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MAC-Layer Packet Loss Models for Wi-Fi Networks: A Survey

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ABSTRACT Technical reports indicate that wireless and mobile devices will account for 71% of all IP traffic by 2022, an increase of 19% over four years. This increase is related to advances in wireless data communication technologies. Wireless networks have become one of the most important ways to connect devices to the Internet, therein improving productivity and encouraging information sharing. IEEE 802.11, known as Wi-Fi, has become the main standard for wireless local area networks. The most important metrics for measuring the quality of Wi-Fi are delay, jitter, and packet loss. Packet loss occurs when one or more packets fail to reach their destination and can occur for a variety of reasons. Packet loss influences the user's perceived quality of applications over Wi-Fi networks, mainly multimedia and real-time applications. The availability of accurate models for packet loss in Wi-Fi networks enables the development of more efficient methods for performance analysis and network design, as well as better computational simulations. Modeling packet loss in such networks presents a major challenge because packets may be lost for many different reasons, including signal attenuation, noise, multipathing, signal refraction, thermal noise, competition for media access and buffer issues. In this paper, we provide an overview of the causes of packet loss and a comprehensive survey of the available models for packet loss in Wi-Fi networks. The potential benefits of the survey are: (i) the systematic presentation of available packet loss models for Wi-Fi networks, their parameters, and respective packet loss rate evaluation, (ii) comparison of models considering validation scenarios and input parameters, and (iii) description of open issues and future research directions. We hope that our analysis will help researchers understand the most important characteristics of the packet loss process in Wi-Fi networks and the strengths and weaknesses of the main packet loss models.

INDEX TERMS Gilbert-Elliot model, packet loss model, packet loss rate, Wi-Fi communication.

I. INTRODUCTION

IEEE 802.11 is a set of specifications for Wireless Local Area Networks (WLANs). Since 1997, when the IEEE 802.11 standard was released, it has been continuously upgraded to improve throughput, security, reliability and quality of service, among other functionalities [1]. Wi-Fi (wireless fidelity) includes IEEE 802.11a/b/g/n standards for WLAN that allow users to surf the Internet at broadband speeds [2] but also includes newest versions such as IEEE 802.11af/ac (2013) and IEEE 802.11ax (2019) [3]. Advances in wireless communication systems have resulted in substantial growth in the number of Wi-Fi-enabled devices, which in turn has facilitated the development of new, cheaper devices and applications with reduced power consumption [4].

The rapid innovations in the wireless data communication area have increased services and application available to mobile device users worldwide. Wi-Fi networks have become very popular and are common in homes, offices, public parks, shops, airports, and hotels. The main applications supported by Wi-Fi are audio/video streaming, web browsing, file sharing, chatting and e-mail [1]. For video streaming, a considerable increase in data traffic is expected due to emergent video coding technologies, e.g., 8K resolution and scalable

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video coding [5]. According to Cisco [6], by 2022 Wi-Fi and mobile networks will account for 71 percent of IP traffic. In 2017 Wi-Fi networks accounted for 43% of all global IP traffic.

A model is an abstraction or a simplified representation of a real or conceptual system and is designed to exhibit significant characteristics of the system that one wishes to study, predict, modify or control [7]. Thus, a model includes some aspects, but not all, of the system being modeled. According to Fournier [8], a model is an ideal representation intended to precisely capture all the relevant properties of the original system and usually involves stochastic components. A packet loss model is valuable when providing useful insights, predictions, and answers to the system under study [7].

Packet loss models for digital communications have been proposed since the 1960s and seek to represent packet loss behavior in real networks. Techniques for modeling and simulating play an important role in understanding the behavior of wireless systems, and analytical models that can describe the packet loss process have proved to be useful in analyzing the performance of wireless networks [9]. The first models for packet loss only considered errors in the physical layer. At the physical layer, the main causes of packet loss in Wi-Fi networks are low signal power, noise, interference, and multipath fading [10], [11]. However, packet loss in Wi-Fi networks can have many causes, including physical and link layer problems. At the link layer, the main causes of packet loss in Wi-Fi networks are buffer overflow, bufferbloat, queuing delay, collisions, and malicious attacks. In the last case, it is difficult to determine whether packet losses are actually the result of malicious attacks or other causes [12]. Mitigating the impact of packet loss could result in important performance improvements, especially for real-time applications such as live video streaming [13]–[15] and voice conferencing [16].

A. CONTRIBUTIONS AND ORGANIZATION

The contributions of this work can be summarized as follows:

- Summary of the main causes of packet loss in Wi-Fi networks.
- Systematic analysis of available models for packet loss in Wi-Fi networks considering the joint effects of physical and MAC layers.
- Description of open issues and future research directions for packet loss models of Wi-Fi networks.

Including this introductory section, the remainder of this paper is organized as follows: Section II presents an overview of the IEEE 802.11 standard. Section III introduces the main causes of packet loss. The packet loss models are presented in Section IV and then compared in Section V. Open issues and future research directions are presented in Section VI. Finally, Section VII presents the conclusions.

II. AN OVERVIEW OF IEEE 802.11

Wi-Fi connectivity for smartphones, tablets, and computers is now well established, and IEEE 802.11 specifications have become the main standard for local area networks. Over the years, several versions of IEEE 802.11 have been released such as 802.11b, 802.11g, and 802.11n [17]. The 802.11 series of standards are designed to be backward compatible and compatible at the MAC link layer. Backward compatibility is an important requirement to ensure interoperability between devices due to the wide diversity of device types and different available networks. Additionally, the Wi-Fi specification provides some optional requirements that manufacturers may or may not implement in their products.

IEEE 802.11 uses 802 logical link control (LLC) to provide an optimized physical layer (PHY) and specifies the medium access control (MAC) and physical sub-layers for wireless communication [18], as shown in Figure 1.

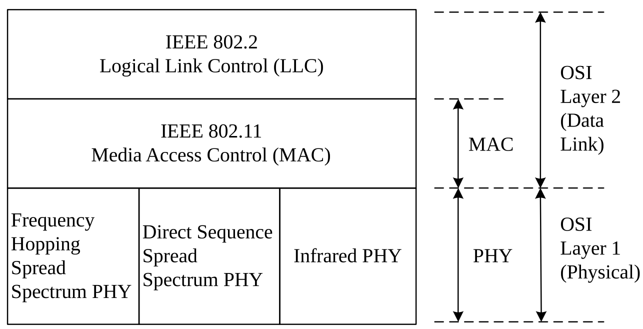

FIGURE 1. Standard for MAC and physical layer for WLANs.

The architecture of IEEE 802.11 is built through a basic service set (BSS), as shown in Figure 2. A BSS is defined as a group of stations under direct control of a single coordination function, as defined later in subsection II-B. The operation area of a BSS is known as the basic service area (BSA), where all stations can communicate with each other.

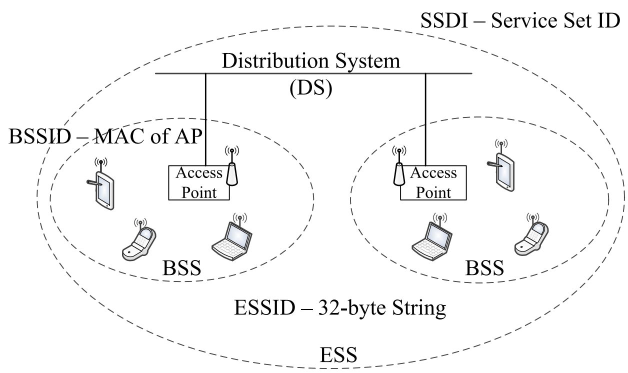

FIGURE 2. Extended service set architecture.

IEEE 802.11 defines two modes of operation:

- infrastructure mode: stations communicate through an access point (AP) [19],
- ad-hoc mode: stations communicate with each other directly [20].

The ad-hoc mode is also known as independent BSS (IBSS) because the communication between the stations

TABLE 1. IEEE 802.11 standard family specifications [18], [27]–[29].

802.11 protocol	Release date	Frequency	Bandwidth	Data Rate (Min-Max)	MIMO streams	Modulation Scheme
802.11	Jun 1997	2.4 GHz	22 MHz	1-2 Mbps	1	DSSS, FHSS
a	Sep 1999	3.7/5 GHz	20 MHz	6-54 Mbps	1	OFDM (SISO)
b	Sep 1999	2.4 GHz	22 MHz	1-11 Mbps	1	DSSS (SISO)
g	Jun 2003	2.4 GHz	20 MHz	6-54 Mbps	1	OFDM, DSSS (SISO)
e	Sep 2005	5 GHz	20 MHz	6-54 Mbps		OFDM
n	Oct 2009	2.4/5 GHz	20 MHz 40 MHz	7.2 -72.2 Mbps (20 MHz) 15 - 150 Mbps (40 MHz)	4	OFDM (MIMO)
ad	Sep 2010	60 GHz	2160 MHz	385-4620 Mbps	>1	Single Carrier, OFDM
ac	Dec 2013	5 GHz	20 MHz 40 MHz 80 MHz 160 MHz	7.2 - 96.3 Mbps (20 MHz) 15 - 200 Mbps (40 MHz) 32.5 - 433.3 Mbps (80 MHz) 65 - 866.7 Mbps (160 MHz)	8	OFDM (MU-MIMO)
af	Feb 2014	0.47-0.71 GHz	6, 7, 8 MHz	569 Mbps	45	OFDM (MIMO)
ah	May 2017	0.9 GHz	1, 2, 4, 8, 16 MHz	Up to 347 Mbps	4	OFDM (MIMO)
ax	2019	2.4/5 GHz	20, 40, 80, 160 MHz	Up to 9.6 Gbps	-	OFDMA

within the BSS is performed without the need for management by a central node or controller. A wireless ad-hoc network (WANET) is a set of services that has gained extensive interest from developers and industrial companies, especially in scenarios with high levels of station mobility such as Vehicular (VANET) and Mobile (MANET) networks [21], [22], Internet-based mobile communication, military applications, and tactical ad-hoc networks.

