

IEEE 802.11h: Technology and Application

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I. INTRODUCTION

Portable computing and communication devices, such as laptops and PDAs, have become increasingly popular, and more and more people rely on various wireless networks to communicate with each other. In recent years, IEEE 802.11 WLAN (Wireless LAN) has become the dominant technology for indoor broadband wireless networking. The vision of pervasive ubiquitous computing, where users have Internet access anytime and anywhere, is being realized by the wide deployment of public WLANs, commonly known as *hotspots* [1], in public places of congregation such as conference venues, airport lounges, and coffee shops. According to reports by DataMonitor.com [2], at the end of year 2003, there were a total of 31,580 hotspots serving 1.53 million users around the world, and these numbers are expected to at least quadruple within the next three years.

IEEE 802.11 Working Group (WG) [3] started its standardization activities in 1991, and published the original 802.11 standard in 1997 and revised in 1999 [4], which specifies the protocols for both MAC (Medium Access Control) sub-layer and PHY (physical) layer. During the past few years, the 802.11 WG has been working on the standardization of new specifications to enhance the performance of the 802.11 WLAN. Fig. 1 illustrates the relationship among the existing and emerging specifications [5], where the direction of each arrow specifies the original and amended standards. For example, the 802.11e [6] MAC is an amendment of the 802.11 MAC, and the 802.11h [7] involves both MAC and PHY amendments.

In this article, we focus on the 802.11h specification for spectrum and transmit power management. We overview the two new mechanisms the 802.11h defines on top of the 802.11 MAC and the 802.11a PHY [8], namely, DFS (Dynamic Frequency Selection) and TPC (Transmit Power Control), and then describe an example

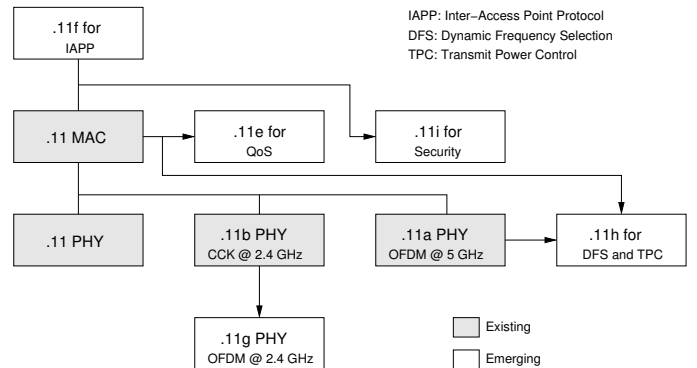


Fig. 1. IEEE 802.11 MAC/PHY and its various enhancements

DFS algorithm and an intelligent TPC mechanism as sample applications of the 802.11h.

II. IEEE 802.11H FOR SPECTRUM AND TRANSMIT POWER MANAGEMENT

The 802.11h was originally developed to extend the 802.11 operation in the 5 GHz band in Europe. In order to co-exist with the primary users in the 5 GHz band in Europe — the radar and satellite systems, the 5 GHz WLAN devices are required to support DFS (Dynamic Frequency Selection) and TPC (Transmit Power Control). For example, the WLAN devices are required to switch its operational frequency channel to another channel once a radar signal is detected in the current channel. On the other hand, when a satellite signal is detected, the WLAN devices are allowed to use the transmit power up to the regulatory maximum minus 3 dB while normally they can transmit at up to the regulatory maximum level. The 802.11h defines the DFS and TPC mechanisms on top of the 802.11 MAC and the 802.11a PHY for these purposes. Note that, even though the 802.11h has been developed to satisfy the European regulatory requirements, it can be apparently used in other countries for multiple purposes, such as automatic

frequency planning, reduction of energy consumption, range control, reduction of interference, and QoS (Quality of Service) enhancement.

Fig. 2 illustrates the layer management model in the 802.11h to realize the DFS and TPC functions. Policy decisions, such as channel switching and transmit power control, reside in the SME (Station Management Entity), while the associated protocols reside in the MLME (MAC subLayer Management Entity). Interactions between entities are via SAPs (Service Access Points) across which primitives are defined and exchanged.

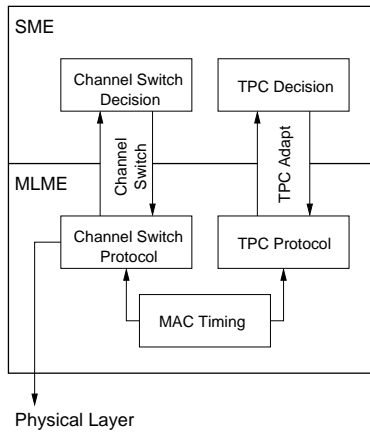


Fig. 2. Layer management model in the 802.11h

Both DFS and TPC involve implementation-dependent algorithms. For example, a TPC algorithm is needed in order to determine the transmit power level of a frame transmission; the 802.11h only defines the mechanisms/protocols to enable a right decision of the power level, not the implementation itself.

