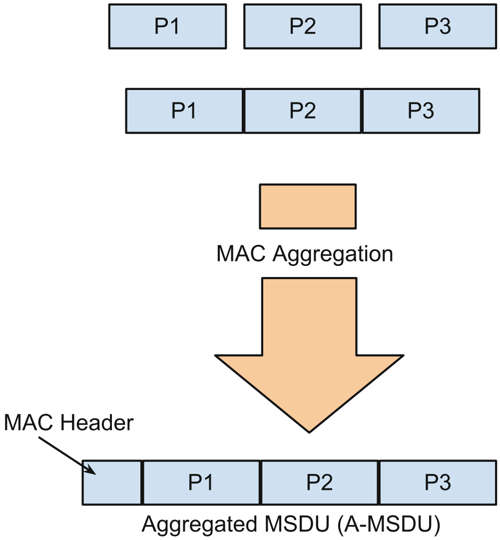

Fig. 2.9 Multiple packets can be aggregated to generate an Aggregate MAC Service Data Unit

tion. 802.11n allows formation of Aggregate MAC Service Data Unit (A-MSDU) where multiple packets destined to a single destination are aggregated to create a large MAC frame (upto 7935 bytes). The process is illustrated in Fig. 2.9.

Shrivastava et al. (2008) experimented with one MIMO link with 3×3 settings in indoor environment, to observe the impact of channel width (20 or 40 MHz) and frame aggregation, for two different packet sizes (600 and 1200 bytes). As expected their results show that 40 MHz channels improve throughput over 20 MHz channels, as does aggregation. The throughput observed is larger for the larger packet size.

In practical terms, another important issue is the coexistence of 802.11g networks, and the effect on 802.11n links. The study by Shrivastava et al. (2008) shows, as expected, that a colocated 802.11g network adversely affects the throughput of the 802.11n network; significantly so, when the 802.11g link transmits at lower rates. The effect vanishes at higher transmission rates of 802.11g link; this is ascribed to the fact that at the higher rate, 802.11g uses the same modulation as 802.11n, hence is more compatible. Also, as before, the 40 MHz channel with aggregation performs well to combat the external interference. Apart from this, other cross-technology interference (baby monitors, cordless phones, microwave oven etc.) in ISM band has also been shown to reduce 802.11n throughput. This was initially identified by Bandspeed (2010), Cisco (2010), Miercom (2010), and was recently addressed by Gollakota et al. (2011). Some of the other solutions for the problem has been suggested by Cisco (2007), Lakshminarayanan et al. (2009), Moscibroda et al. (2008), Rahul et al. (2008).

2.3 Multihop Cellular Networks (MCN)

By using a WLAN technology for link layer communications, 802.11 based mesh networks explicitly leave the question of multi-hop paths to higher layer protocols, such as IP. This seems a natural development since 802.11, targeted at a local area span and context, has always depended on IP or other technology for wider area access. However, link layer technologies for cellular wireless networks, though conceptually also designed for single-hop communication with the base station, were targeted at wider areas of coverage. Thus it seems more natural to extend them for multi-hop paths within their own purview, and there have been advances along these lines in recent times.

In the last decade, cellular networks have leveraged a large number of physical layer technology such as CDMA, OFDMA etc. With other augmenting techniques like MIMO, they have become a strong contender for broadband wireless access networks. The most important advantage of cellular networks is the communication range of the cell tower, or base station. The larger communication range further allows better mobility management for highly mobile clients (e.g. a moving vehicle) as compared to 802.11 based systems. These advantages notwithstanding, cellular networks face various challenges. The first and foremost challenge is to meet the ever increasing traffic demand of clients. The data rates of cellular networks are typically lower than their 802.11 counterparts. A second issue is the design of cellular network to minimize the number of coverage holes. The users at the edge of the cells often face degraded services. A widely used solution to the problem is to use smaller cells which can well cover the desired area with sufficient quality of service. The downside of the solution is that this increases the cost of deployment dramatically.

Multihop cellular networks (MCN) (Oyman et al. 2007) use a different strategy to deal with the issues of performance and coverage. They deploy lightweight relay stations (RS) into cells that can relay the data between the base stations (BS) and mobile stations (MS). Several cellular network standards for 4G services have considered relaying in their drafts. As an example, WiMAX has included relaying in an amendment called IEEE 802.16j. Similarly, the recently released 3GPP Relase 10 Long Term Evolution-Advanced standard for IMT-advanced (4G) includes relaying stations. We next discuss both these MCN technologies from the aspect of their support of relaying.

