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Road Safety on the Example of Wireless Services – Case Study

Abstract: The paper considers organising wireless access in vehicular environments. Such environments are normally affected by Doppler effects, so the IEEE 802.11p standard is expected to ensure an appropriate quality of service for moving objects. Theoretically, the IEEE 802.11p standard compensates for Doppler effects, but it should be ascertained whether 802.11p is still efficient at tiny Doppler shifts and when an object moves at higher speeds. The 802.11p link provides a data rate which is twice as low for 802.11a. Thus, an end-to-end simulation is carried out for the links at wide ranges of signal-to-noise ratio by varying the Doppler shift from 0 Hz to 100 Hz. The simulation also involves 8 modulation types for 128-, 512-, and 1024-bit packet transmissions to cover all possible study cases. The efficiency criterion is the packet-error rate, to which the data rate is additionally considered. The main simulation result is that the 802.11p link is efficient only at not high speeds. The packet length should be shortened to suppress the influence of the object's speed. Therefore, to enable high-quality wireless access in vehicular environments, a combination of the 802.11p and 802.11a links should be used, where phase shift keying is more effective for 802.11a and quadrature amplitude modulation is more effective for 802.11p. The trade-off herein is a data rate versus margin speed.

Keywords: *wireless access, vehicular environment, IEEE 802.11p standard, modulation type, service quality, link selection*

Introduction

Wireless communication networks are an essential part of present-day activity. Although it is a hardly noticeable data transfer tool, wireless communication networks like Wi-Fi, WLAN, Bluetooth, etc., are everywhere. As the amount of such networks increases, their density increases as well. It unavoidably leads to overloads within the radio spectrum used for wireless communications. The aftermath of the overloads is the badly growing interference amongst users. Due to incomplete studies on negative environmental impacts, health issues are not excluded (Sinha et al., 2015; Chuah & Zhang, 2006).

There are two main ways to prevent and control interference. On the one hand, the generation and transmission of radio waves is strictly regulated by national laws, coordinated by an international body, the International Telecommunication Union (ITU), which coordinates the spectrum policy internationally (Stojmenović, 2002). The ITU manages the spectrum dispatching radio frequencies (bands). On the other hand, power control is a process of adjusting amplitudes within the bands and their parts allocated for users. This process is directed to prevent interference and ensure high quality of service (QoS). The QoS standards aim to grant as many user connections as possible by simultaneously controlling uplink powers transmitted to the base node (hotspot, base station, etc.) (Kubal, 2020, p. 167). The standards consider various user mobility, also distinguishing common mobiles (walkers or, at the most, runners) and vehicular communications (IEEE…, 2010; Fernandez et al., 2010, p. 542).

Motivation

The basic principle of QoS is to connect everyone as far as possible within the range at the same link rate. If the hotspot base is overcrowded, the nearest users obtain priority by simultaneously decreasing their uplink powers (Sinha et al., 2015; Dahlman et al., 2011, pp. 265–270; Romanuke, 2019, pp. 147–150). However, trying to meet QoS high standards concerns a few issues. Firstly, the most distant to the hotspot base users may be frequently disconnected. Secondly, even a satisfactory link rate may be unstable. Thirdly, a minimal link rate may be inappropriate for some users (e.g., those who watch live-stream videos). Besides, the velocity of a user matters due to potential Doppler effects (Skolnik, 2001). For these reasons, 802.11p in 2010 was an approved amendment to the IEEE 802.11TM standard to support wireless access in vehicular environments (WAVEs). This standard uses the half-clocked mode with a 10 MHz channel bandwidth, operating at the 5.85...5.925 GHz bands. It allowed supporting applications for Intelligent Transportation Systems (ITS) (Sirohi et al., 2020, pp. 459–460).

One of the basic approaches to ensuring high QoS consists in increasing the number of power levels at which the uplink connection is executed. For instance, a table of GSM power levels is defined, and the hotspot base controls the power of the mobile by sending a GSM power level identifier. Then, the mobile adjusts its power: at the higher power levels, it is typically ±2 dB, whereas, at the lower levels, this relaxes to ±5 dB (Romanuke, 2019, pp. 46–50). The power level numbers vary according to the GSM band in use (Chuah & Zhang, 2006; Kennington et al., 2011): the power level tables for GSM 900/1800/1900 have 18/19/18 power levels, respectively.

The UMTS uses its own conception of uplink power control, where the transmitter is capable of changing the output power with a step size of 1, 2, and 3 dB depending on a set of transmit power control commands (Dahlman et al., 2011, pp. 265–270; Romanuke, 2019, pp. 46–50; Dahlman et al., 2018, pp. 301–302; Hossain & Bhargava, 2007). Thus, once the set is for "down"/"up", the transmit power is reduced/increased by 1/2/3 dB depending on the respective power control range; otherwise, the transmit power is not changed. However, the main problem with such a power adjustment is that it is too slow. Indeed, the update frequency of GSM cellular systems is just 2 Hz. Moreover, although the UMTS updates powers at 1500 Hz, it reacts against weaker or stronger signals (received by the hotspot base) only with a single step, so it is impossible to compensate abrupt changes in signal (Romanuke, 2019, pp. 147–148; Hossain & Bhargava, 2007).

As of July 2020, a few attempts have been made to speed up the power update process. One part of the attempts presumes that mobiles' powers can be updated autonomously, becoming independent of the hotspot base. Thus, mobiles are considered selfish agents (players) trying to maximise their throughput and connectivity (Hossain & Bhargava, 2007). Then the wireless network power control is modelled by the non-cooperative game theory. According to this approach, a utility function is assigned for each mobile, and the game's most stable and advantageous situation is determined (Hossain & Bhargava, 2007). However, substantiation of the utility function relies only on distances from the mobiles to the hotspot base rather than distances between each pair of mobiles, which does not improve measuring interference if compared the game theory approach to the table-of-power-levels approach. Besides, re-calculation of the power according to the most favourable situation becomes exponentially slow when the number of mobiles operating simultaneously linearly increases. Another part of the attempts to speed up power update relies on centralised power control, according to which the hotspot base manages a definite set of power levels of the mobiles linked to it. In particular, this is a method of multi-step power updates leading to a balance of QoS (Romanuke, 2019, pp. 46–56; Nowak et al., 2020, pp. 263–265). However, the methods may work ineffectively in vehicular communications, requiring compensations for Doppler effects.

The IEEE 802.11p standard was intended to support short-range communications, including data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure. It is the basis for vehicle-based communication networks for highway toll collection, vehicle safety services, and commerce vehicular transactions. In general, 802.11p is proposed for networks enabling vehicle communications and roadside access points (hotspots). Unlike GSM and UMTS, the 802.11p exploits a straightforward power control algorithm (Yoon et al., 2011, pp. 290–292). According to this algorithm, if the number of all active devices within the range of an 802.11p access point is less than a threshold (maximum) number, then the power of every device is increased so that it would not exceed a maximal power. Otherwise, the power of every device is decreased by a decrement factor so that it would not drop below a minimal power. As a result, the single device power level can be reduced by 6 dB, which should reduce the sum of radiated power of all devices currently transmitting by at least 3 dB. To prevent interference, some optional enhanced channel rejection requirements are used. Along with the 10 MHz channel bandwidth, which is half the bandwidth or double the transmission time as used in 802.11a, this allows the receiver to reduce the influence of vehicular communication environments (like Doppler effects, signal echoes, diffraction, etc.) (Yoon et al., 2011, pp. 290–292; Khan & Härri, 2017).