On the other hand, the infrastructure mode's AP generally remains stationary and concentrates all traffic between stations. The AP announces the BSS through beacon messages containing its link layer address (BSSID) and the network identifier name (SSID). Station devices associated with the AP leave all coordination of network functionality to the AP [23].

The use of mixed mode, therein combining infrastructure and ad-hoc modes, was investigated as an opportunity to improve network performance [24]. The AP can provide necessary integration for networks between multiple BSSs, resulting in an extended service set (ESS). The ESS can be described as one large BSS to the LLC sublayer of each station and extends the coverage area to a single BSS. The ESS consists of multiple BSSs integrated together using a common distribution system (DS). The DS can be understood as a backbone responsible for transporting MAC service data units (MSDUs) and is specified in IEEE 802.11 as implementation independent. An ESS can provide a gateway for wireless users to wired networks such as the Internet. This is accomplished via a device known as a portal. The portal is a logical entity that specifies the integration point on the DS where the Wi-Fi network integrates with a non-IEEE 802.11 network [19].

A. PHY LAYER

IEEE 802.11 uses unlicensed frequencies of 2.4 GHz and 5 GHz. The first standard specified two methods of radio frequency transmission: direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS).

- In DSSS, each bit of the original signal is represented by multiple bits in the transmitted signal using a spreading code. The spreading code spreads the signal across a wider frequency band in direct proportion to the number of bits used.
- In FHSS, the signal is broadcasted over a pseudo-random series of radio frequencies. The receiver, hopping between frequencies in synchronization with the transmitter, picks up the message. Attempts to jam the signal in one frequency succeed only at knocking out a few bits of it [25].

Newer versions of IEEE 802.11 use orthogonal frequency-division multiplexing (OFDM) [18]. OFDM is a modulation technique for data transmission, where the bandwidth is equally divided into multiple orthogonal subcarriers. The main advantages of OFDM over classical techniques are that OFDM can obtain a similar transmission rate, decrease the effects of fading, and offer better equalization. OFDM can also adjust the modulation technique in the subcarriers, e.g., one subcarrier with a poor channel condition can use binary phase shift keying (BPSK), and other subcarriers with good channel conditions may use a more efficient modulation technique such as 64-QAM (quadrature amplitude modulation) [26].

Table 1 presents the main physical layer characteristics of each version of IEEE 802.11. IEEE 802.11a can operate over 3.7 GHz or 5 GHz using OFDM and single-input, single-output (SISO). SISO allows communication between one transmitter and one receptor. However, the use of multiple-input multiple-output (MIMO) has become increasingly popular, therein using several transmitters and receptors. The use of the ISM (industrial, scientific and medical) unlicensed bands as 2.4 GHz enabled the development of newer versions of Wi-Fi such as IEEE 802.11b, IEEE 802.11g and IEEE 802.11n. In 2005, the IEEE 802.11 Working Group for WLAN Standards established an activity to enhance the current 802.11 MAC protocol to support applications with QoS requirements [30] such as video streaming or real-time applications. The results of this group's work established the IEEE 802.11e standard with QoS capacity [31]. IEEE 802.11n increases reliability using MIMO systems and achieves longer communication distances and higher transmission rates [32]. For the 40 MHz bandwidth, the optional data rate defined by 802.11n is 600 Mbps [33], which is achieved by using four antennas and a 400 ns guard interval [34]. 802.11ac uses a bandwidth of 20, 40, 80 or 160 MHz [35]. Bandwidths of 80 and 160 MHz are formed by a combination of two adjacent non-overlapping 40 and 80 MHz channels, respectively [36]. IEEE 802.11ad addresses personal area networking and introduces new capabilities such as wireless docking with multi-gigabit per second links using a large spectrum in the 60 GHz band. IEEE 802.11ad uses directional antennas to enhance the link quality and modifies channel access to address directionality and spatial reuse [37]. Additional information about Wi-Fi standards can be found in [33].

B. MAC LAYER

The MAC sublayer is responsible for channel allocation procedures, protocol data unit addressing, frame formatting, error checking, fragmentation, and reassembly. The 802.11 MAC sublayer supports two basic media access functions: the distributed coordination function (DCF) and an optional point coordination function (PCF). When the PCF is enabled, the wireless channel is divided into several superframes. Each superframe consists of a contention-free period for a PCF and a contention period for the DCF [18]. At the beginning of the PCF, the coordinating point, usually represented by the AP, conducts different disputes over the wireless channel. Once the AP acquires the channel, it periodically performs a high-priority scan of the stations to allow privileges for transmission. PCF is a centralized service and operates in infrastructure mode [18].

DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA). The CSMA/CA protocol is designed to reduce the collision probability at the points where collisions would most likely occur. By default, in IEEE 802.11, carrier sensing is performed in the PHY layer. RTS/CTS (request to send/clear to send) is the optional mechanism used by CSMA/CA to reduce the collision probability, therein implementing virtual carrier sensing in the MAC layer. Typically, the RTS/CTS strategy is used if the packet exceeds a threshold of 2347 octets [18]. Before a station sends out a data frame, it senses the channel. If the channel is idle after a period of time called the distributed inter-frame spacing (DIFS), the RTS frame is transmitted. Otherwise, a backoff time slot is chosen randomly in the interval from 0 to a contention window (CW). The CW is incremented exponentially as a function of the number of attempts to retransmit the frame [18]. The receptor receives the RTS, and after waiting a period of time called the short inter-frame space (SIFS), it replies with a CTS message to the source station. Stations that receive the CTS update their own self net allocation vector (NAV), which indicates the time interval that the station must wait before any attempts to use the channel. When the transmitter receives the CTS, it starts to send the data to the receiver that replies with an acknowledgment (ACK) message to confirm the reception of the data [38].

The random backoff mechanism of the RTS/CTS scheme is an important feature for reducing collisions in Wi-Fi networks, thereby greatly reducing packet loss. The random backoff time is evaluated using

$$\text{Backoff\_Time} = R.T_s, \tag{1}$$

where R is a pseudorandom generator of an integer in the interval [0, CW], $CW_{min} \leq CW \leq CW_{max}$, and T_s is the slot time length. Depending on the type of the PHY layer characteristics, the CW_{min}, CW_{max} and T_s can assume different values, as indicated in [39] and [29].

Every node uses a backoff counter when data packets are attempting to send for the first time. The contention window is initially set to the minimum CW_{min} before sending, and transmission is carried out with equal probability at a choice time in the interval (0, CW_{min}). If the channel is sensed free for the DIFS time, the backoff counter would decrease by 1 every T_s. If the channel is sensed busy, the station freezes its backoff counter until the channel is sensed free for the DIFS time [40]. When the backoff counter reaches zero, the station starts transmitting. If the sender does not receive the ACK within a certain amount of time, it assumes that the data packet was lost and repeats the above procedure, doubling the CW. Doubling of the CW stops after the maximum window size (CW_{max}) is reached [39].

III. CAUSES OF PACKET LOSS

Bolot [41] understands a loss as the failure of a packet sent on a network to be received correctly by the receiver. Packet loss occurs for various reasons, including problems in the physical or media access control layer. Understanding the causes of packet loss so that appropriate procedures can be followed or action can be taken is crucial. In some cases, collisions and signal-related problems lead to performance issues and need to be considered separately [42]. Iyer *et al.* [43] suggested that the successful decoding of received data is a random event whose probability depends upon the signal strength, level of thermal noise interference, and strength of interfering signals.

The causes of packet loss can be classified into three categories:

- Physical factors, such as signal strength, noise and multipath effect;
- Contention for medium access; and
- Buffer overflow due to network congestion or bufferbloat due to an excessive queue memory.

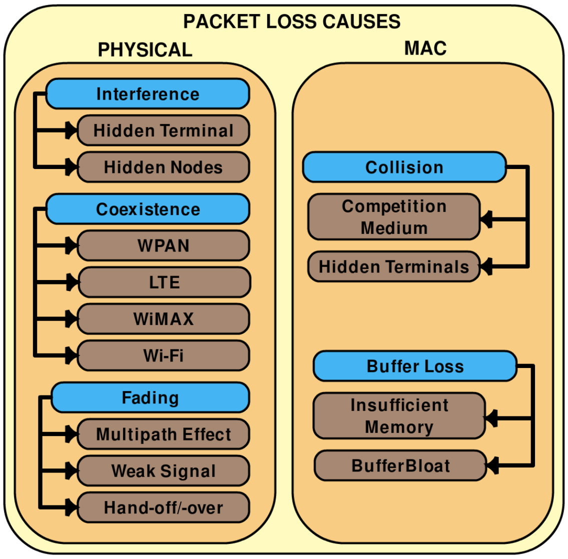

FIGURE 3. General overview classification of packet loss causes.

Because of the characteristics of losses in wireless links, one challenge is to determine if a packet loss is due to wireless-induced effects, such as channel pairing and interference, or malicious discarding during transmission [44]. However, it is difficult to determine whether packet loss is a result of problems in the physical layer (e.g., low signal power at the receiver) or competition for access at the MAC layer (e.g., hidden terminals) [45]. Figure 3 presents a classification of packet loss causes based on the PHY and MAC layers.