2.3.1 IEEE 802.16: WiMAX

The IEEE 802.16 (Andrews et al. 2007; Eklund et al. 2002; Ghosh et al. 2005) working group was formed in 1999, and the first draft for point-to-multipoint, line-of-sight (LOS) communication with immobile users was proposed in 2004. This was later improved to accommodate non-LOS communication with mobile users in the draft standard of 2005. The draft has been widely known as 802.16e standard or mobile WiMAX, though officially it was merged into the 801.16-2009 standard, the

Air Interface for Fixed and Mobile Broadband Wireless Access System. To address the issues of performance and coverage, 802.16e was extended to incorporate multi-hop relaying. The task force derived a standard for 802.16 relays that is known as 802.16j, drafted to allow devices to provide backward compatibility with 802.16e (since 802.16e was standardized as early as 2006). 802.16j devices do not require any modifications to 802.16e based mobile devices, while the BS needs to be updated in order to accommodate relays.

2.3.1.1 Motivations for 802.16j

802.16j (referred to as 16j here onwards) was designed to address various design challenges. These challenges and the solutions by which 16j can address them are listed below.

1. Coverage: Relay stations can be used to solve the coverage problem in two ways. First, the locations where there exists a coverage hole due to significantly low signal strength from the BS can be now covered using RSs. An RS in such a case provides coverage to an area which is already within the ideal coverage region of BS (Fig. 2.10). The advantage of using RS instead of another BS is that typically RSs are cheaper and lightweight as compared to BSs. The solution works well especially in covering indoor coverage holes or other shadowed regions. Second, RSs can be used to extend the coverage of a BS in a specific region. Such regions are typically not within the coverage of BS but in near proximity (edge of BS) where deploying another BS is not cost-effective or otherwise not viable. This is shown in example in Fig. 2.11. This method also has wide application in terms

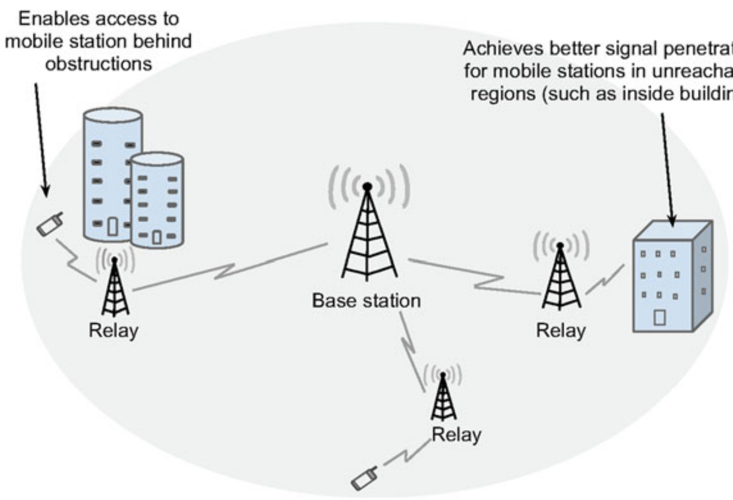

Fig. 2.10 Relay stations used at coverage holes in multihop cellular networks

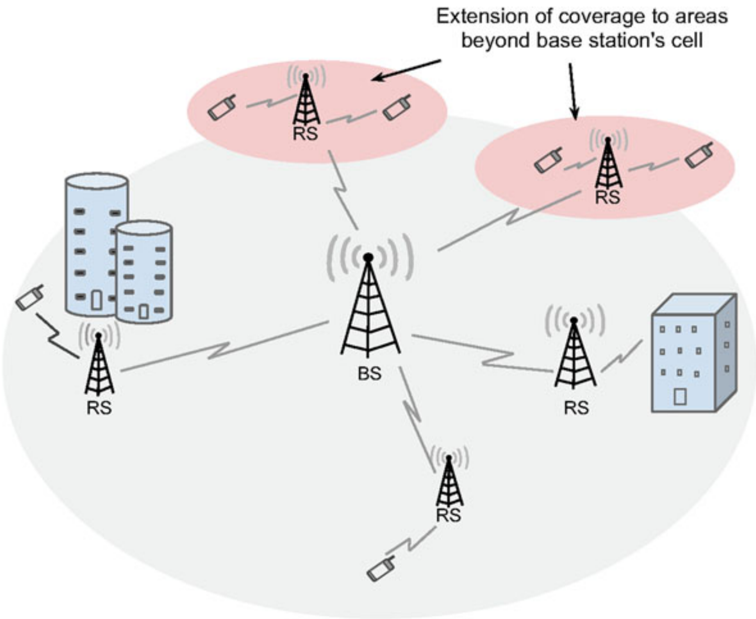

Fig. 2.11 Relay stations used for coverage expansion in multihop cellular networks

of coverage expansion. In coverage expansion, regions with no BS deployed, but closer to a coverage area, can be covered using an RS.