The IEEE 802.11p standard is expected to ensure an appropriate QoS within WAVEs normally affected by Doppler effects. Indeed, relative motion between a signal source and a receiver produces shifts in the frequency of the received waveform. Measuring this Doppler shift provides an estimate of the relative radial velocity of a moving target. Theoretically, the IEEE 802.11p standard compensates for Doppler effects. However, there are a few still open questions. Are those compensations effectively mitigated for smaller Doppler shifts (i.e., for vehicles which normally travel at low velocities)? What is the maximum Doppler shift at which the IEEE 802.11p standard is still more efficient than 802.11a? These and other questions are to be answered to ascertain the real efficiency of 802.11p.

Goal

The goal is to ascertain a range of maximum Doppler shift within which the IEEE 802.11p standard is efficient. The efficiency implies that the packet-error rate (PER) for 802.11p transmissions is less than PER for 802.11a transmissions over a range of signal-to-noise ratio (SNR). However, it is assumed that 802.11p may not have a lesser PER at tiny Doppler shifts. This assumption is to be verified as well.

Simulation Parameters and Ranges

This study simulates non-HT format transmissions using the MATLAB® R2019a Communications System ToolboxTM functions supporting an end-to-end simulation. The simulation is carried out to determine the PERs for 802.11p and 802.11a links with fading channels at a selection of SNR points. For each SNR point, multiple packets are transmitted through a fading channel, demodulated and recovered. The recovered data are compared to those transmitted to determine the number of packet errors and calculate the PER. Front-end components, including packet detection, timing synchronisation, carrier frequency offset correction and phase tracking, are optionally enabled for the receiver.

For 802.11p, a 10 MHz channel bandwidth is used, whereas a 20 MHz channel bandwidth is used for 802.11a. The two individual format parameters are specified using non-high throughput (non-HT) format configuration objects by the wlanNonHTConfig MATLAB function. In our study, both links are configured by one of the eight modulation and coding schemes (MCS) with orthogonal frequency division multiplexing (OFDM) using the following modulation types: binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and quadrature amplitude modulation (QAM) with 16 and 64 signal constellation sizes. The studied MCS with the associated system configuration parameters are presented in Table 1 (802.11a-1999…, 1999).

Table 1. The eight MCS to be used in the study

MCS	Modulation type	Coding rate	Coded bits per sub-carrier	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data Rate (Mbps)	
						20 MHz channel bandwidth	10 MHz channel bandwidth
0	BPSK	1/2	1	48	24	6	3
1	BPSK	3/4	1	48	36	9	4.5
2	QPSK	1/2	2	96	48	12	6
3	QPSK	3/4	2	96	72	18	9
4	16-QAM	1/2	4	192	96	24	12
5	16-QAM	3/4	4	192	144	36	18
6	64-QAM	2/3	6	288	192	48	24
7	64-QAM	3/4	8	288	216	54	27

Source: Own study

Additive white Gaussian noise (AWGN) is added to the received waveform to create the desired average SNR per subcarrier after OFDM demodulation (Panagoulias et al., 2020, pp. 215–220). We use a HIPERLAN/2 SISO fading channel model with delay profile Model-E representing NLOS conditions with an average RMS delay spread of 250 ns (Medbo & Schramm, 1998). This model corresponds to a large open space environment with NLOS propagation. The large delay spread makes it applicable for outdoor vehicular operation. HIPERLAN/2 channel models with different delay profiles can be modelled using the flat-fading Rayleigh channels (Sklar, 1997, pp. 90–95).

We set the packet length variable. Thus, the packet length to be studied is 128 bytes, 512 bytes, and 1024 bytes.

Let the SNR range for the case of MCS #0 be from 0 dB up to 30 dB. As the number of MCS increases (Table 1), the fading margin shifts to the right. So, for MCS #*m*, the starting value of SNR is 3m, m = $\overline{0,7}$. Thus, the SNR range for the case of MCS #7 is from 21 dB to 30 dB. Despite the SNR range “shrinks” as the data rate increases, it is believed sufficient for obtaining statistically consistent (or, in other words, stable) PER performance results. Additionally, we set the maximum number of errors (denoted by N_{error}) at 20, whereas the maximum number of packets is at 200. Nevertheless, if these margins are too low (that depends on the PER performance stability or repeatability), we will increase them in the same proportion.

The maximum Doppler shift denoted by s_{Dopp} should be varied from the lowest possible to the reasonably high magnitude. So, let it be varied from $s_{\text{Dopp}} = 0$ Hz up to $s_{\text{Dopp}} = 100$ Hz with a step of 5 Hz. The case of $s_{\text{Dopp}} = 0$ corresponds to the situation in which the object does not move with respect to an access point (or, that is the same, and vice versa). When the object moves, its factual speed in kilometres per hour (km/h) can be calculated from the following relationship (Skolnik, 2001):

$$s_{\text{obj}} = \frac{c \cdot s_{\text{Dopp}}}{f_{\text{carrier}}}, \quad (1)$$

Where:
c is an approximate speed of light in km/hr,
f_{carrier} is the frequency of the carrier in Hz.
Thus, considering the carrier frequency as $f_{\text{carrier}} = 5.9$ GHz in the relationship (1), the object speed is

$$s_{\text{obj}} = \frac{3 \cdot 10^8 \cdot 3.6 \cdot s_{\text{Dopp}}}{f_{\text{carrier}}}. (2)$$

So, formula (2) allows estimating the object speed using just the Doppler shift. For instance, it is about 18 km/hr for the shift in 100 Hz.

Simulation Results

The PER performance versus SNR (in dB) for the eight modulation types with the coding rates according to Table 1 by transmitting 128 bits in the packet is shown in Fig. 1–8. It is seen that, by using BPSK and QPSK, whichever the Doppler shift (the object speed) is, neither 802.11p nor 802.11a link has an advantage. By using 16-QAM with the coding rate of 1/2, however, the 802.11p link provides better performance (Fig. 5), which does not depend on the Doppler shift. The difference between the 802.11p and 802.11a performances becomes very significant at the coding rate of 3/4 (Fig. 6), where almost every tenth packet by the 802.11a link is lost. By using 64-QAM, the 802.11a link cannot be used at all (Fig. 7, 8).

These results are not the same by transmitting 512 bits in the packet (Fig. 9–16). In this case, using BPSK is more advantageous for 802.11a, especially when the object moves faster (Fig. 9, 10). If the Doppler shift is not greater than 30 Hz, which corresponds to approximately 5.5 km/hr (which, in its turn, is a common human walking speed), both the links can be used successfully (not to mention the data rate, which is twice as great for 802.11a).