A. PHYSICAL LAYER PROBLEMS

1) COEXISTENCE AND INTERFERENCE OF Wi-Fi AND OTHER TECHNOLOGIES

This section presents a description of coexistence and interference phenomena for Wi-Fi with other technologies. In wireless communication, interference is any signal or noise that modifies or disrupts the original wireless signal between the transmitter and receiver. On the other hand, coexistence refers to different wireless devices sharing bandwidth.

In communication networks, two types of interference should be considered: interference caused by another station and interference due to noise. Station interference occurs in channel access schemes and is considered MAC interference (i.e., collisions - explained in greater detail in Section III-B), while noise interference is due to the physical medium and is considered PHY interference [46].

IEEE 802.11 operates in an unlicensed frequency of 2.4 or 5 GHz. Technologies such as Bluetooth (IEEE 802.15.1) [47], ZigBee (IEEE 802.15.4) [48], wireless phones, and different specifications of IEEE 802.11 can be sources of interference because they commonly use the same unlicensed frequencies. Figure 4 presents a diagram of frequency overlapping possibilities between Wi-Fi and competing technologies. Wi-Fi channels commonly use the range of frequencies between 2401 MHz and 2483 MHz. IEEE 802.11b divides the band into 13 channels with a bandwidth of 22 MHz each. As a result, there are only three non-overlapping channels (i.e., 1, 6, and 11 [49]). Given the high density of Wi-Fi hotspots, it is common to share the bandwidth with neighboring Wi-Fi networks. IEEE 802.11n can operate with 20 or 40 MHz, increasing the probability of interference between channels. The problem of coexistence between Wi-Fi networks has become even more pressing, as IEEE 802.11ac expects to increase the channel bandwidth to 80 and 160 MHz [50]. Thus, Wi-Fi networks must be carefully designed in such a way that channels do not overlap adjacent networks.

Yoon *et al.* [51] and Shin *et al.* [52] analyzed the interference of WPANs on Wi-Fi networks using the IEEE 802.15.4 and IEEE 802.11b standards, respectively. The packet error rate (PER) of a Wi-Fi network was calculated using the bit error rate (BER) and collision time. Their results showed that for distances greater than four meters, the interference of the WPAN did not significantly impair the Wi-Fi signal. However, for distances of less than three meters, the authors suggested reducing the payload size to mitigate the effects of interference and improve the throughput of the Wi-Fi network [53]. WPANs can also adversely affect the performance of IEEE 802.11 g/n networks, as shown by Petrova *et al.* [54].

Another type of interference is known as pulsed interference and has been studied by Zarikoff and Leith [55], who proposed a technique to detect packet loss. The authors suggested classifying lost transmission as noise-related, collision-induced, and hidden node (HN) losses. Soomro and Cavalcanti [56] discussed the challenges in identifying the coexistence of WPAN and WLAN technologies in strategic areas such as medical environments due to coexistence with other technologies in the ISM bands, e.g., locations such as health care apartments with devices, bedside monitoring, patient wireless sensors, remote alarms in monitoring equipment, and home/residential care environments.

On the other hand, Bluetooth also operates at 2.4 GHz over short distances and uses 79 channels with 1 MHz bandwidths from 2.402 to 2.480 GHz. Bluetooth uses FHSS, divides transmitted data into packets and transmits each packet using one of the designated channels. Bluetooth low energy (LE) is a promising technology aimed at implementing short-range, low-cost, low-power networks with broad compatibility and low-power characteristics using 40 channels of 1 MHz [57]. In 2003, a task group published the IEEE 802.15.2-2003 standard that defines several coexistence mechanisms that can be deployed to make the coexistence of WLAN and WPAN networks possible [58].

The coexistence of IEEE 802.16 (worldwide interoperability for microwave access, also known as WiMAX) and Wi-Fi poses major difficulties because the frame-based media access of IEEE 802.16 requires rigorous protection against interference from wireless local area networks for proper operation [59], [60].

Long term evolution (LTE) has become the *de facto* standard for 4G networks. The deployment of LTE in unli-

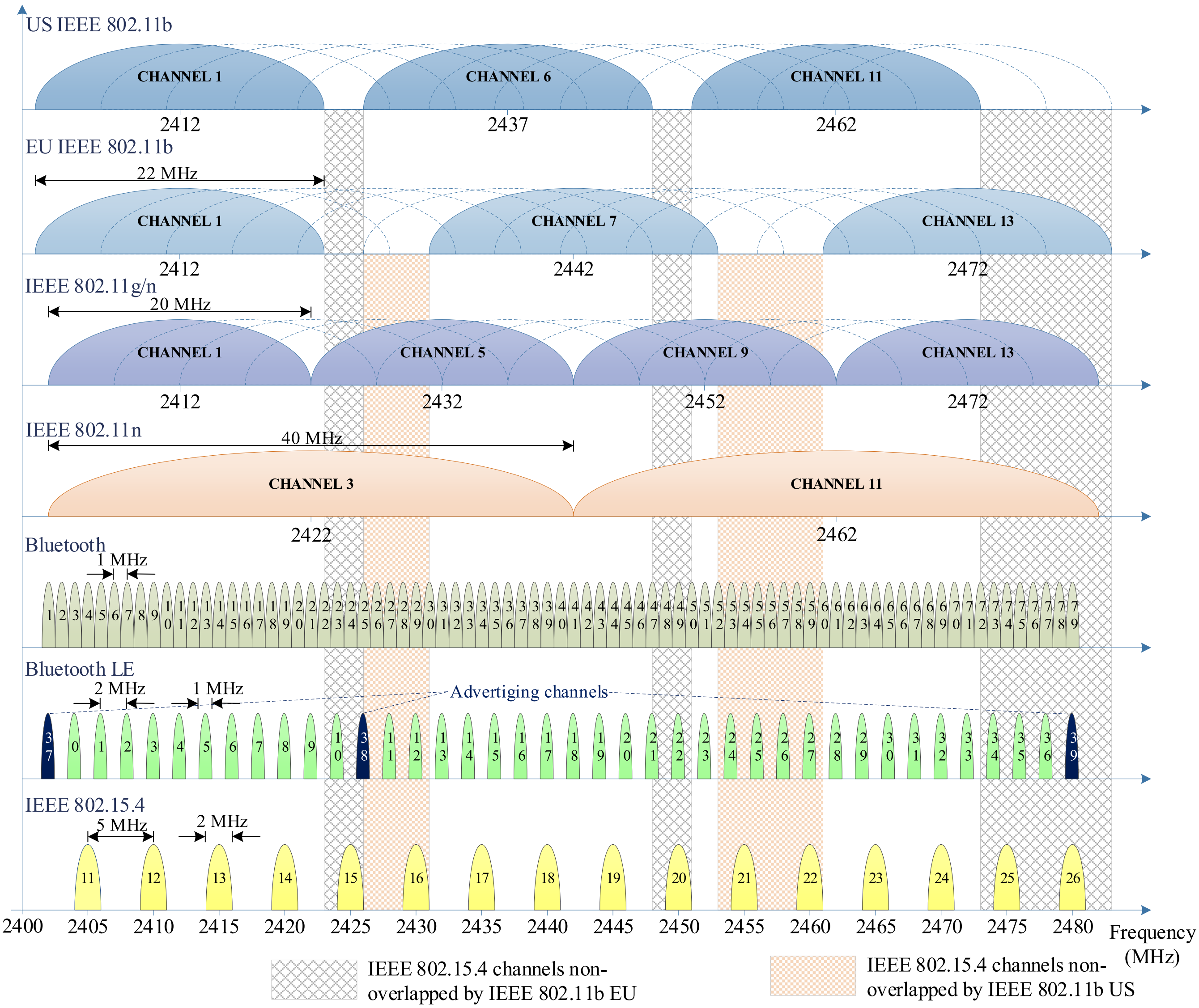

FIGURE 4. Overlapping map of wireless technology.

censed bands is being considered in the 3rd Generation Partnership Project (3GPP) release 13 of LTE. This feature is called licensed-assisted access (LAA) to LTE. Currently, there is no embedded scheme in Wi-Fi devices to mitigate or avoid the negative effects of the coexistence of LTE and Wi-Fi networks. The coexistence of LTE and Wi-Fi systems has thus become a primary challenge [61]. Chen *et al.* showed that competing LTE systems can impair Wi-Fi performance, causing severe packet dropping (especially in scenarios with several APs and eNodeB, i.e., 3 APs and 3 eNodeB), whereas the LTE performance is only slightly affected [61]. Cavalcante *et al.* [62] indicated that Wi-Fi performance is further degraded when it operates concurrently with LTE due to the fundamental limitation of the Wi-Fi protocol, which blocks the Wi-Fi channel and forces the Wi-Fi nodes to remain in listen mode for a considerable amount of time. Simulation results presented by Rupasinghe and Güvenç [63] showed that 802.11n performance is more vulnerable to LTE interference, while LTE performance is degraded only slightly in the unlicensed spectrum.

Noise interference is caused by external sources and can lead to packet loss. Other systems may emit electromagnetic waves (e.g., microwave ovens [64]) that could affect the communication within the WPAN [65] and Wi-Fi networks [66]. Devices that can interfere with Wi-Fi networks include plasma lighting systems (PLS), wireless phones, and video transmission devices (e.g., robots used for detecting explosives in airports) [67]–[69]. Table 2 presents a list of related works on interference between wireless network technologies.