A. DFS (Dynamic Frequency Selection)

BSS (Basic Service Set) is the basic building block of an 802.11 WLAN and it consists of a set of stations controlled by a single coordination function and operating in the same frequency channel. An 802.11a/h BSS occupies a channel of 20 MHz and there are 12 channels available for the 802.11a in the U.S. and 19 channels available for the 802.11h in Europe. DFS is used to switch the operational frequency channel of a BSS to another dynamically. In addition to fulfilling the regulatory requirements, there can be many other reasons why a BSS may want to change its operational frequency channel. One interesting example is when the current channel condition is too bad due to the interference from

neighboring devices. In this context, DFS can be used to enhance the QoS of the WLAN.

In an infrastructure BSS, which consists of an AP (Access Point) and multiple stations associated with the AP, it is the AP who determines when to switch and which channel to switch to. For this purpose, the AP should monitor the status of the current and other frequency channels and it may also request other stations to measure and report the channel status. There are three types of measurement:

- Basic type — determines whether another BSS, a non-802.11 OFDM signal, an unidentified signal, or a radar signal is detected in the measured channel;
- CCA (Clear Channel Assessment) type — measures the fractional duration of the channel busy period during the total measurement interval;
- RPI (Received Power Indication) histogram type — measures the histogram of the quantized measures of the received energy power levels as seen at the antenna connector during the measurement interval.

Based on its own measurement as well as the reports from the associated stations, the AP continues to monitor the channel status so that the channel switching can be conducted at a proper instance. The channel switching occurs immediately before a TBTT (Target Beacon Transmission Time), which is specified by the AP, so that a normal communication operation can be conducted for the following Beacon interval at the new operational frequency channel. Note that the Beacon frames are transmitted periodically. The channel-quieting operation is also defined since the European regulation requires the station to become silent once a radar system is detected in the operational frequency channel. An example DFS algorithm for the infrastructure-based 802.11h system is described in Section III.

In an independent BSS, which consists of multiple stations but without an AP, a similar protocol is defined for the DFS operation. Basically, in such a network, the wireless station who initiated the BSS is called the DFS owner, and it takes the responsibility of collecting the channel status as well as making the channel-switching decision.

B. TPC (Transmit Power Control)

For wide-area cellular systems, such as IS-95 CDMA (Code-Division Multiple Access) and 3G W-CDMA (3rd Generation Wide-band CDMA), TPC is critically important in order to (1) ameliorate the near-far problem,

specifically, for CDMA uplink transmissions; (2) minimize the interference to/from other cells, i.e., co-channel interference; and (3) improve the system performance on fading channels by compensating fading dips. In comparison, most of today's 802.11 devices use a fixed transmit power for the frame transmissions, and TPC in 802.11 WLANs was not considered as critical to success as in CDMA systems.

In recent years, TPC in 802.11 WLANs has attracted more and more attention since the 802.11a devices are required to support TPC in order to operate in Europe and meet the regulatory requirements. Moreover, as most WLAN devices such as laptops and palmtops are battery-powered, and extending the operation time of such devices is always desirable and important, applying TPC to save the battery energy is also an attractive idea. Furthermore, in the multi-cell WLANs often found in office and public access environments, reducing the inter-cell interference via TPC could be quite beneficial as well since it results in better error performance in a given area.

The 802.11h specifies two TPC-related functions. First, the AP in an infrastructure BSS or a wireless station in an independent BSS advertises the regulatory and local maximum power level for the current frequency channel in the Beacon and Probe Response frames using the combination of a Country element and a Power Constraint element. The local maximum specifies the actual maximum power level allowed in the BSS, and it is smaller than or equal to the regulatory maximum. The stations in the BSS can use any transmit power smaller than or equal to the local maximum value.

Second, the 802.11h provides a transmit-power reporting mechanism. It defines a TPC Report element that contains a Transmit Power field and a Link Margin field, where a TPC Report element is included in a TPC Report frame in response to a TPC Request frame. The Transmit Power field simply contains the transmit power used to transmit the frame containing the TPC Report element, and the Link Margin field contains the link margin calculated as the ratio of the received signal strength of the corresponding TPC request frame to the minimum desired by the station. Besides, the AP in an infrastructure BSS or a wireless station in an independent BSS autonomously includes a TPC Report element with Link Margin field set to zero and containing its transmit power information in any Beacon frame it transmits.