Fig. 1. The PER versus SNR (in dB) for BPSK with the coding rate of 1/2 (—▫—802.11p —+—802.11a) by transmitting 128 bits in the packet

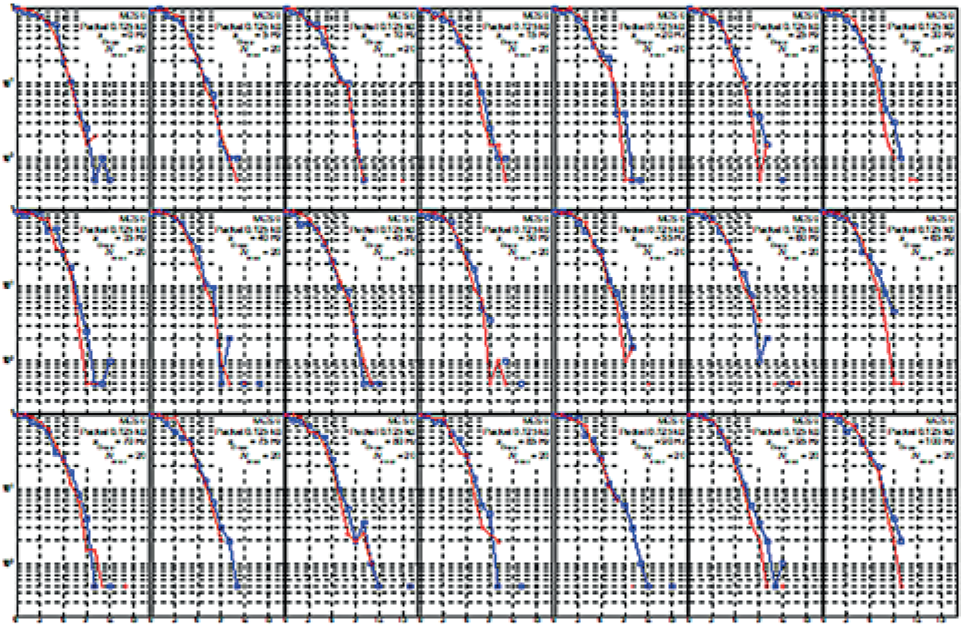


Fig. 2. The PER versus SNR (in dB) for BPSK with the coding rate of 3/4 (—▫—802.11p —+—802.11a) by transmitting 128 bits in the packet

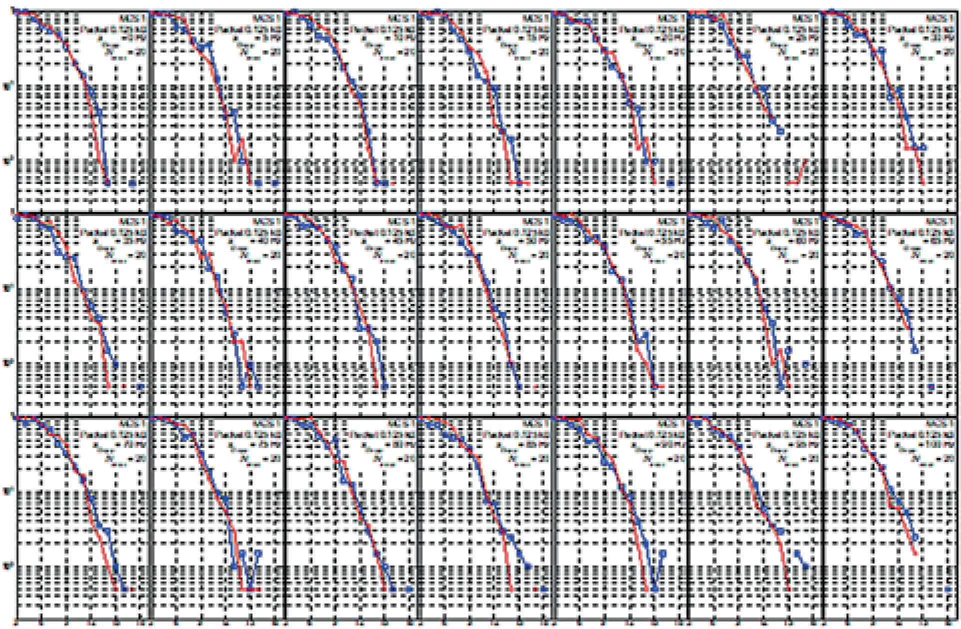


Fig. 3. The PER versus SNR (in dB) for QPSK with the coding rate of 1/2 (—□—802.11p —+—802.11a) by transmitting 128 bits in the packet

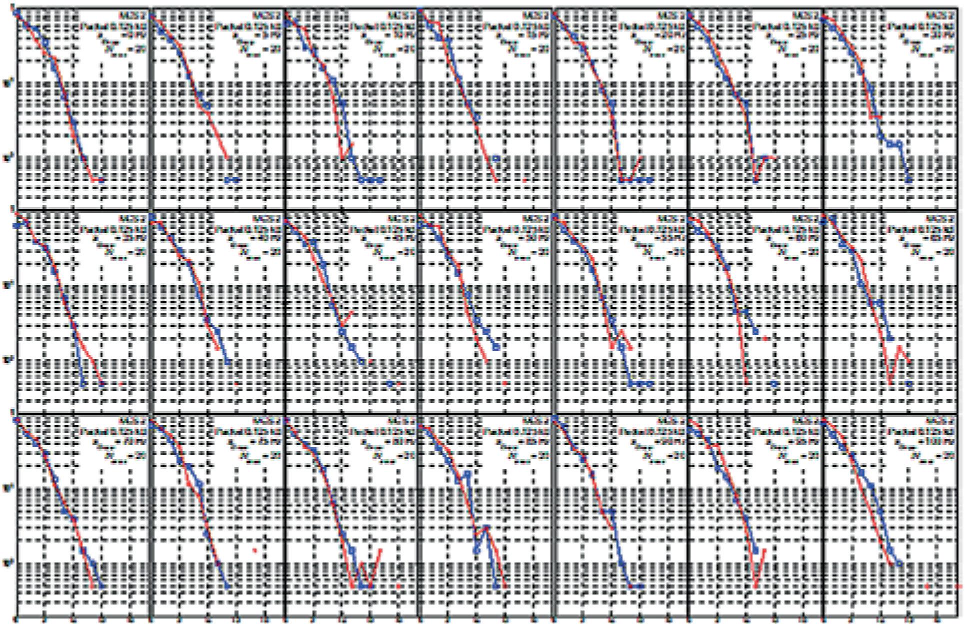


Fig. 4. The PER versus SNR (in dB) for QPSK with the coding rate of 3/4 (—□—802.11p —+—802.11a) by transmitting 128 bits in the packet