2. Performance: There may be regions in the coverage area of a BS that generate high traffic demand, which cannot be directly satisfied by the BS. Such clustered traffic demand places (parks, event venues etc.) can be further served using a RS. In such case, the purpose of deploying is to meet the localized traffic demand that can not be otherwise met by the BS. RSs can also be deployed in order to meet certain fast moving vehicles (such as trains, buses etc.) that have fixed routes and are expected to generate a large traffic demand. The low cost and ease of deployment make RS an appropriate choice for such cases (Fig. 2.12).

2.3.1.2 Relay Modes and Scheduling

The relays in 16j can be of two types: transparent and non-transparent. We define them below, identifying key differences between the modes.

- Transparent Mode: In transparent mode, framing and synchronization information is not forwarded by RSs but instead MSs receive the information from the BS. The main purpose of deploying RSs in such mode is to increase the capacity. The transparent RSs are within the coverage area of the BS and do not provide coverage extension because MSs are still dependent on the BS from framing and synchronization information. Transparent RSs are low complexity and their cost is lower than that of non-transparent (defined below). The scheduling of transmission

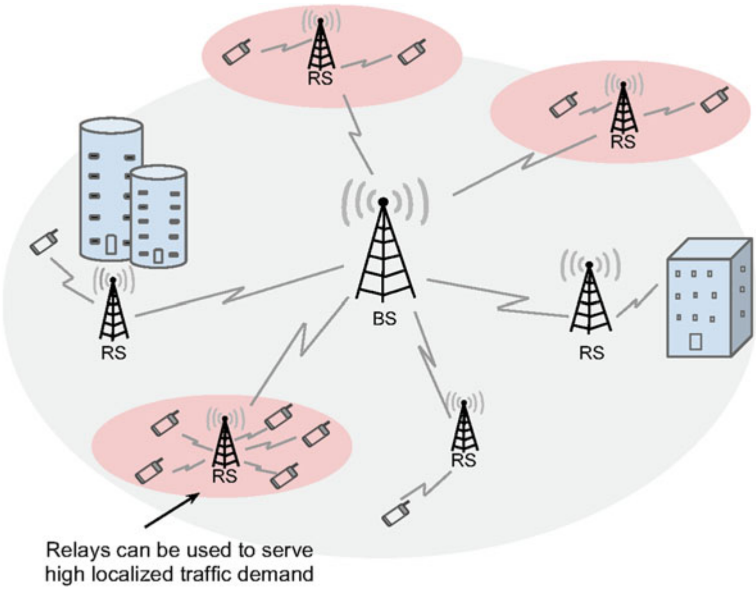

Fig. 2.12 Relay stations used for localized high traffic demand and fast moving fixed-route vehicles in multihop cellular networks

between MS and RS is handled by the BS (called centralized scheduling). Every RS in transparent mode is connected directly to the BS, hence the maximum number of hops from the MS to the BS can not no more than 2.

- Non-transparent Mode: In non-transparent mode, RSs generate their own framing and synchronization information, and forward them to the MSs. The main purpose of deploying RSs in this mode is to expand the coverage. The capacity increase achieved by such RSs is not very high due to possible inter-RS interference. Their cost is typically higher than transparent RSs. They support distributed scheduling where RSs and their MSs coordinate in frame transmission. Non-transparent RSs can be interconnected to create topologies where number of hops between MS and BS can be more than two.

Note that since the original 802.16e standard was not designed to support relaying, 16j included certain modifications that can enable relay support while maintaining the backward compatibility with 16e devices. The modifications are mostly at MAC and PHY layers. We discuss these modifications next.