2) FADING

Fading is defined as the attenuation of signal strength. For wireless communications, path loss (PL) is a measure

TABLE 2. **Literature on the coexistence of Wi-Fi networks and other technologies.**

Wi-Fi Network	Interfering Technology	Related works by year
IEEE 802.11	IEEE 802.15.4	2000 [70], 2001 [71], 2002 [72], 2004 [73], 2006 [53], [74], 2007 [75]–[78], 2008 [79]–[82], 2009 [83], 2010 [84], [85], 2011 [86]–[88], 2012 [89], 2013 [90], 2014 [91], 2015 [92], 2016 [93], and 2017 [94]
	IEEE 802.15.1	2001 [95], [96], 2002 [97], 2003 [98], 2006 [99], and 2012 [89]
	IEEE 802.15.4a	2003 [100], and 2004 [101]
	IEEE 802.15.6	2011 [102], and 2014 [103]
	LTE	2013 [62], 2014 [104], 2015 [61], 2016 [105], [106], and 2018 [107]

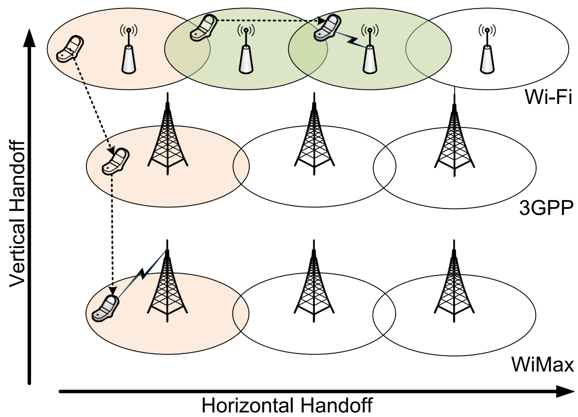

FIGURE 5. **Vertical and horizontal handoffs.**

of the average radio frequency attenuation suffered by a transmitted signal when it arrives at the receiver [108]. Sarkar *et al.* described that fading can be classified into two types: large-scale fading due to motion over a large area (e.g., mean signal attenuation vs distance) and small-scale fading due to small changes in position (e.g., time spreading of the signal and time variance of the channel) [108]. In typical wireless networks, the base station is at a fixed position, while the devices are constantly moving. User mobility can impair the performance of networks and result in a slight increase in the packet loss ratio [109].

The process of transferring a call or session to/from base stations is known as handoff [110]. Handoff can be classified into two types: horizontal handoff (HHO), which means that devices move within the same wireless access network technology, and vertical handoff (VHO), which means that devices move among heterogeneous wireless access network technologies, e.g., from Wi-Fi to WiMax, as illustrated in Figure 5. For vertical handoff, the VHO infrastructure must provide a minimum overhead, authentication capability, and low delay to minimize the packet loss. To avoid packet losses during horizontal handoff, several methods have been proposed [111].

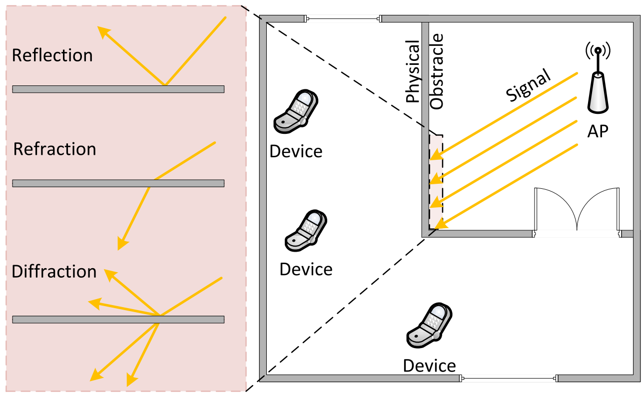

FIGURE 6. **Signal propagation in wireless environments: reflection, refraction and diffraction.**

An original signal from a transmitter can arrive at the receiver with multiple copies due to reflection (caused by, e.g., reflective surfaces), refraction (caused by, e.g., media with different propagation velocities), and diffraction (caused by, e.g., edges) [112], as illustrated in Figure 6.

Multipath propagation occurs when multiple copies of a signal arrive at the receiver with different amplitudes, phases, and delays and can lead to severe dispersion of the transmitted signal [108]. Interference between multiple copies of received signal causes fading [113], which is a particularly severe channel impairment. To mitigate the impact of multipath propagation, solutions such as diversity and cooperative techniques [114] can be applied.

B. COLLISIONS

In wireless communication, especially in Wi-Fi networks, collisions are a major issue. Usually, a communication channel has three states: busy due to a transmission, busy because of a collision, and idle [115]. In the first state, the channel remains busy while successful transmission is occurring, and only the sender has permission to access the medium. In the second state, the channel remains unavailable because of a collision, and in the last state, the channel is available to new transmissions [115].

The phenomenon known as hidden nodes (HN) is common in Wi-Fi networks. A HN occurs when nodes outside other nodes' carrier-sensing ranges are nevertheless close enough to interfere with each other [116]. Figure 7 presents an HN scenario with a collision event. Device A can hear device B, and device B can hear both devices; however, A and C cannot hear each other. When A transmits B, C cannot detect this transmission. Therefore, if C transmits to B, a collision will occur at device B. This problem is known as the hidden terminal problem. Thus, the collision probability can be correlated with the number of terminals competing for the channel.

HNs not only result in packet loss but also impair the throughput of Wi-Fi networks. In some cases, HNs can reduce network throughput by more than 33% in medium-to high-traffic conditions compared with scenarios in which there are no HNs. However, the HN phenomenon barely

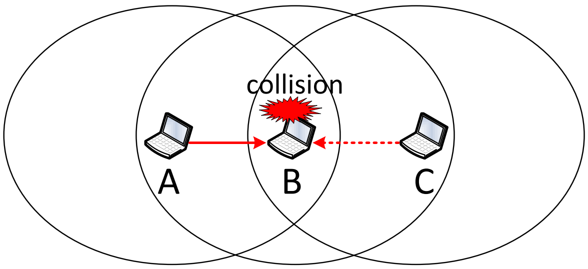

FIGURE 7. Collision scenario of Wi-Fi networks.

affects systems with low traffic [117]. HNs produce interference due to hidden traffic (HT). Portoles-Comeras *et al.* [118] correlated HTs with packet loss in wireless transmissions. They used renewal theory to show that packet losses constitute biased samples of HTs, with a significant correlation between the packet transmission time and its loss probability. Simulations showed that the packet loss probability increases proportionally to the airtime occupation and number of HNs [118]. Borgo *et al.* showed that the CSMA/CA scheme can be more effective in avoiding hidden terminal problems for low transmission rates and in scenarios with severe interference [119].

The IEEE 802.11 DCF does not rely on a privileged station to control the number of terminals competing for a channel. However, in infrastructure mode, the information about terminals consists only of the number of associations between the AP and the devices, and it is difficult to estimate the interference caused by unassociated devices. Thus, the number of competing devices could be very different from the number of real associations [120].

C. BUFFER LOSSES

Network congestion is a further cause of packet loss [121] due to the limitation of buffers to store packets. Detecting congestion in wireless networks presents a significant challenge [122]. One solution to avoid network congestion is to use devices with faster processors or increase the size of buffers used to store received packets.

Many important applications (e.g., video streaming) generate bursty traffic and require larger buffers [123] to avoid discards. Several congestion control techniques have been developed to improve the network performance [124]. Transmission control protocol (TCP) adjusts the congestion window size in such a way to avoid sending excessive packets to the destination, thus preventing drops by buffer overflow. The congestion window size is estimated using the time it takes for a packet to be sent to the receiver and for an ACK to be received. This time is known as the RTT (round trip time).

The availability of inexpensive memory and the need to avoid packet loss have led to larger buffers being deployed in network devices without sufficient thought or testing. It is expected that the increase in buffer size will improve the performance of the network by decreasing the packet loss rate. However, this could lead to an increase in latency, which may impair the quality of services, e.g., real-time video streaming. Additionally, larger buffers could cause a problem called bufferbloat (persistently full buffers) [125]. Nakayama and Sezaki [126] stated that bufferbloat refers to the phenomenon of excess buffering of frames causing high latency and low throughput. Even when being studied mainly in the context of wired networks, persistently full buffers can deteriorate the fairness of rate allocation and increase the RTT in wireless networks [127].

IV. PACKET LOSS MODELS

The problem of modeling packet loss in networks has been studied since the 1960s. This section presents the main packet loss models available, with emphasis on models applicable to Wi-Fi networks.

The first packet loss models presented were developed for wired networks (e.g., the Gilbert and Gilbert-Elliot models) and later applied to wireless networks. Newer models were designed considering the behavior of Wi-Fi networks, mainly the burst loss phenomenon. Many of the models described can be used for other wireless networks such as ZigBee and LTE.

A. Bernoulli

In the Bernoulli model, a good run-length (or reception run-length, RRL) and a loss run-length (LRL) are represented by an independent and identically distributed random variable. In RRL, all packets are successfully received, and in LRL, all packets are lost. For a given packet i, the random variable X_i can be 0 or 1, with $X_i = 1$ indicating a packet being lost and X_i being independent of other values in the time series. The model uses a single parameter r, estimated from $\hat{r} = n_1/n$, where $\hat{r}$ is the average loss rate, n_1 is the number of times that the value of 1 has been observed in a time series $\{x_i\}_{i=1}^{n}$ and n is the number of samples. The packet loss rate (PLR) is estimated by $\hat{r}$.