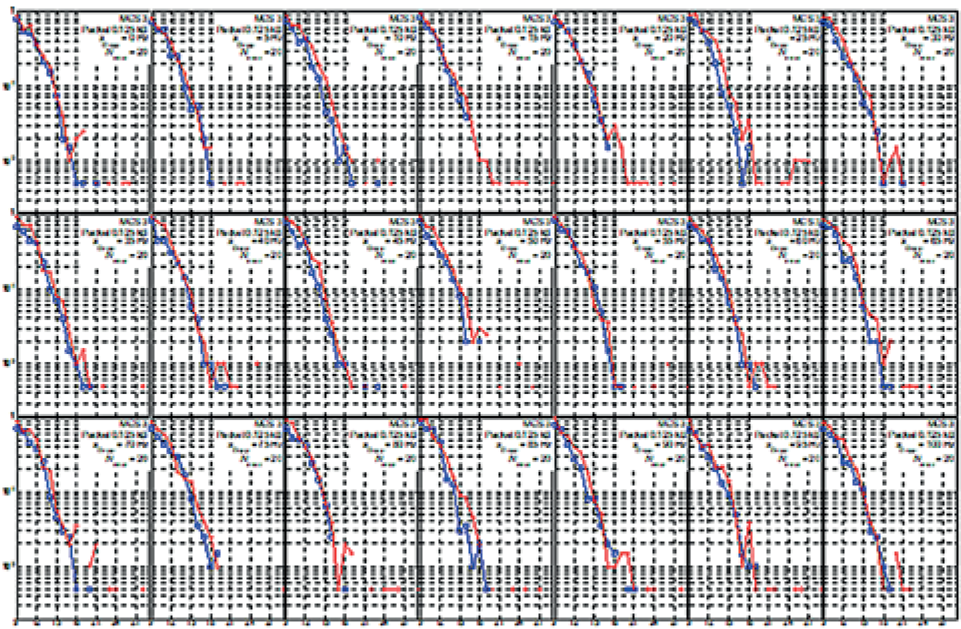


Fig. 5. The PER versus SNR (in dB) for 16-QAM with the coding rate of 1/2 (—▫—802.11p —◦—802.11a) by transmitting 128 bits in the packet

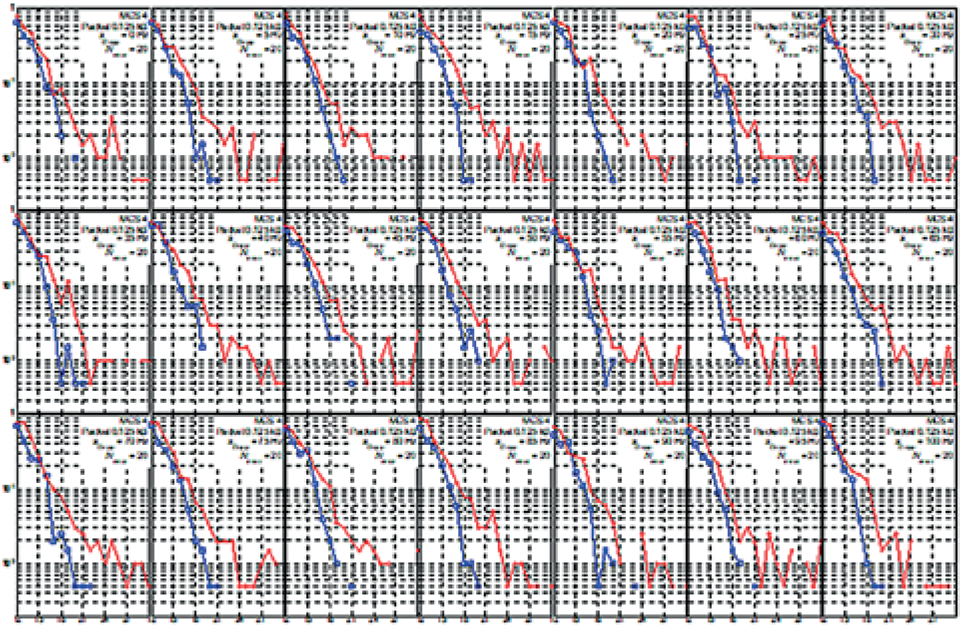


Fig. 6. The PER versus SNR (in dB) for 16-QAM with the coding rate of 3/4 (—▫—802.11p —◦—802.11a) by transmitting 128 bits in the packet

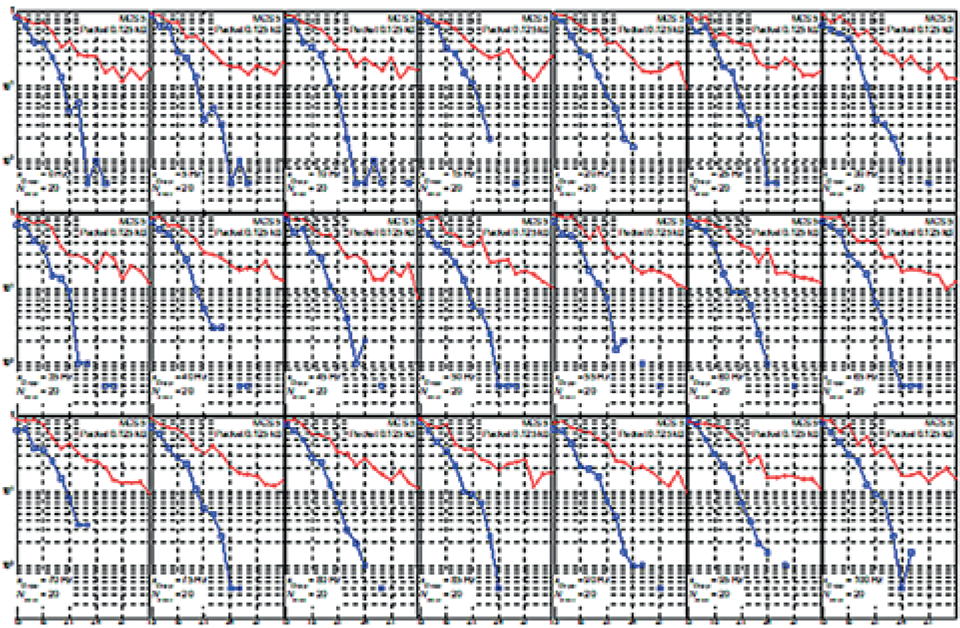


Fig. 7. The PER versus SNR (in dB) for 64-QAM with the coding rate of 2/3 (—▫—802.11p —+—802.11a) by transmitting 128 bits in the packet

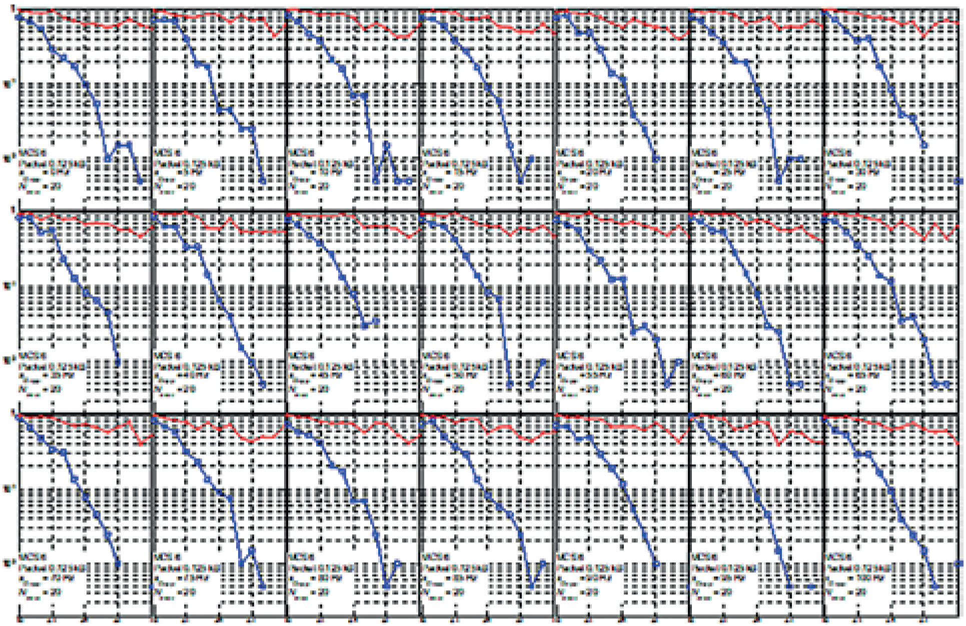


Fig. 8. The PER versus SNR (in dB) for 64-QAM with the coding rate of 3/4 (—▫—802.11p —+—802.11a) by transmitting 128 bits in the packet