2.3.1.3 PHY Layer Enhancements

The original frame structure of 16e frames included two subparts—uplink (UL) and downlink (DL). These semantics made sense because the communication was always

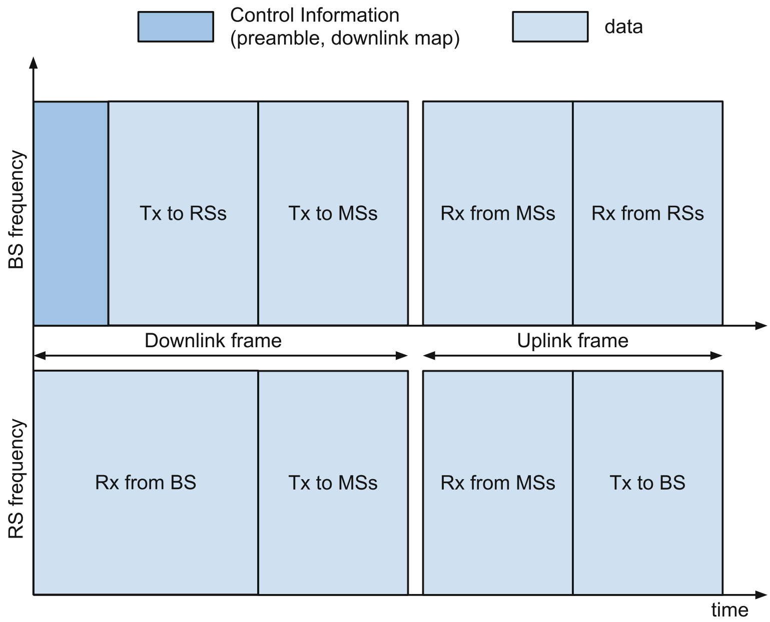

Fig. 2.13 Frame structure of 802.16j in transparent relay mode

between BS and MS. With the added support of RSs in 16j, it became necessary to support BS-RS and RS-MS communications, and stretch these semantics.

Transparent Relay Stations (T-RS) Frame Structure

As we remarked, in transparent relaying, frame and synchronization information is sent by the BS directly to the MSs. This is shown in Fig. 2.13. The DL frame in transparent mode is divided into two zones:

- Access zone: In the access zone of the DL frame, the BS first sends out information to RSs, as well as MSs directly connected to the BS. During this period, RSs receive from the BS.
- Transparent zone: In the transparent zone, the RSs transmit to their MSs while the BS can transmit to the MSs it is directly connected to.

The BS-RS and RS-MS communications that might happen at the same time during the transparent zone of the downlink period can be achieved by providing different frequencies for BS and RS transmissions. The uplink transmissions begin after the downlink period. As with downlink, uplink period is also divided into two zones:

- Access zone: During this period, the mobile stations receive from the BS or the RS.

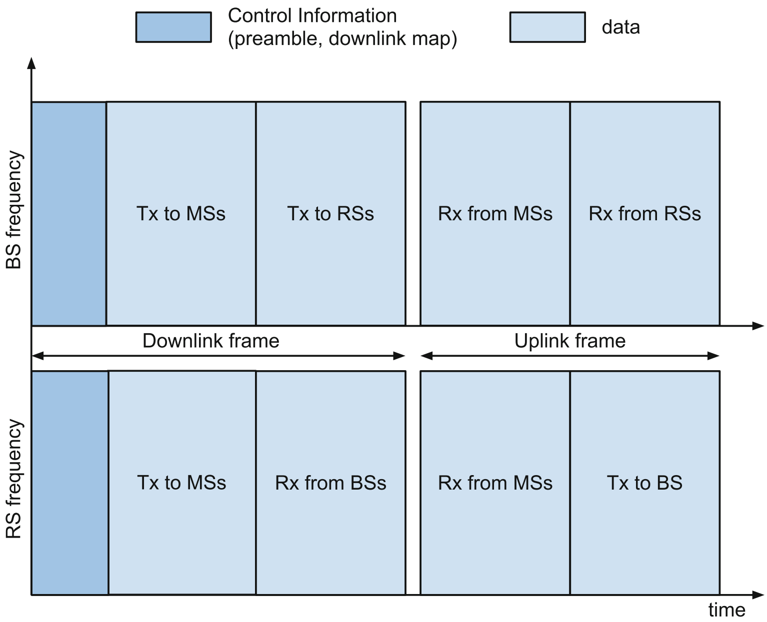

Fig. 2.14 Frame structure of 802.16j in non-transparent relay mode

- Relay zone: In the relay zone, RSs transmit their data to BS.

Since the maximum number of hops in transparent relaying is no more that two, the above mentioned division of UL and DL works well. The same can be defined when using non-transparent relaying as below.