The distributions of the RRL and LRL are given by $f(j)$ and $g(j)$ as follows [128]:

$$f(j) = \hat{r}(1-\hat{r})^{j-1} \quad \text{for} \quad j = 1, 2, \ldots, \infty \tag{2}$$

$$g(j) = (1-\hat{r})\hat{r}^{j-1} \quad \text{for} \quad j = 1, 2, \ldots, \infty \tag{3}$$

For wireless networks, the Bernoulli model has disadvantages because the model is not capable of capturing the temporal dependence of packet losses [129]. According to Nguyen *et al.* [130], this model is clearly not able to describe many real-world scenarios. Recently, the Bernoulli model has been used only for comparison to other models.

B. TWO-STATE Markov CHAIN

The Markov chain-based models attempt to represent the correlation between losses and free losses in communication networks according to several states with different loss probabilities.

A two-state Markov chain model, also known as Simple Gilbert, uses a success (S) state to represent a packet being correctly received and a lost (L) state to represent a packet being lost. Figure 8 illustrates the two-state Markov chain,

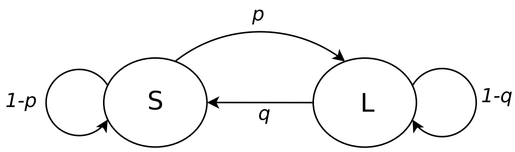

FIGURE 8. Two-state Markov chain.

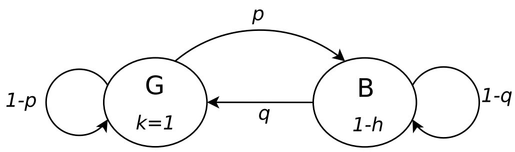

FIGURE 9. Gilbert model.

which shows that its behavior is governed by the transition probabilities, where p is the transition probability from the S to L state if a packet is lost. The transition probability from the L to S state is given by q.

PLR can be evaluated using the limiting distribution for Markov chains with steady-state distribution given by $\Pi = \{\pi_1, \pi_2\}$ using $\Pi P = \Pi$ and $\sum \Pi = 1$ [131] and is given by

$$\mathrm{PLR} = \frac{p}{p+q} \tag{4}$$

where P is the transition matrix for this chain.

Unlike the Bernoulli model, this two-state model is able to capture the dependence between consecutive losses in the network due to an additional parameter p [128], in which $p = P[X_i = 1|X_{i-1} = 0]$.

1) Gilbert MODEL

In 1960, Gilbert [132] proposed the use of a 1-st-order Markov chain to model consecutive binary losses in burst-noise channels. The burst term is widely used to describe consecutive events, e.g., losses or noise, that impair the quality of a link on which data are transmitted. Later, the Gilbert model was used to represent packet loss processes in simulations of communication networks. An advantage of this model is the capacity to capture the temporal dependence of the packet loss process [133].

The model has two states, identified as "Good" (G) or "Bad" (B), in which Gilbert considered the special case of an error-free good state ($k = 1$). Additionally, it is common to use the terms "Reception" and "Loss" to describe the states [133]. In state B, the probability of discarding is $1 - h$, with $0 \leq h \leq 1$, and the G state transmission is error free. The variables p and q represent the transition probabilities between states G and B and between B and G, respectively. A representation of the Gilbert model is shown in Figure 9.

For the Gilbert model with $k = 1$, the PLR is given by

$$\mathrm{PLR} = \left(\frac{p}{p+q}\right)(1-h). \tag{5}$$

2) Gilbert-Elliot MODEL

The Gilbert model was extended by Elliot [134] in 1963, therein including the possibility of losses in both states, as the Gilbert-Elliot model. The Gilbert-Elliot model is illustrated in Figure 10. The parameter p is the transition probability from state G to state B, and q is the opposite transition probability. A loss can occur in each state as independent events with a probability of $1 - k$ and $1 - h$, with $0 \leq h \leq 1$ and $0 \leq k \leq 1$, respectively, for states G and B [135]. The values of k and h can be chosen arbitrarily [136]. Usually $p + q < 1$, and if $p + q = 1$, the model is reduced to the Bernoulli model.

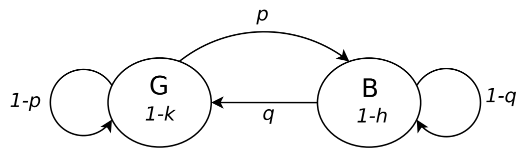

FIGURE 10. Gilbert-Elliot model.

TABLE 3. Comparison of Bernoulli, Gilbert and Gilbert-Elliot parameters [135].

Model	Parameter	Training Complexity	Simplification
Simple Gilbert	*p, q*	simple	k=1, $h \in \{0,0.5\}$
Gilbert	*p, q, h*	medium	k=1, h=0.5
Gilbert-Elliot	*p, q, h, k*	high	$k, h \in \{0,...,1\}$

The matrix P of transition probabilities is given by

$$P = \begin{matrix} & G & B \\ G & 1-p & p \\ B & q & 1-q \end{matrix} \tag{6}$$

The stationary probabilities for the states G and B are given by $\pi_G = q/(p+q)$ and $\pi_B = p/(p+q)$, respectively. The PLR is obtained using steady-state probabilities [137], [138] and is given by

$$\mathrm{PLR} = (1-k)\pi_G + (1-h)\pi_B \tag{7}$$

The parameters of the two-state Markov models are presented in Table 3, including a simple Gilbert model. For a simple Gilbert model, the G state is always error free because $k = 1$. McDougall and Miller [139] attempted to reproduce the packet error rate and the average burst error length of a Wi-Fi channel using the simple Gilbert model but failed to reproduce the variance in the error burst lengths. For the Gilbert-Elliot model, a loss can occur with probabilities $1 - h$ and $1 - k$, respectively, in the states B and G. However, the estimation process of k and h for the complete model presents high computational complexity. The parameters k and h can be estimated using samples collected from real networks based on packet loss observations, e.g., as indicated by [135] and [140].

Hasslinger and Hohlfeld [135] evaluated the performance of the simple Gilbert, Gilbert, Gilbert-Elliot models and included additional tests with a model based on a Poisson process. The results indicated that the Gilbert model is not appropriate for small sample traces, and the Gilbert-Elliot model achieves better fitting to real packet loss sample traces [135]. The accuracy of the models was validated using IP wired networks. The authors introduced a new method to fit the parameters of a two-state Markovian model to match the second-order statistics over several timescales. The results indicated that fitting procedures based on second-order statistics yield a closer match in several time scales than classical fitting methods, which, on the other hand, are better at modeling error bursts [135]. The model based on a Poisson process provides a linear lower bound without any autocorrelation.

Russ and Haghani [141] presented a distribution of consecutive packet losses as a combination of the classical Gilbert-Elliot model and heavy-tailed distribution, resulting in an alternative hybrid model. A distribution is heavy tailed if $P[X > x] \sim x^{-\alpha}$, as $x \longrightarrow \infty, 0 < \alpha < 2$. The simplest heavy-tailed distribution is the Pareto distribution [142]. Russ and Haghani suggested that burst size can be expressed by two different distributions modeling the number of consecutively dropped packets N. If $N \leq 3$, packet loss is represented by the Gilbert-Elliot model; if $N > 3$, packet loss can be modeled by a heavy-tailed distribution. Due to this phenomenon, the Gilbert-Elliot model fails to characterize the packet loss observed in IEEE 802.11b networks [143].

C. THREE-STATE Markov MODEL (3SMM)

The 3SMM is a three-state Markov model, therein introducing a new Intermediary (I) state to the Good (G) and Bad (B) states of the Gilbert-Elliot model. It is suggested that only the B state presents packet loss, whereas the other two states are free-loss states [144]. A simple 3SMM is presented in Figure 11.

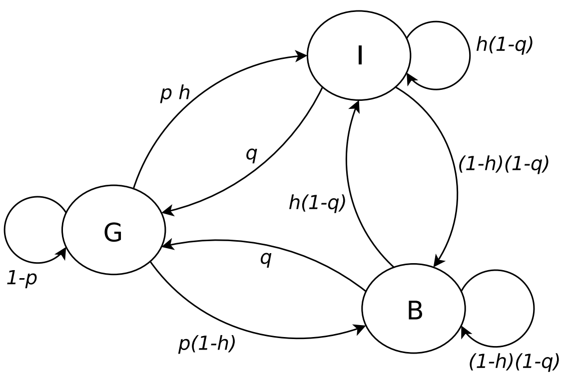

FIGURE 11. Three-state Markov chain Gilbert model [144].

A second alternative eliminates the transitions between states I and G and allows state I to have an independent self-loop probability $(1-Q')$, as illustrated in Figure 12 [144].

The matrix P of the transition probabilities of the model presented in Figure 12 is given by

$$P = \begin{array}{c} \\ G \\ B \\ I \end{array} \begin{array}{c} \begin{array}{ccc} G & B & I \end{array} \\ \begin{pmatrix} 1-p & p & 0 \\ q & w & 1-q-w \\ 0 & Q' & 1-Q' \end{pmatrix} \end{array} \tag{8}$$

An independent self-loop probability for state I enables two categories of error-free periods to be defined that occur between periods of packet loss. Setting the self-loop probability to be high in state G and low in state I leads to long periods

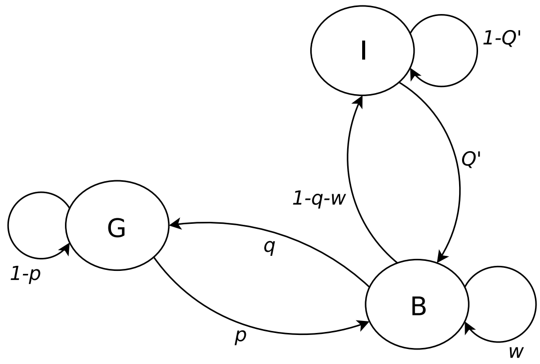

FIGURE 12. Three state packet loss model [144].

of no losses in state G, while state I models short periods of no losses that occur in-between packet losses in burst-like conditions. This gives more control over the characteristics of packet loss and loss-free periods [144].