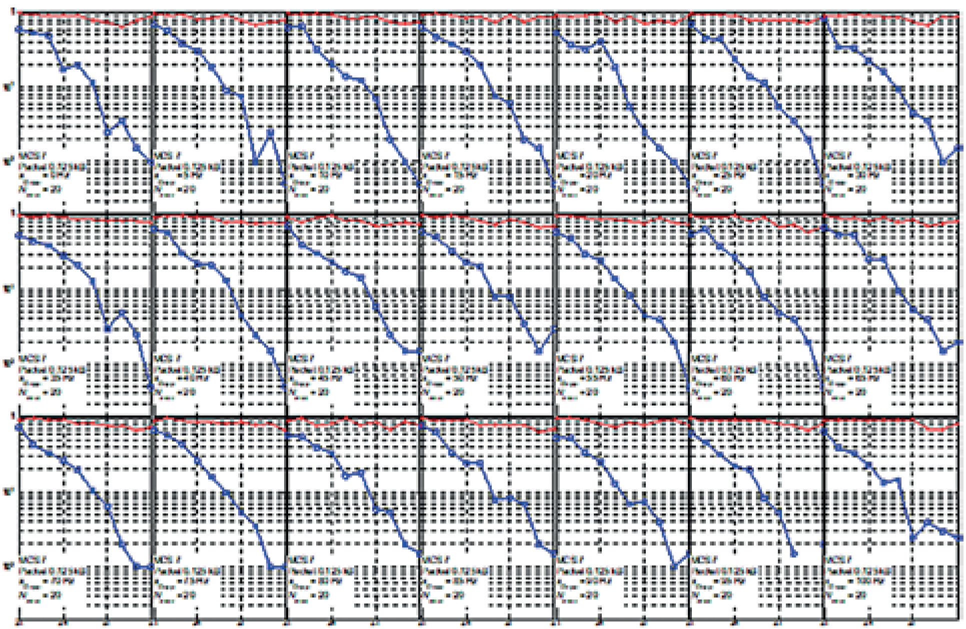


Fig. 9. The PER versus SNR (in dB) for BPSK with the coding rate of 1/2 (—□—802.11p —+—802.11a) by transmitting 512 bits in the packet

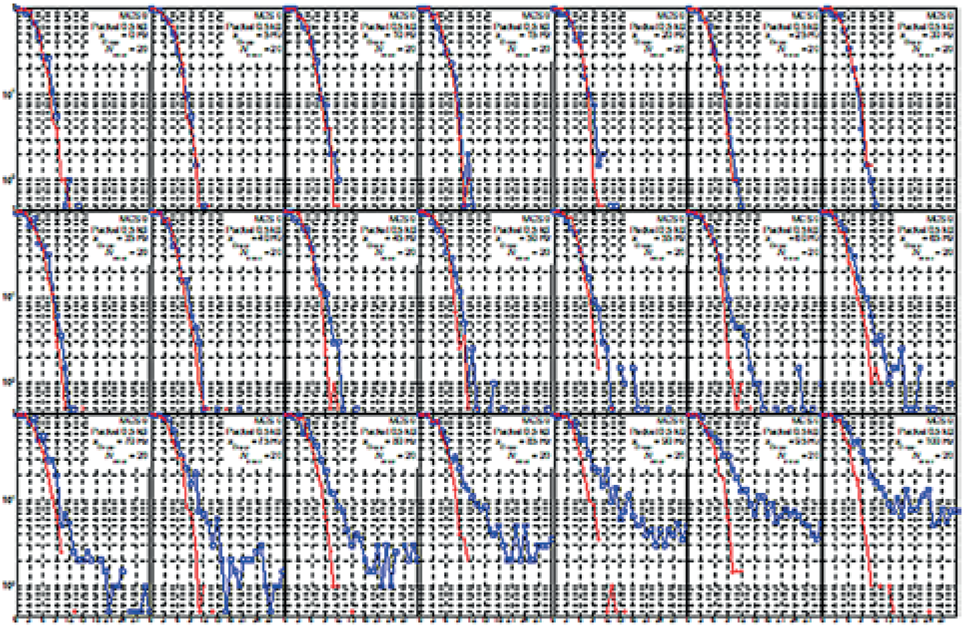


Fig. 10. The PER versus SNR (in dB) for BPSK with the coding rate of 3/4 (—□—802.11p —+—802.11a) by transmitting 512 bits in the packet

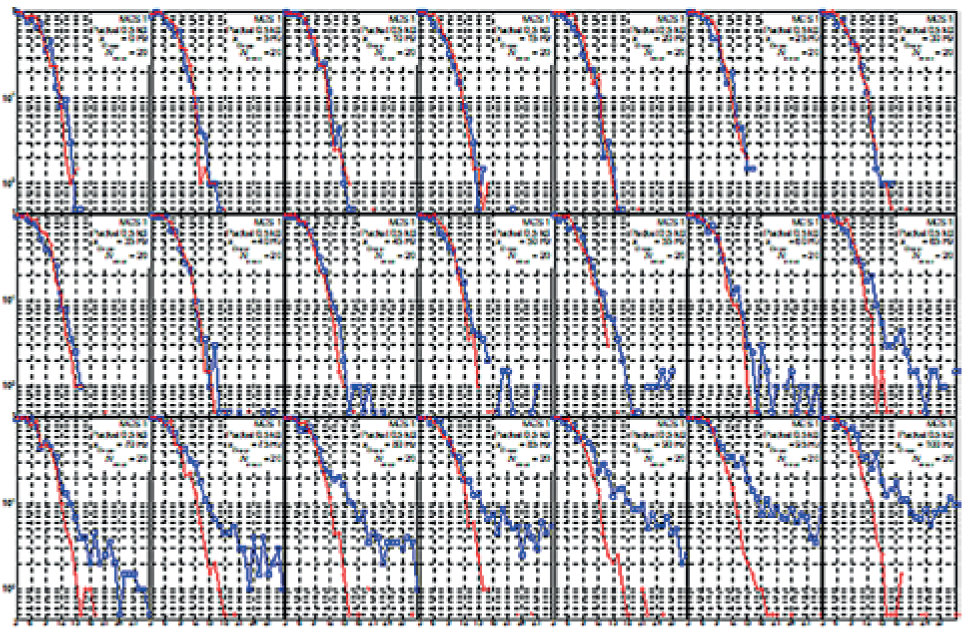


Fig. 11. The PER versus SNR (in dB) for QPSK with the coding rate of 1/2 (—▫—802.11p —+—802.11a) by transmitting 512 bits in the packet