Non-Transparent Relay Stations (NT-RS): Frame Structure

In non-transparent relays, framing and synchronization information is sent by the RSs, in addition to by the BS. This is shown in Fig. 2.14. In this case, during DL access zone, BS and RSs transmit information to their associated MSs. During the DL relay zone, BS sends out information to RSs. During the UL access zone, MSs send information to their BS or RS, while during UL relay zone, RSs transmit information to the BS.

Note that this is simple when there are only two hops in non-transparent topology, but the case where there are more than two hops between MS and BS require more attention. The problem can be solved by having multiple relay zones in UL and DL as shown in Fig. 2.15. The hierarchical handling of RSs and MSs requires the introduction of more zones, with some stations inactive in certain zones to let the information percolate through the hierarchy.

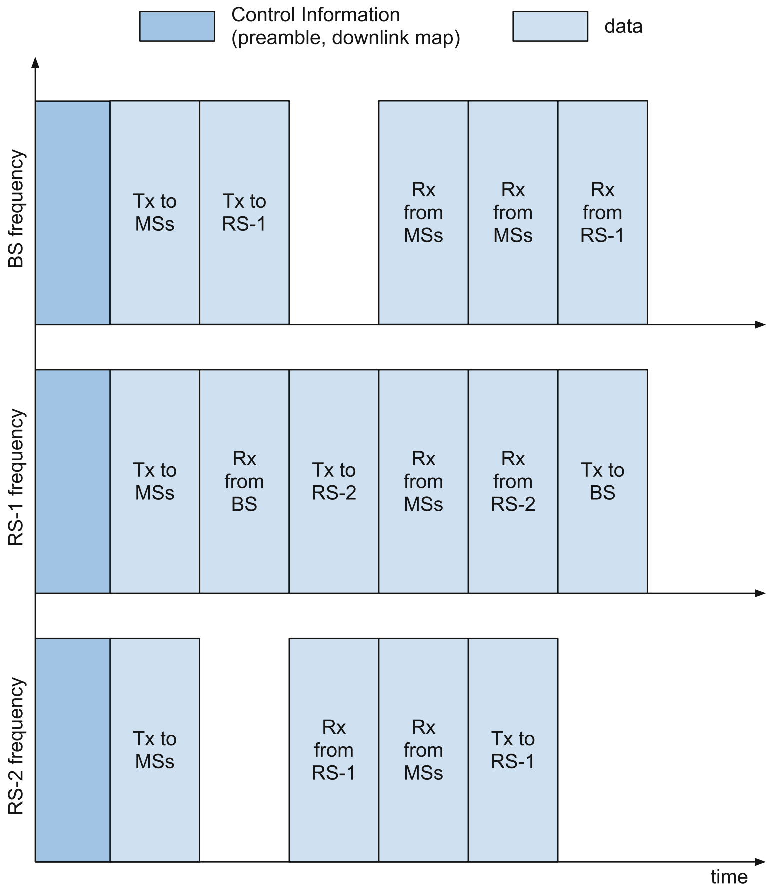

Fig. 2.15 Frame structure 802.16j in non-transparent relay mode with two levels of relay stations

2.3.1.4 MAC Layer Modifications: RMAC and Tunneling

As we noted before, link scheduling in MCNs can be centralized (transparent RS) or distributed (non-transparent RS). Also, it is worth noting that data exchange between MS and BS is in general connection-oriented. This means that every connection initiated by MS or BS receives a unique connection ID. In the case where a MS connects to a RS, the connection ID is provided by the RS. To further support connections, 16j includes a MAC protocol called R-MAC. In R-MAC, various connections initiated at MSs connected to a RS can be treated as a single connection from the point of view of other intermediate RSs. This way, tunneling abstracts the difference between various connections for the intermediate RSs. The access RS and the BS can interpret the tunneled connections. The tunneling support of R-MAC protocol has multiple advantages. First, it ensures that MSs are unaware of intermediate RSs in order to provide backward compatibility with 16e MS devices. Second, since one of the goals of relays is to satisfy highly localized traffic pattern, multiple MS connections from such a hot-spot can be treated as a logically stand-alone connection. During procedures like handoffs, this tunneled connection can be handed over to another cell as if all the MSs of the tunneled connections are moving together.

Other specific issues which are the topics of active research, such as relay placement (Lin et al. 2007), security (Dai and Xie 2010) etc. involved in 16j design are discussed in later chapters.