An immediate impact of such transmit-power reporting mechanism is that energy-efficient frame transmissions now become feasible in 802.11h WLANs. In general, to

determine the proper transmit power level for a given frame, a wireless station needs to estimate the link quality between itself and the receiver. With the 802.11h, a simple link-quality estimation scheme may work as follows. Whenever a wireless station receives a frame containing the TPC Report element, with the knowledge of the received signal strength via RSSI (Receiver Signal Strength Indicator) as well as the transmit power contained in the TPC Report element, the wireless station can estimate the link quality (in terms of path loss) from the sending station to itself by performing a simple subtraction. An intelligent TPC mechanism, called *MiSer*, based on this link-quality estimation scheme is presented in Section IV.

III. AN EXAMPLE DFS ALGORITHM

In general, a DFS algorithm for an infrastructure-based 802.11h system consists of the following two phases: startup phase and regular phase. At startup, the AP performs a full DFS measurement on all frequency channels. Based on the measurement results, the AP selects a starting frequency channel that is not occupied by the primary users for its BSS. Moreover, the AP tries to avoid selecting the frequency channels that are already used by other secondary users, e.g., other operating 802.11a/h systems.

Once the starting frequency has been decided, the AP begins broadcasting Beacon frames so that the wireless stations can detect its presence and associate themselves with the AP. The BSS is then started and enters the Normal Operation state of the regular phase. The DFS algorithm in the regular phase can be better described with a finite state machine [9], as shown in Fig. 3, with four different states: *Normal Operation*, *Channel DFS Test*, *Full DFS Test*, and *Frequency Change*.

The BSS remains in the Normal Operation state until either the measurement timer expires or the link quality degradation occurs which suggests possible appearance of interference sources. In case the timer expires, state is changed to Channel DFS Test, during which the AP re-assesses the current operating frequency channel. If the channel status is good enough to continue operation, state is changed back to Normal Operation; otherwise it is changed to Full DFS Test, during which the AP performs a full DFS measurement on all frequency channels. Notice that, during the normal operation, if the link quality degradation occurs, state is changed directly to Full DFS Test.

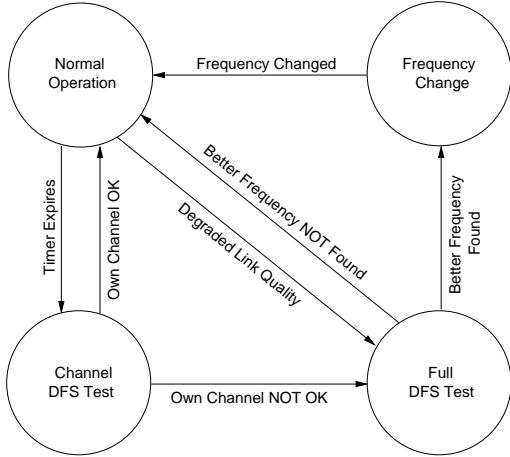


Fig. 3. Finite state machine for a DFS algorithm

In the Full DFS Test state, the AP measures or asks wireless stations to measure all the frequency channels. Then, based on the measurement results, the AP makes the channel switching decision. If the current frequency channel is the best in terms of link quality, the BSS continues operation in the current channel and state is returned to Normal Operation; otherwise state is changed to Frequency Change. In the Frequency Change state, the AP wakes up all the sleeping wireless stations, if any, and announces what the new frequency channel is and when the operation in the new frequency channel will start. Finally, after the frequency channel is successfully switched, state is returned to Normal Operation.

IV. MISER: AN INTELLIGENT TPC MECHANISM

According to the 802.11 standard, a WLAN device can operate in one of the following modes: *transmit mode*, *receive mode*, *idle mode*, or *doze mode*. It consumes the highest power in the transmit mode and very little energy in the doze mode. In the idle mode, a WLAN device is required to sense the wireless medium, and hence, consumes a similar amount of power as when it is in the receive mode. Many power-management policies [10] have been proposed to force a WLAN device to enter the doze mode adaptively at appropriate moments to save battery energy. An alternative way to conserve energy is to apply TPC in WLAN systems, which allows a WLAN device to use the minimum required power level in the transmit mode and is complementary to the power-management policies.

With support of the transmit-power reporting mechanism, an 802.11h wireless station can estimate the link

quality between itself and the receiver and, hence, is able to apply intelligent TPC to minimize the communication energy consumption. MiSer (Minimum-energy transmission Strategy) [11] reflects our latest research results on the topic, and it is an intelligent TPC mechanism for 802.11h systems.