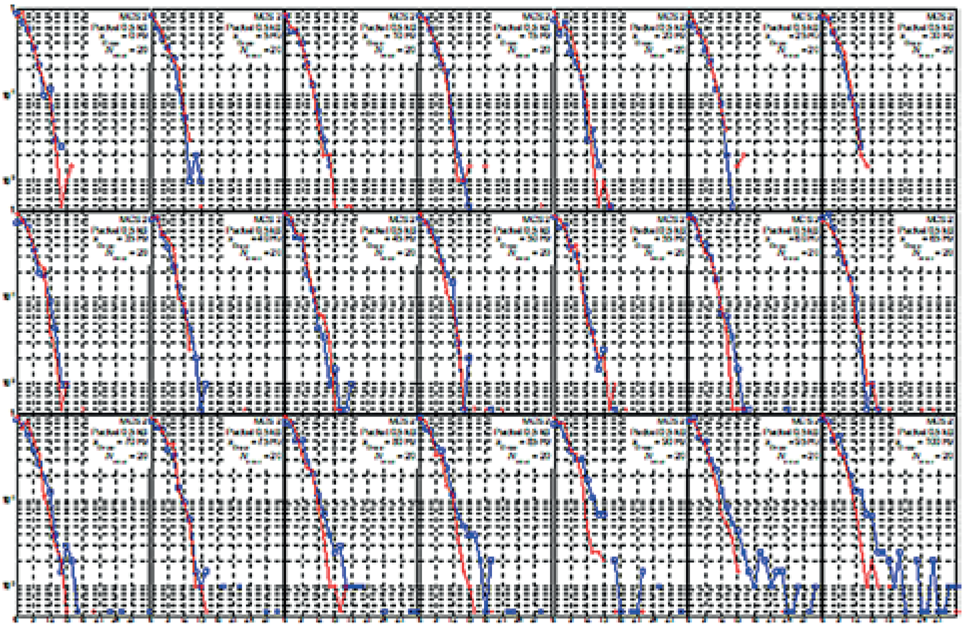


Fig. 12. The PER versus SNR (in dB) for QPSK with the coding rate of 3/4 (—▫—802.11p —+—802.11a) by transmitting 512 bits in the packet

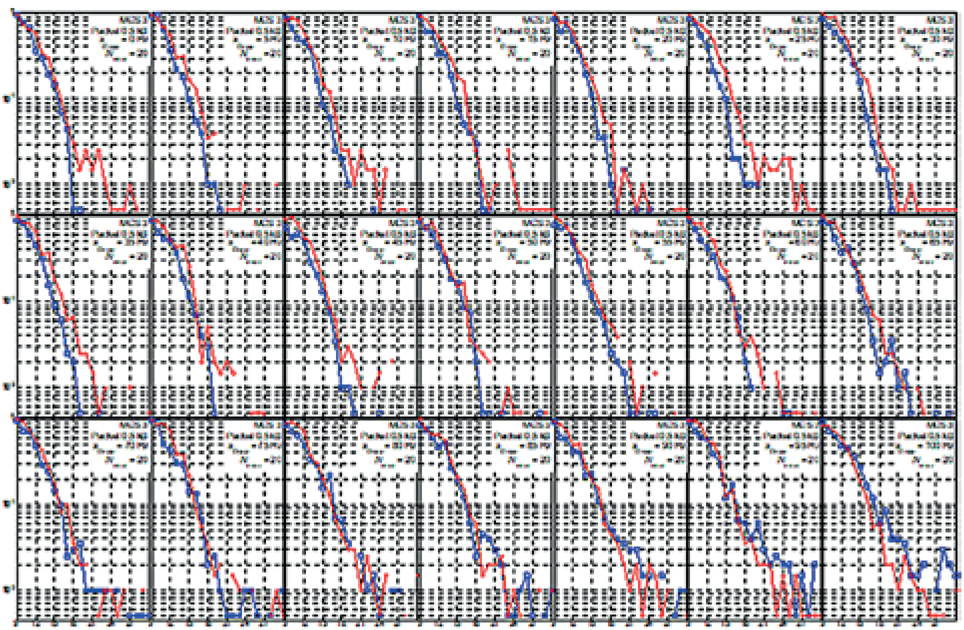


Fig. 13. The PER versus SNR (in dB) for 16-QAM with the coding rate of 1/2 (—□—802.11p —+—802.11a) by transmitting 512 bits in the packet

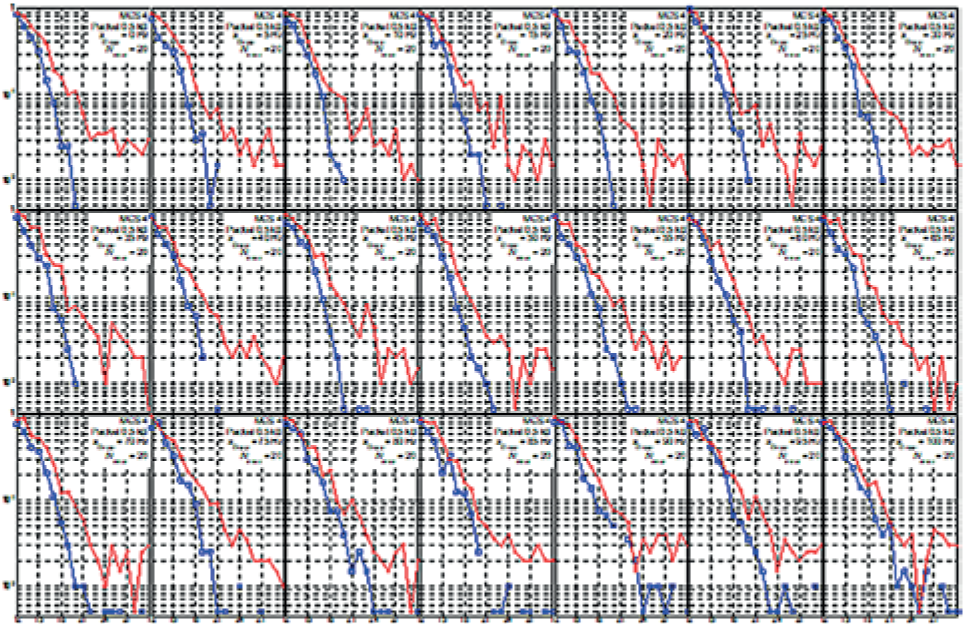


Fig. 14. The PER versus SNR (in dB) for 16-QAM with the coding rate of 3/4 (—□—802.11p —+—802.11a) by transmitting 512 bits in the packet