2.3.2 3GPP LTE-Advanced Relaying

The ongoing development of the Long Term Evolution standards by the 3GPP organization to meet the International Telecommunication Union's requirements of 4G cellular standards provides another example of the introduction of relaying into a framework originally designed for single- or two-hop communication. ITU (ITU-R 2008) has stated the following requirements for realizing true 4G mobile systems:

- High mobility environment (speed <350 Kms/h)
  - Peak data rate of 100 Mbps
  - Average case latency of 100 ms
- Low mobility environment (speed <10 Kms/h)
  - Peak data rate of 1 Gbps
  - Average case latency of 10 ms

Systems using the 3GPP LTE-Advanced (Abeta 2010; Bai et al. 2012; Ghosh et al. 2010; Lo and Niemegeers 2009; Mogensen et al. 2009; Sawahashi et al. 2009; Wirth et al. 2009; Yang et al. 2009) Release 10 (currently under process of standardization at ITU-T) have the potential to achieve these requirements. LTE-A includes advanced physical layer technologies such as carrier aggregation etc. and also includes relaying.

As in the case of 802.16j, the purpose of relaying in LTE-A systems is twofold, embodied by two types of relay stations proposed.

- Type-1 Relay Stations: They are similar to 802.16j non-transparent stations. Their purpose is to extend coverage to MSs beyond the coverage region. Conceptually the only differences between Type-1 relay stations of LTE-A and non-transparent relay stations of 802.16j are that LTE-A does not allow more than two hops in relaying, in order to guarantee improved latency.
- Type-2 Relay Stations: They are similar to 802.16j transparent stations. Their purpose is to improve the signal quality and quality of service to MSs within the cell of the BS.

Apart from the differences mentioned above, relaying in LTE-A and 802.16j standards are very similar in concept. Individual design problems of relaying in MCNs will be discussed further in later chapters.

2.4 Cognitive Radio Networks

In the last decade, the proliferation of wireless technology standards have given rise to the problem of spectrum scarcity. This is due to the fact that spectrum allocation authorities have traditionally used fixed block assignment scheme for newer technologies. As an example, such a problem has been reported by the US FCC (FCC 2002). Depending on the current utilization of wireless technologies, it has been observed that certain blocks of spectrum are underutilized while other parts are overly congested. The 400–700 MHz spectrum block that is only utilized sporadically provides an example, while the ISM bands (especially 2.4 GHz) are excessively crowded.

Dynamic Spectrum Access, or *cognitive radio* technology can be used to mitigate the spectrum scarcity. Cognitive radios can dynamically access the spectrum when it is not in use. The term was first introduced by Mitola and Maguire (1999) and subsequently used by seminal work such as by Akyildiz et al (2006), Haykin (2005). A cognitive radio has the ability to sense the medium widely, re-configure itself to transmit in some targeted spectrum, and thus utilize the medium dynamically. An unutilized spectrum block (typically known as “white space”) can be exploited in temporal, spatial and frequency domain in order to use it for communication. In the context of cognitive radio, spectrum users can be divided into two classes—primary and secondary users. The primary users are incumbent users who have licensed access to the spectrum block, and their access to the block must be given the highest priority. On the other hand, the secondary users access the spectrum opportunistically whenever the primary users are not using the spectrum. This is shown in Fig. 2.16.

2.4.1 Cognitive Mesh Networks

The cognitive radio technology holds a special importance in design and development of wireless access networks especially wireless mesh networks. This is because one of the most widely adopted wireless standard—802.11 standard operates in the ISM band. The current infrastructure deployments of 802.11 has resulted in congestion in the ISM band (Akella et al. 2005). Apart from this, other technologies such as Bluetooth has resulted into the ISM band being excessively utilized. Since most of the wireless mesh networks are deployed using 802.11 radio technology, they are expected to further contend for access to the ISM band. To address the issue, cognitive radios are necessary at each mesh node to detect and opportunistically switch to non-congested channels. This can yield improved performance because of its dynamic access to medium.