Using the stationary distribution of the Markov chain, the average packet loss burst length can be evaluated as $\beta_{loss} = \frac{1}{1-w}$. PLR is given by

$$\text{PLR} = \frac{Q'p}{p(1-q-w) + Q'(p+q)}. \tag{9}$$

Milner and James [144] evaluated the accuracy of the 3SMM model compared with the two-state Markov and Gilbert models for WLAN and GSM (Global System for Mobile communications). Analysis reveals that all models are able to accurately reproduce the packet loss rate and burst lengths. A comparison of the average packet loss burst lengths of the real packet loss data and loss-free burst lengths reveals that for more lossy channels, the 3-state Markov chain and Gilbert model are more effective than the 2-state Markov chain. The distribution of loss-free bursts shows that the 3SMM is most effective in reproducing the characteristics of the real sample traces [144].

D. Gilbert-Elliot WITH DELAY PARAMETER

Usually, packet loss models do not use delay or jitter. However, models that allow us to use and investigate these parameters can increase the reliability of models, as proposed by Lee and Chanson [145].

The model is based on two Markov chains, where the state space is designed using the parameters D, A and C. D is the maximum delay limit, A is the maximum packet inter-arrival time, and C is the highest error state number. The first Markov chain keeps track of the packet delay, and the second Markov chain models the error process. The delay dimension is used by negative states to keep track of future arrivals, and A can be set to infinity for handling infinite inter-arrival times [145]. The authors assumed that a finite buffer is sufficient because the arrival packets do not exceed a delay limit; however, if they exceed the packet, they are discarded.

The error dimension is given in the transition matrix P, where state 0 represents a successful transmission and state 1

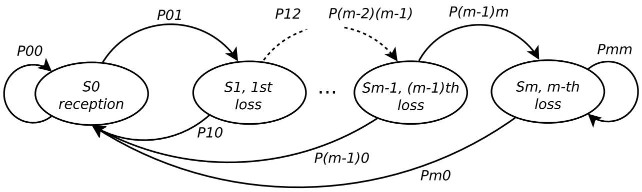

FIGURE 13. Extended Gilbert model [9].

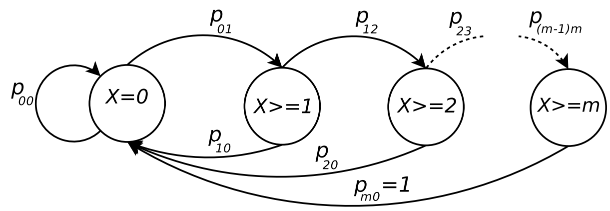

FIGURE 14. Loss run-length model with unlimited state space ($m \to \infty$) [146].

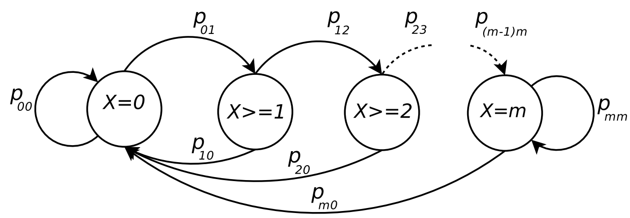

FIGURE 15. Loss run-length model with limited state space [146].

represents packet failure.

$$P = \begin{pmatrix} c_{0,0} & c_{0,1} \\ c_{1,0} & c_{1,1} \end{pmatrix} \tag{10}$$

The steady-state probability $\pi_{i,j}$ of the state (i, j) is expressed in terms of $\pi_{D,1}$, i.e., $\pi_{i,j} = k_{i,j}\pi_{D,1}$, where $\pi_{D,1}$ is the transition probability to an error state, and $k_{i,j}$ is to be found using the balance equations of the Markov chain [145]. $(D, 1)$ is the only state where a packet can be dropped due to excessive delay. PLR is given by

$$\text{PLR} = \frac{\pi_{D,1}}{a} \tag{11}$$

where a is the arrival probability of a packet in a slot and is used to obtain the fraction of packets lost [145].

Simulation tests with $C > 1$ indicate a non-two-state Markov chain that would consequently increase the complexity of the model; thus, [145] used $C = 1$. The results indicate that PLR is affected by the delay threshold and is nearly independent of the arrival rate except if the rate is close to 1. Similar to other models, Lee and Chanson also assumed that packet losses may occur in bursts, which means that, in a success state, all packets are received, and the queue length will likely decrease to zero before the next error burst arrives. The results showed that increasing the threshold delay exponentially decreases the probability of packet losses because the delay limit does not result in overflow of the finite buffer. The results also showed that reducing the delay limit results in higher PLR. The authors stated that the parameter estimation has a higher computational complexity, therein being a major disadvantage of the model.

E. EXTENDED Gilbert

An extension of the Gilbert model using multiple states is shown in Figure 13 [138], [146]. There are two categories of states, described as RRL and LRL. The single state S_0 represents the RRL state, which is a loss-free state, and LRL has m states $\{S_1, \ldots, S_m\}$, where the state S_1 represents the first lost packet after a previously received packet in S_0, and state S_m represents m consecutive packets lost. When a packet is successfully received, the system returns to S_0. Every loss event will lead the system to a subsequent loss state S_{i+1} until the LRL reaches the m-th state [9]. The occurrence of a loss event will depend upon the history.

There are two types of LRL models, i.e., those with non-limited and limited state spaces.

1) LRL WITH NON-LIMITED STATE SPACE

This model is defined by a random variable X. If $X = 0$, the packet is not lost. $X = N$ means that N consecutive packet are lost, and if $X \geq N$, at least N consecutive packets are lost. This condition allows us to establish a LRL model as shown in Figure 14 with a possible infinite number of states and gives loss probabilities dependent on the burst length. Each packet loss increases the burst loss length, and if the packet is successfully transmitted, then the system returns to the $X = 0$ state [146].

The probability of transition between states for $N > 1$ can be described as conditional loss probabilities $p_{(N-1)(N)} = P(X \geq N)/P(N \geq N-1)$ [146]. A random variable Y describes the distribution of the burst loss length. $E[Y]$ is the expected value of the mean burst loss length within v arrivals using the loss run-length occurrences Θ_N. The PLR for $v \to \infty$ is represented by [146].

$$\text{PLR} = \sum_{N=1}^{\infty} N \frac{\Theta_N}{v} \tag{12}$$

where N is the number of consecutive packets lost, Θ_N is the loss run-length, and v is the number of arrival packets.

2) LRL WITH LIMITED STATE SPACE

This model is shown in Figure 15, where m is the last state of the model. In the last state, a loop transition with p_{mm} probability is added. If $0 < N < m$, X represents the number of N consecutive packets lost [146].

Changes in m influence the performance of the model due to the computational complexity, in which higher m results in higher loss burst lengths. The PLR can be expressed by [146]

$$\text{PLR} = \sum_{N=1}^{m} \frac{N\Theta_{w,m}(N)}{mv} \tag{13}$$

where $\Theta_{w,m}(N)$ is the number of N consecutive packets lost within a window of length m, N is the number of consecutive

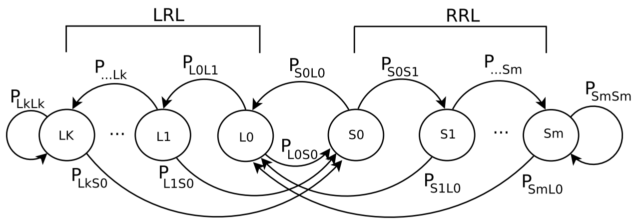

FIGURE 16. Adaptation of the extended Gilbert.

packets lost, m is the last state, and v is the number of arrival packets.

The authors designed models of different complexity that capture loss characteristics, with the well-known Gilbert model being a special case of these models, and showed how to parameterize the model using data traces. They concluded that to support a wide range of applications, an "intermediate model" is needed, which has to be more complex than the simple Gilbert model. The complexity of such an intermediate model is determined by the application requirements [146].

F. ADAPTATION OF THE EXTENDED Gilbert

A multi-state model is proposed as an adaptation of the extended Gilbert model. The model is based on Markov chains with two run lengths (RRL and LRL) with m- and k-order mechanisms, respectively. The mechanism is shown in Figure 16 [9] and has the following main elements.

- In RRL, every received packet drives the system to the next state with a transition probability of $P_{S_iS_{i+1}}$ until RRL reaches the state S_m. In the last state, if a packet is received, the system remains in the same state with transition probability $P_{S_mS_m}$. Otherwise, if a packet is lost, the system returns to the state L_0. In each state of RRL, if a packet loss occurs, the system returns to the initial state L_0 with a transition probability of $P_{S_iL_0}$. With every return to L_0, the system becomes free of temporal dependencies on the past RRL states [9].
- In LRL, each packet loss drives the system to the next loss state with a transition probability of $P_{L_iL_{i+1}}$ until it reaches the state L_k. In the last LRL state, if a packet is lost, the system remains in the same state with probability $P_{L_kL_k}$. If a packet is received in any state, the system returns to the state S_0 with a transition probability of $P_{L_iS_0}$ [9]. In every return to S_0, the system becomes free of temporal dependencies on the past LRL states [9].

The steady-state probability of the model is defined as the sum of all steady-state probabilities of RRL and LRL $\sum_m \pi_S + \sum_k \pi_L = 1$, where π_S and π_L are the steady-state probabilities of successful and failed states for states m and k, respectively. PLR is given by [9]

$$\text{PLR} = \sum_k \pi_L; \tag{14}$$

thus, PLR is a sum of all state probabilities of LRL [9].