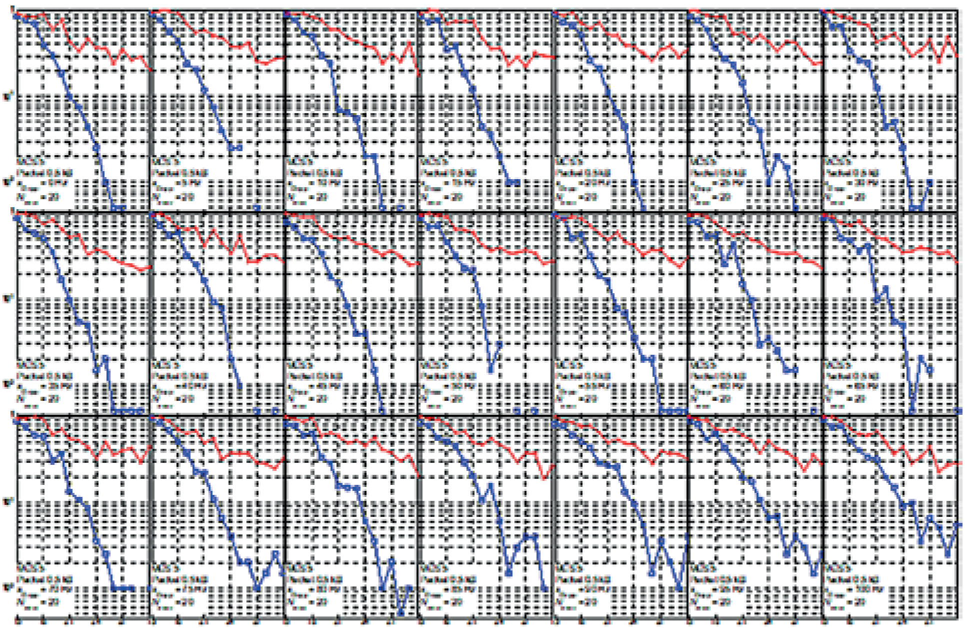


Fig. 15. The PER versus SNR (in dB) for 64-QAM with the coding rate of 2/3 (—□— 802.11p —+— 802.11a) by transmitting 512 bits in the packet

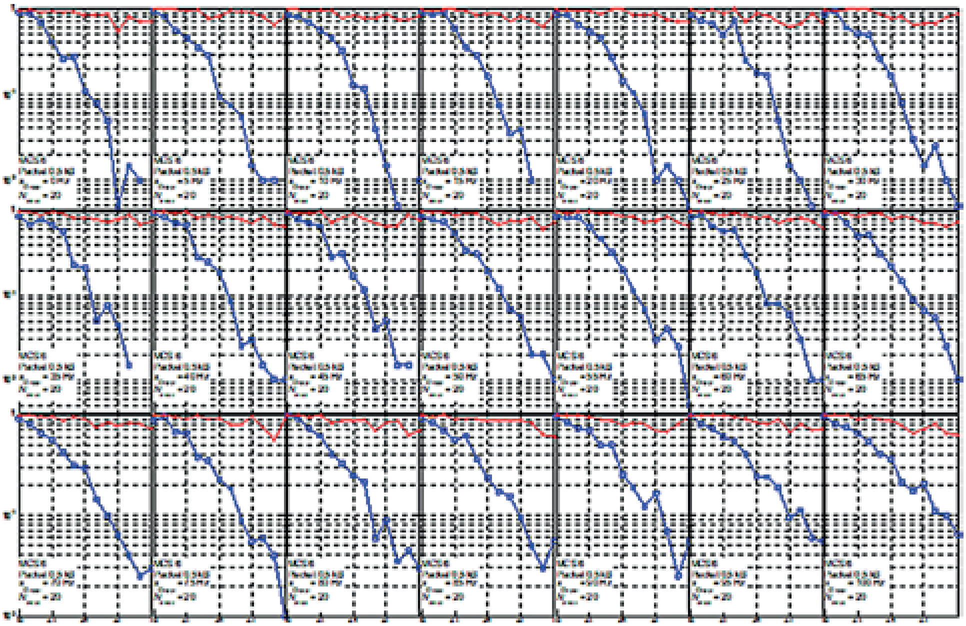
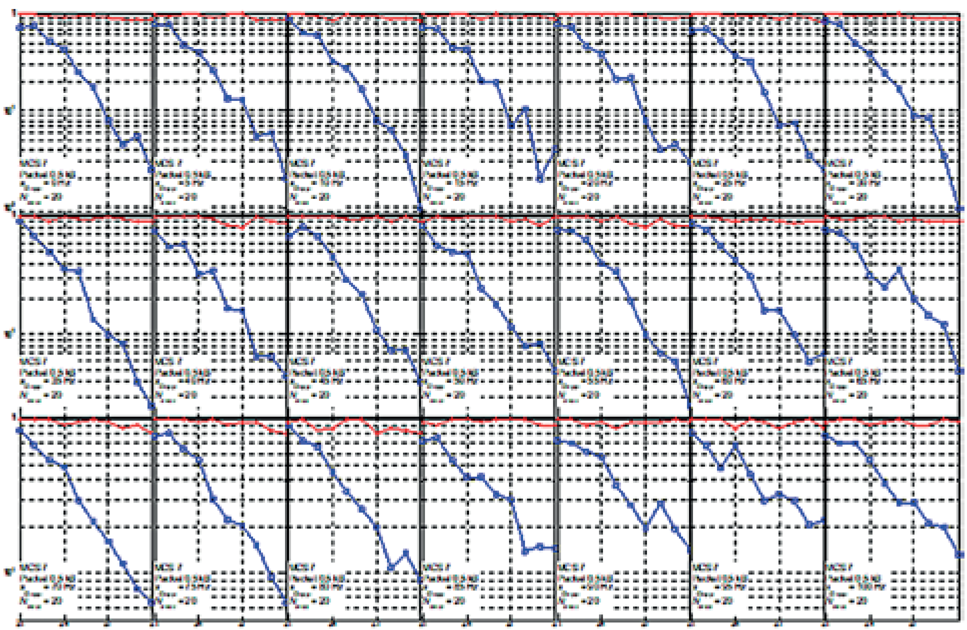


Fig. 16. The PER versus SNR (in dB) for 64-QAM with the coding rate of 3/4 (—□— 802.11p —+— 802.11a) by transmitting 512 bits in the packet



Using QPSK, the 802.11p link is almost as effective as the 802.11a link (Fig. 11, 12). Moreover, at the coding rate of 3/4 (Fig. 12), the 802.11p link has a tiny advantage at up to 65 Hz Doppler shift. Then, however, at greater Doppler shifts, the 802.11a link has a lower PER. It is worth noting that, in general, Fig. 11 and 12 resemble Fig. 3 and 4 (with the PER plots by transmitting 128-bit packets), whereas Fig. 9 and 10 are completely different from Fig. 1 and 2.

As in the case of 128-bit packets, by using 16-QAM, whichever the coding rate is, the 802.11p link provides better performance (Fig. 13, 14). At the coding rate of 1/2, the Doppler shift does not influence as well (Fig. 13). Nevertheless, if we increase the data rate by 50 % using the coding rate of 3/4 (MCS #5), the Doppler shift starts influencing since 65 Hz and greater (Fig. 14). For this MCS, the 802.11a link can hardly be used due to very poor PER performance, which is greater than 0.1. As in the case of 128-bit packets, by using 64-QAM, the 802.11a link cannot be used at all (Fig. 15, 16). Unlike the plots for BPSK, Fig. 13–16, showing the advantage of the 802.11p link, resemble Fig. 5–8.