There are numerous design challenges when designing a mesh network where mesh nodes opportunistically switch to vacant white spaces in order to improve the performance. First and foremost, due to dynamic spectrum access, mesh nodes no longer share a common control channel that can be used to exchange necessary control information. It was shown by Zhao et al. (2005) that neighboring nodes

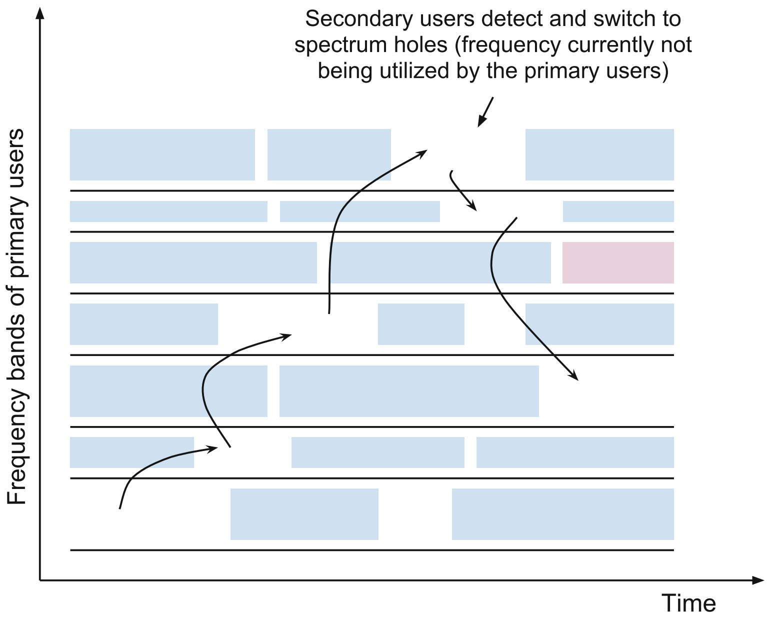

Fig. 2.16 Secondary users can dynamically access different parts of the spectrum opportunistically when they are not being utilized by the primary users

may have some common channels that are vacant for them simultaneously but the network-wide availability of a common vacant channel is very rare. This requires that nodes operate using a distributed control plane which in turn imposes numerous design challenges for upper-layer protocols.

In order to design efficient upper-layer protocols, it is first necessary to understand the interference relationship between primary and secondary users. There are two types of interference models largely used.

- Binary interference model: whenever there is any activity of primary users in a given channel, the channel becomes useless for secondary users.
- Interference temperature model: secondary users can communicate via a channel that is currently being utilized by primary users if the interference caused by secondary users to the primary users is below a certain pre-defined interference temperature threshold.

It is clear that interference temperature model is more general but further complicates the design problems.

2.4.2 IEEE 802.22

The issue of spectrum scarcity and under-utilization, and potential solution using cognitive radio has attracted tremendous interest from both research community and standardization bodies. One of the first standards to be developed using this cognitive radio technology is IEEE 802.22. The standard aims to utilize the unused spectrum of broadcast television service to provide broadband access to rural areas with low population density. These unused TV spectrum bands are often referred as TV white spaces. Even though the standard does not specify implicit support for multi-hop networking, in such cases mesh networking can be especially useful in rural regional networks.

2.4.3 TV White Spaces

The reports FCC (2004, 2006) outline how and which TV channels can be used for the purpose of rural broadband development. Figure 2.17 shows the spectrum and its channels that are made open as TV white spaces. As shown, channels above 700 MHz were auctioned to wireless service providers by the FCC in 2008. Due to the transition to digital television, FCC was able to free the TV white space block in 2009. These channels are 5–13 in the VHF band and 14–51 in the UHF band. The usage of the channel for secondary users is only permitted so that no interference is caused to the licensed TV subscribers and other low power devices such as wireless microphones.

Secondary users can either attempt to predict the activities of primary users or can use readily available information from any third party. In 802.22, there are two ways by which secondary users can perceive the activities of primary users.

- Geo-location database: In this method, devices equipped with GPS can query the central database using their location to determine the activity of primary users. This approach is especially useful for low-mobility or fixed devices.
- Spectrum sensing: Secondary users can sense the medium for its availability and utilize the information to make the transmission decision. This method is especially attractive since it does not require any central authority for decision making. On the other hand, the method is also very difficult to implement since even neighboring nodes might end up determining different information about the spectrum. This distributed sensing and decision making has attracted a lot of research which we will cover in later chapters.

Further details of 802.22 standard, its PHY and MAC layer considerations can be found in Stevenson et al. (2009). Figure 2.18 shows a network in which nodes of mesh network operate as secondary nodes to primary network of TV broadcast stations and its subscribers. Such networks have been studied by Akyildiz et al. (2009), Chen et al. (2008), Chowdhury and Akyildiz (2008) and others. In such a case, mesh nodes can have multiple frequency-agile radios to serve the associated clients and facilitate intra-mesh communications.