A. MiSer Design

Due to the contention nature of the 802.11 DCF (Distributed Coordination Function) [4], the effectiveness of MiSer relies on the condition that applying TPC to data transmissions will not aggravate the “hidden nodes” problem or the interference in the network. For this reason, MiSer exchanges short RTS (Request-To-Send) and CTS (Clear-To-Send) frames before each data transmission attempt to deal with the “hidden nodes” problem. More importantly, it is deployed in the format of RTS-CTS(strong)-Data(TPC)-Ack, which not only allows the data frames to be transmitted at lower power levels to save energy, but also ameliorates the potentially aggravated interference caused by TPC by transmitting the CTS frames at a stronger power level.

MiSer uses a simple table-driven approach to determine the most energy-efficient combination of transmission rate and transmit power for each data frame. The basic idea is that a wireless station computes offline a rate-power combination table indexed by the data transmission status and each entry of the table is the optimal rate-power combination in the sense of maximizing the energy efficiency under the corresponding data transmission status. Here, *data transmission status* is characterized by the data payload length, the path loss between the transmitter and the receiver, and the number of unsuccessful transmission attempts for the data frame, and *energy efficiency* is defined as the ratio of the expected delivered data payload to the expected total energy consumption. At runtime, the wireless station estimates the path loss between itself and the receiver, updates the data transmission status, and then selects the proper transmission rate and transmit power for the current data transmission attempt by a simple table lookup.

B. MiSer Performance

Fig. 4 shows a snapshot of MiSer’s rate-power combination table with certain data payload length and number of unsuccessful transmission attempts. The optimal combinations of transmission rate and transmit power, which

achieve the most energy-efficient data communications, under different path loss conditions are shown in Fig. 4(a) and (b), respectively. For example, when the path loss is 80 dB, this figure reads that the most energy-efficient strategy is to transmit at 54 Mbps with 9 dBm power. Other snapshots can be viewed approximately as shifted versions of Fig. 4. In general, when a data frame carried a larger payload or less transmission attempts remain for a data frame, the figure shifts left and a more conservative combination (i.e., lower rate and/or higher power) is selected under the same path loss condition; otherwise, it shifts right.

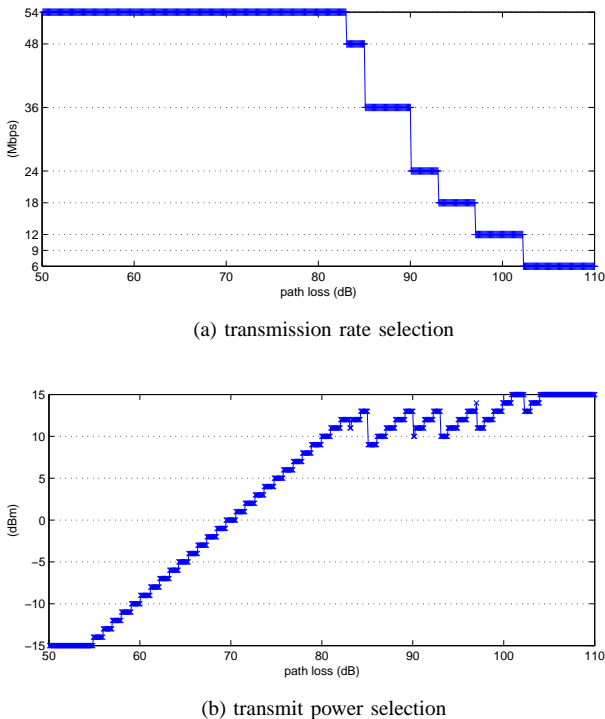


Fig. 4. A snap shot of MiSer's rate-power combination table

Simulation results show MiSer's clear superiority to the two-way Data-Ack frame exchange mechanisms in the presence of hidden nodes. Besides, compared with other four-way RTS-CTS-Data-Ack frame exchange mechanisms, MiSer delivers about 20% more data per unit of energy consumption than the transmission rate adaptation (alone without TPC) scheme, and outperforms single-rate TPC schemes significantly thanks to the excellent energy-saving capability of transmission rate adaptation.

V. CONCLUSION

The IEEE 802.11 WLAN has become very successful in the U.S. market as the prevailing technology for indoor

broadband wireless networking. Along with its success, the demand on the evolution of the technology became evident. During the past few years, remarkable efforts have been made to enhance the current 802.11, and the 802.11h is the one specifically developed to extend the 802.11 operation in the 5 GHz band in Europe. Even though the 802.11h was originally developed to satisfy the European frequency and power regulatory requirements, it can be used in other countries for additional purposes, such as automatic frequency planning, reduction of energy consumption, range control, and QoS enhancement. In this paper, we overview the key components of the 802.11h, namely, DFS and TPC, and describe corresponding example algorithms to apply DFS for automatic frequency planning and to apply TPC for energy conservation, respectively.

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