The model was evaluated using three different transition probability distributions: constant, Gaussian, and exponential. The scenarios considered are 6LoWPAN and Wi-Fi networks. In both scenarios, PLR was calculated by varying the transition probabilities between states with the following results [9]:

- *Constant* transition probability distribution: if the successful transition probability is close to 1, then PLR is low. Otherwise, a smaller successful transition probability (1%) results in a higher PLR [9].
- *Gaussian* transition probability distribution: if the successful transition probability is larger, then PLR is smaller. In this case, the minimum PLR is less than 2%. On the other hand, the largest PLR value occurs when the successful transition probability has the smallest value. In this situation, the packet loss is approximately 45% [9].
- *Exponential* transition probability distribution: a maximum PLR of 30% was identified for a loss transition probability close to 1 and the smallest successful transition probability. On the other hand, a minimum packet loss transition probability and maximum value of successful transition probability result in a PLR close to 0.4% [9].

G. PH DISTRIBUTION

Wolter *et al.* [147] proposed a revision of the Gilbert-Elliot model for wireless communication. The original exponentially distributed sojourn time is replaced by a phase-type (PH) distribution, which was considered using a continuous- or discrete-time PH distribution. In a discrete phase-type (DPH) distribution, the transition to the next state is performed with regard to packet arrival instances and based on the previous state probability. On the other hand, the continuous phase-type (CPH) distribution uses the packet arrival process to determine the lengths of the loss and loss-free periods. Simulations results compared with experimental data show that while the simple Gilbert models fit the density of the LRL well, they cannot capture the oscillations present in the histogram of the RRL [147]. Both DPH and CPH fit the oscillation of RRL well; however, DPH presents better fits. Extending the distribution of the sojourn time in the Gilbert-Elliot model to a PH distribution adds more complex loss-length curves to achieve a good fit; however, this increases the parametrization complexity.

H. Gilbert-Elliot WITH SUBSTATES

Because burst losses are assumed to be a natural behavior of Wi-Fi, the classical Gilbert-Elliot model does not fit RRL with spikes. The DPH distribution method solves this problem but at high computational complexity due to the additional states. To solve the problems of DPH, Feng *et al.* [148] suggested a Gilbert-Elliot model with multiple states, as illustrated in Figure 17.

The multi-state model is based on a general G state defined as a set of four sub-states (G_1, G_2, G_3 and G_4) and a single B state. The packet loss probability p_i, $i \in \{1, 2, 3, 4\}$ is calculated for each state G_i to transit to the single B state.

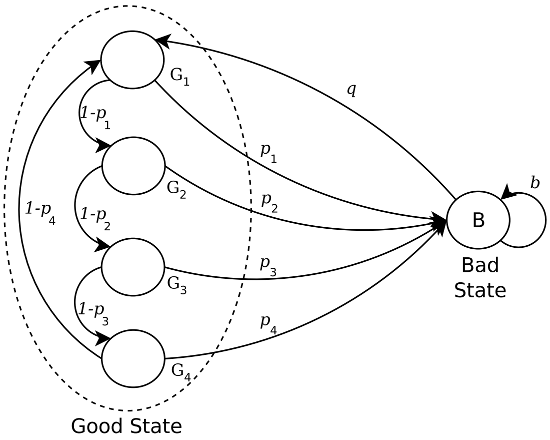

FIGURE 17. Gilbert-Elliot model with multi-states.

The B state can transit only to the G_1 state, with a transition probability of q. In state B, the packet loss has a probability of b.

The accuracy of the Gilbert-Elliot model with sub-states is verified using the log-likelihood method, and the results indicate that this model significantly outperforms the Gilbert-Elliot and PH distribution models [148].

I. HIDDEN Markov MODEL (HMM)

The HMM is a category of stochastic processes that are used in several applications, such as speech recognition, video identification, finance, and tool wear monitoring [149], and has become an alternative for modelling packet loss in Wi-Fi networks. An HMM is a double stochastic process formed by two parts: an underlying stochastic process that is not observable directly (i.e., it is not possible know the exact actual state) and can only be observed through another process and a second process formed by a set of stochastic processes that produce the observable sequence [150]. Silveira and Silva [151] explained that the first process is a Markov chain and that the second process is an observation process whose distribution at any given time is fully determined by the actual state of the Markov chain. Strong statistical foundations and efficient learning algorithms are some of the advantages of HMMs for Wi-Fi due to the statistical behavior and massive amount of data available.

Hartwell and Fapojuwo [152] tested the performance of the HMM using 3, 4 and 5 states with 2 million incoming UDP packets collected in an 802.11a network. Gilbert and Gilbert-Elliot models were also considered. The authors suggested the use of the Baum-Welch algorithm for the estimation of the HMM parameters. The Baum-Welch algorithm is an iterative expectation-maximization algorithm that, given an initial parameter configuration, adjusts model parameters to locally maximize the likelihood of unlabeled data [153]. The Gilbert model presents worse results when compared with HMM. In addition, increasing the number of states improves the performance of the HMM model [152].

Cardoso and Rezende [154] proposed an HMM with three states using two different structures for indoor IEEE 802.11 networks. The first structure has transitions between all states (HMM3g), and the other structure has transitions only between adjacent states (HMM3bd). Computer simulations comparing the HMM3g, HMM3bd, and Gilbert-Elliot models show that both HMM3g and HMM3bd achieve good fitting of the autocorrelation function (ACF) and the complementary cumulative distribution function (CCDF) of a data sample. The ACF of HMM3bd achieves better fitting with real data samples. However, even with some improvements, HMM3bd is not yet sufficient to adequately describe the loss process, and it is necessary to increase the number of states to improve the accuracy. The increase in the number of states leads to problems in the convergence of HMM training due to its computer complexity. The investigation of the ideal number of states is a future research topic [154].

J. LOGARITHMIC SERIES DISTRIBUTION

Carvalho *et al.* [155] proposed modeling the length of consecutive losses and successful sequences of packets transmitted over RTP/UDP/IP/802.11g networks with a logarithmic series distribution.

The model considers X as being the burst length of n lost packets and supposes that X is a logarithmic series random variable. The probability mass function of X is given by $P[X=n] = -\frac{\theta^n}{n\ln(1-\theta)}$, where θ is the distribution parameter that must be estimated from a sample data [155]. The PLR is given by

$$\mathrm{PLR} = \frac{1}{\frac{P[X=0]}{E[X](1-P[X=0])} + 1} \tag{15}$$

where $P[X=0]$ represents a successful packet transmission, i.e., an error burst of zero length, and $E[X]$ is the expected value of X.

The model was evaluated using several types of multimedia content over IEEE 802.11 g and compared with the Gilbert-Elliot model. The results using the chi-square test show that the proposed model was 1.77-times more accurate than the Gilbert-Elliot model. In addition, the authors stated that the packet rate is the only factor that influences the proposed model, and its performance is independent of the bitrate in a range of source video traffic cases between 64 Kbps and 1 Mbps [155].

V. MODEL COMPARISON

In this section, we present a comparison between packet loss models described in the previous section, herein showing the main features and contributions of the models and their ability to represent the packet loss behavior of modern Wi-Fi networks.

Table 4 shows the separate characteristics of models based on their input parameters, validation and method used for evaluation, type of Markov chain if applied, and communication network. The communication network column shows if the IEEE 802.11 standard had been used; it is possible verify that Wi-Fi was used in almost all cases.

TABLE 4. Main features of the models.

Model	Year	Input parameters						Validation			Markov Chain		
		Delay/Jitter	Transition probability	Throughput	Distance between nodes	Packet inter-arrival time	Payload size	Testbed	Simulation	Analytical	Two-states	Finite variable states	Finite fixed number of states
Gilbert-Elliot with delay parameter [145]	2002	✓	✓				✓		✓		✓		
Algorithms for correlating packet losses [156]	2003			✓	✓			✓	✓		✓		
PLR through delay model [157]	2004	✓	✓			✓			✓		✓		
HMM with 3, 4 and 5 states [152]	2004		✓	✓			✓	✓	✓				✓
Three-state Markov model (3SMM) [144]	2004		✓					✓	✓				✓
Logarithmic series distribution [155]	2005					✓		✓	✓	✓			
PLR using two-state Markov bit error model [158]	2007		✓				✓	✓	✓		✓		
Hidden Markov Model (HMM) [154]	2009		✓					✓	✓				✓
Packet loss probability in multi-hop Ad Hoc Networks [159]	2009	✓			✓				✓				
Hybrid GE and heavy-tailed distribution model [141] [160]	2009		✓					✓	✓		✓		
Extended Gilbert model [9]	2014		✓					✓	✓			✓	
Discrete phase-type (DPH) model [148]	2014		✓					✓	✓		✓		

A. INPUT PARAMETERS

We list the parameters used in the models to compare the model complexity. Parsimonious models are simple models with great explanatory and predictive power, thereby explaining the data with a minimum number of parameters. Overparametrization adds complexity without benefit to the model. However, an oversimplification of the model can also cause accuracy problems. Packet loss in Wi-Fi systems can be considered a complex problem due to the numerous reasons for packet losses, including user behavior patterns.

There is a tradeoff between goodness of fit and parsimony. Models with many parameters tend to achieve a better fit than high-parsimony models. Adding many parameters can result in a better fit for the data at hand; however, that same model will likely be useless for prediction on other data sets, and their training would be impractical because of their complexity. Table 4 presents the input parameters of the main available models.