	TV Channel No.	Start - end Frequency (MHz)
Ultra High Frequency (UHF) Band	51	692 - 698
	50	686 - 692
	49	680 - 686
	48	674 - 680
	47	668 - 674
	46	662 - 668
	45	656 - 662
	44	650 - 656
	43	644 - 650
	42	638 - 644
	41	632 - 638
	40	626 - 632
	39	620 - 626
	38	614 - 620
	37	608 - 614
	36	602 - 608
	35	596 - 602
	34	590 - 596
	33	584 - 590
	32	578 - 584
	31	572 - 578
	30	566 - 572
	29	560 - 566
	28	554 - 560
	27	548 - 554
	26	542 - 548
	25	536 - 542
	24	530 - 536
	23	524 - 530
	22	518 - 524
	21	512 - 518
	20	506 - 512
	19	500 - 506
	18	494 - 500
	17	488 - 494
	16	482 - 488
	15	476 - 482
	14	470 - 476
Very High Frequency (VHF) Band	13	210 - 216
	12	204 - 210
	11	198 - 204
	10	192 - 198
	9	186 - 192
	8	180 - 186
	7	174 - 180
	Channels used for FM, Ham and military applications	88 - 173
	6	82 - 86
	5	76 - 82
	4	66 - 72
	3	60 - 66
	2	54 - 60

Fig. 2.17 TV white space spectrum

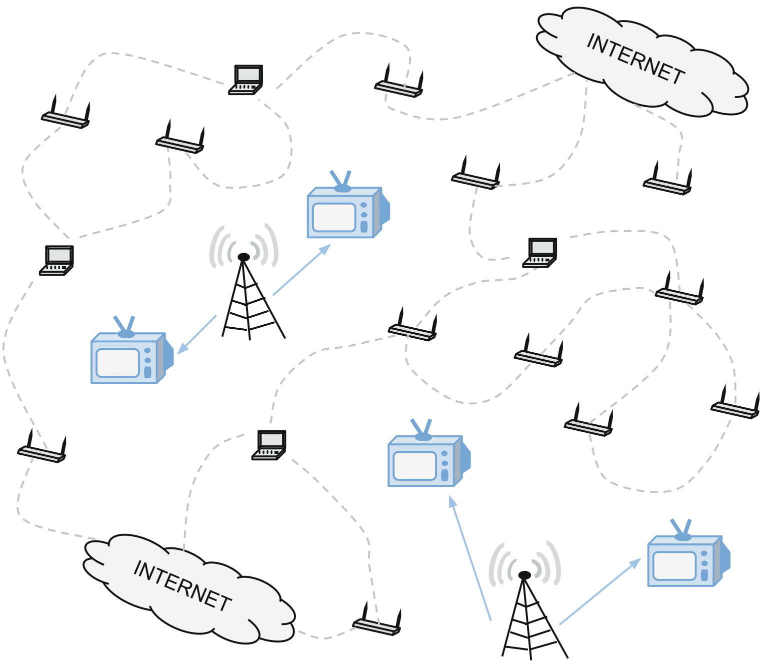

Fig. 2.18 Mesh routers operating as secondary users in holes of TV white space spectrum

One major advantage of TV white space is that FCC has not enforced any specific physical layer mechanisms (such as modulation etc.). This can allow the TV white spaces to be treated as an ISM band, and numerous devices, technologies and applications can be developed. (It should be noted, however, that the concern that white space networking may impact incumbents has led the FCC to mandate a tighter spectrum mask for TV white space use, so that existing 802.11 devices cannot be simply frequency-shifted and used in this spectrum.) In order to understand the success of such white space-based technology, it is first necessary to understand when and how much vacancy is indeed available in these channels. To this end, Chowdhury et al. (2011) first studied the availability of TV white spaces using USRP2 (Ettus 2009) radios. They observed a large variation in the mean received power on channels 21–51, indicating the potential for white space usage. They noted that the temporal behavior of the signal introduces further complexity.

While white space networks may be promising for the future of mesh networking, at this time they are far from being as mature as the existing technology we have previously described in this chapter. Especially from the point of view of designing mesh networks for predictable performance and behavior, cognitive radio technology appears to be a research horizon rather than a development one. Individual design problems such as sensing, collaboration among cognitive radio nodes, and their upper layer protocols will be discussed in later chapters.

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