In packet loss models, the parameters are commonly estimated using traces collected from networks [9], [144], [145], [148], [152], [154], [157], [160]. The available models for packet loss commonly use the following input parameters: maximum payload size, node SNR, network traffic pattern, and state transition probabilities. We could not find a systematic analysis of the importance of each input parameter and their influence on the packet loss rate.

Additionally, no studies were found incorporating Wi-Fi backoff time in the packet loss model. Researchers have suggested modifications of the original backoff mechanism to prevent collisions such as scaling the contention window according to the priority of each flow or user [161], a multi-chain backoff algorithm [162], a cognitive backoff mechanism for 802.11ax [163], an enhanced backoff algorithm [164], and a centralized random backoff [165].

B. VALIDATION

Model validation can be defined as "*substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model*" [166], [167]. The model validation involves the comparison of model outputs with our knowledge of the real world or system. The validation scenarios commonly used to check Wi-Fi packet loss models include the use of testbeds, analytical comparison, and computer simulations.

Analytical comparison checks whether the proposed model is able to reproduce certain features of the actual system, e.g., the auto-correlation function of the losses. Computer simulations are widely used to check whether the model is able to generate an artificial data trace with the same characteristics as the real trace. A testbed is a controlled experimentation platform that implements specific use cases and scenarios.

Table 4 shows the validation strategy used by the main models. It can be observed that all authors use computer simulations for validation. The use of testbeds was also very common. The use of analytical strategies is unusual because of the complexity of the system, which does not allow derivations of simple expressions for performance comparison.

Most models use testbeds, allowing us to utilize a specific scenario to test the model. Table 5 presents the characteristics of each testbed used to validate the packet loss models. Some characteristics were not provided (Not Inf.) by the authors, making it difficult to reproduce those scenarios in the future.

TABLE 5. Testbed characteristics.

Reference	IEEE Std.	Number of samples	Sample length (minutes)	Payload packet size (bytes)	Data rate (Kbps)	Distance (meters)
[156]	802.11	16	15	1400	2000/6000	2/4/5/10/20/30
[152]	802.11a	Not Inf.	60	1500	Not Inf.	Variable (Not Inf.)
[144]	Not Inf. Just Wi-Fi	1	Not Inf.	Not Inf.	Not Inf.	Not Inf.
[155]	802.11g	Not Inf.	Not Inf.	50/200/ 160	4/13.3/ 256	10/15
[158]	802.11	Not Inf.	Not Inf.	16/32/64/128/ 256/512/1024	Not Inf.	Not Inf.
[154]	802.11	18	1440	500/1400	11	Not Inf.
[141]	802.11g	2	60/240	1470	500/1000/2000	Not Inf.
[9]	Not Inf. Just Wi-Fi	Not Inf.	Not Inf.	Not Inf.	Not Inf.	Not Inf.
[148]	Not Inf. Just Wi-Fi	3	20	1442	Not Inf.	4

TABLE 6. Model used for benchmarking.

Reference	Goodness of fit real trace	Bernoulli	2-State Markov chain	Gilbert	GE Model
[156]	✓	✓			✓
[152]	✓			✓	✓
[144]	✓		✓	✓	
[155]	✓				✓
[158]	✓				✓
[154]	✓				✓
[141]	✓				✓
[148]					✓

Performance comparison with previous models is also common for showing the benefits of a new model. Table 6 presents the model used for benchmarking. It is possible to verify that most models are compared with real samples using goodness-of-fit tests.

The use of the Gilbert-Elliot model for performance comparison is popular because it was one of the first models to capture burst loss behavior, and its use is widespread in wired networks.

C. Markov CHAIN-BASED MODELS

The use of the Markov chain-based model has some advantages. First, Markov chains have been the subject of studies for a long time, and they provide a theoretically solid foundation to explore such data. Second, their use usually involves the discretization of the loss behavior, facilitating the parameterization of the loss in each state.

Thus, we classify the models based on Markov chains into three types: models with two states, e.g., the Gilbert-Elliot model; models with variable numbers of states; and models with a finite but fixed number of states not equal to two. The use of two-state Markov chains is the most common. However, two-state Markov chains have limited power to capture the memory behavior of burst losses in Wi-Fi networks. Additional states are added to capture the temporal dependence on the loss-run length. When the number of states is increased, the complexity of the model also increases. Hartwell and Fapojuwo suggested the use of Markov chains with 3, 4 and 5 states [152]. Milner and James [144] proposed a 3-state model. Cardoso and Rezende [154] studied the performance of an HMM to model packet loss using 3, 4, 7 and 11 states. The results indicated that the performance of the model does not depend on the number of states. Younesian *et al.* [9] also used a Markov Chain with a variable number of states; however, the number of states was not given.

D. SELECTION OF A SUITABLE MODEL

The selection of an appropriate packet loss model in wireless networks should consider the following:

- It is well established that packet losses in Wi-Fi networks occur in bursts. Markov-Chain-based models need to use multiple states, i.e., as suggested in [9]. However, this increases the complexity of parameter setting and simulation.
- Usually, the models are not generic and require parametrization to reflect the actual scenarios. User behavior and the use of specific applications can strongly affect the model.
- Many models were designed, tested, and compared with traces collected from networks under controlled scenarios, which means that, in most cases, the resulting model is specific to the studied case [141], [144], [152], [154]–[156], [168].
- Due to the diversity of available 802.11 standards, it is not easy to obtain a suitable packet loss model for all variants because of differences in PHY and MAC layer specifications.

VI. OPEN ISSUES AND FUTURE RESEARCH DIRECTION

Based on our comprehensive review of available packet loss models for Wi-Fi networks, we outline the potential challenges and open issues that require future solutions and research.

We observe that most of the models use input parameters such as the discard probability per state, transition probability between states, delay, jitter, bitrate, collision probability, distance between devices, packet size, and packet inter-arrival time. However, we note that other variables, such as the channel occupation, the number of devices (connected to the AP or not) sharing the same bandwidth, SNR, and the backoff time, were not explored. The use of additional parameters could allow the development of new models to improve accuracy. As stated earlier, the use of additional parameters can lead to non-parsimonious models. The large amount of information available in data samples should also be considered. Thus, for the development of future models, it is suggested to use data mining techniques to identify the most relevant parameters and identify their inter-correlations.

The new IEEE 802.11ax standard uses orthogonal frequency division multiplexing/multiple access (OFDMA), in which each device transmits data using a frequency-time scheduling, resulting in a collision-free solution [29]. This should lead to a major change in packet loss behavior, which in turn requires new models to be developed. It is expected that new physical layer specification based on OFDMA and new medium access control functions can improve (i) the quality of service provisioning, (ii) coexistence between technologies, (iii) throughput, and (iv) energy efficiency [169]–[171].

The design of the packet loss models presented in this survey did not consider the type of application running over the Wi-Fi network. We recognize that this is a significant issue, e.g., file sharing, video streaming, and browsing the Internet differ greatly in terms of transmission pattern. The application traffic pattern is directly related to the collision probability, which in turn is related to the packet loss probability. New models can be developed targeting specific applications running over the Wi-Fi network.

The self-similarity of network traffic could induce the same phenomenon in the packet loss behavior. None of the related works presented a systematic analysis on the time-scale effects of self-similarity for packet losses in Wi-Fi networks. None of the available models were designed to capture typical characteristics of self-similar processes such as the long-term dependence on burst behavior.

Another major change in traffic behavior will be driven by the growth of smart city applications. The key technology behind the success of smart cities is the Internet of Things (IoT), which is a network of systems that can potentially grow to be composed of up to millions of different components, therein involving massive machine-to-machine (M2M) communication. The enabling technologies for IoT include radio frequency identification (RFID), Bluetooth low energy (BLE), near-field communication (NFC), fourth generation cellular systems (4G), IEEE 802.15.4, IEEE 802.11ah, the LoRaWAN protocol, and the future cellular IoT [172]. IEEE 802.11ah is a Wi-Fi standard published in 2017, designed for IoT device integration and attempting to provide extended ranges and low power consumptions. The development of packet loss models specific to IoT systems, such as IEEE 802.11ah networks, remains an open area of research.

Cognitive radio (CR) has emerged as a new design paradigm for the next generation of services in wireless networks. CR aims to increase the utilization of the radio spectrum, thereby automatically detecting available channels and then adapting its transmission or reception parameters to allow more concurrent communications, e.g., allowing unauthorized users to opportunistically access authorized frequencies [173]. CR technology can increase the utilization of the radio spectrum from a global perspective, thereby generating new media access patterns and changing packet loss characteristics for secondary users and even primary users, depending on the type of CR implementation. Currently, techniques such as dynamic frequency selection (DFS) and transmit power control (TPC) for the purpose of facilitating spectrum sharing are available in IEEE 802.11h, allowing the detection and sharing of other systems using the same Wi-Fi channel and protecting primary users [174]. The design of packet loss models for CR/Wi-Fi remains an open area of research.

VII. CONCLUSION

This survey describes the main packet loss models currently available for Wi-Fi networks and presents a brief description of the major causes of packet loss. Packet loss models can be used to simulate the performance of Wi-Fi systems and to develop new techniques and algorithms. The causes of packet loss can be classified as physical and medium access losses. Physical losses may be caused by interference from other networks or devices, coexistence with other technologies, and fading due to impairment of the signal. Medium access losses can be caused by buffer overflow and collisions due to competition in the medium or hidden terminals.

The use of Markov chains is currently the dominant strategy to model packet loss in Wi-Fi networks. A common feature among the models is the attempt to capture the burst behavior of losses. This survey can help researchers understand the main packet loss models available for Wi-Fi networks.

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