The PER performance versus SNR by transmitting 1 KB packets is shown in Fig. 17–24. In this case, as well as in the case of 512-bit transmissions, BPSK is more advantageous for 802.11a (Fig. 17, 18). When the object moves faster, 802.11p starts losing its applicability. Indeed, if the Doppler shift exceeds 50 Hz, corresponding to approximately 9 km/hr, almost every tenth packet by the 802.11p link is lost. At the same time, the 802.11a link is still roughly applicable (at the appropriate SNR) even at 18 km/hr (the Doppler shift in 100 Hz). Nevertheless, if the object is moving slowly (producing the Doppler shift of up to 20 Hz, which is slower than a human normal walking speed), both the 802.11p and 802.11a links are quite effective and thus applicable.

Almost the same inference can be made from Fig. 19 and 20 for QPSK: for an object moving at 9 km/hr and faster, 802.11p is a poor link, whereas 802.11a is still sustainable. However, a peculiarity for QPSK at the coding rate of 3/4 exists: if the object is not moving or moving at a human normal walking speed (up to the Doppler shift of 25 Hz), the 802.11p link appears to be more efficient than 802.11a (Fig. 20). The 802.11a link becomes more advantageous only since the Doppler shift of 50 Hz. At the coding rate of 1/2, its advantage is apparent also since that shift, but both the 802.11p and 802.11a links are similarly effective at lower shifts.

The subcase of using 16-QAM at the coding rate of 1/2 (Fig. 21) has an interesting feature: unlike the cases of shorter packet transmissions, 1 KB packet transmissions are more efficient by the 802.11p link at lower speeds (up to the Doppler shift of 65 Hz). Then, when the speed increases, the 802.11a link becomes more efficient, and 802.11p loses its applicability since $s_{\mathrm{Dopp}} = 85$ Hz. At the coding rate of 3/4 (Fig. 22), 802.11a is inapplicable at all, whereas 802.11p is applicable up to $s_{\mathrm{Dopp}} = 85$ Hz. At $s_{\mathrm{Dopp}} > 85$ Hz (16 km/hr), almost 30 %...50 % of packets are lost, so neither link is applicable at speeds greater than approximately 16 km/hr.

By using 64-QAM, as in the cases of shorter packet transmissions, the 802.11p link provides indisputably better performance, and the 802.11a link is inapplicable at all (Fig. 23, 24). However, at the coding rate of 2/3, the 802.11p link can be effective only up to s_{Dopp} = 55 Hz (Fig. 23), corresponding to 10 km/hr. At the coding rate of 3/4, the margin speed is even lesser (Fig. 24): it is about 6.4 km/hr (the Doppler shift of 35 Hz).

All the features of advantage, effectiveness, and applicability described above are repeated and confirmed for the case of setting the maximum number of errors at 100 (Fig. 25–32). The only difference is that the PER performance plotted for N_{error} = 100 appears smoother than that plotted for N_{error} = 20 (Fig. 17–24). It also implies that all the features for the cases of transmitting 128-bit and 512-bit packets are described validly. A comparative recapitulation of the simulation results is presented in Table 2, in which the more efficient link is given by its respective letter, along with the speed at which it is valid. A similar efficiency is followed by selecting the 802.11a link owing to its twice greater data rate.

Table 2. Recapitulation of the simulation results

Packet length	MCS	Modulation type	Data Rate (Mbps)		The more efficient link (speed at which it is valid, km/hr)			Limit of applicability (comments)
			802.11a	802.11p	low	parity point, km/hr	high	
128 bits	0	BPSK	6	3		a		802.11a is still efficient at high speeds
	1	BPSK	9	4.5				
	2	QPSK	12	6				
	3	QPSK	18	9				
	4	16-QAM	24	12		p		802.11p is still efficient at high speeds
	5	16-QAM	36	18				
	6	64-QAM	48	24				
	7	64-QAM	54	27		p		30...40 km/hr
512 bits	0	BPSK	6	3		a		802.11a is still efficient at high speeds
	1	BPSK	9	4.5				
	2	QPSK	12	6				
	3	QPSK	18	9	p	11.9	a	
	4	16-QAM	24	12		p 30...40 km/hr		40...60 km/hr
	5	16-QAM	36	18				
	6	64-QAM	48	24				
	7	64-QAM	54	27				
1 KB	0	BPSK	6	3		a 20...25 km/hr		20...30 km/hr
	1	BPSK	9	4.5				
	2	QPSK	12	6		a		40...60 km/hr
	3	QPSK	18	9	p	6.4	a	30...40 km/hr
	4	16-QAM	24	12	p	11.9	a	20...30 km/hr
	5	16-QAM	36	18		p		16.5 km/hr
	6	64-QAM	48	24		14.6 km/hr		
	7	64-QAM	54	27		11 km/hr		

Source: Own study

Fig. 17. The PER versus SNR (in dB) for BPSK with the coding rate of 1/2 (—□—802.11p —+—802.11a) by transmitting 1 KB in the packet

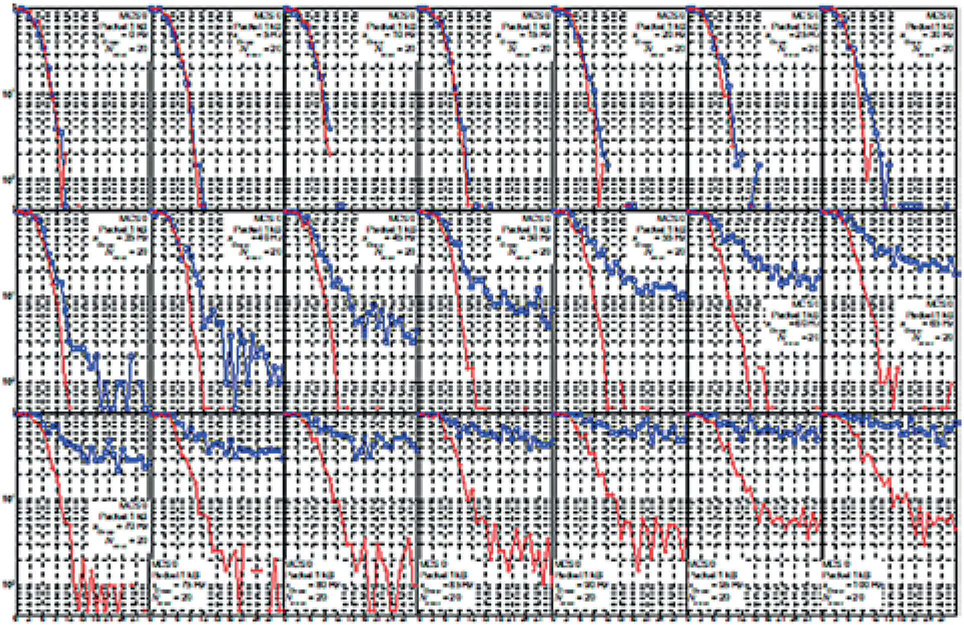


Fig. 18. The PER versus SNR (in dB) for BPSK with the coding rate of 3/4 (—□—802.11p —+—802.11a) by transmitting 1 KB in the packet

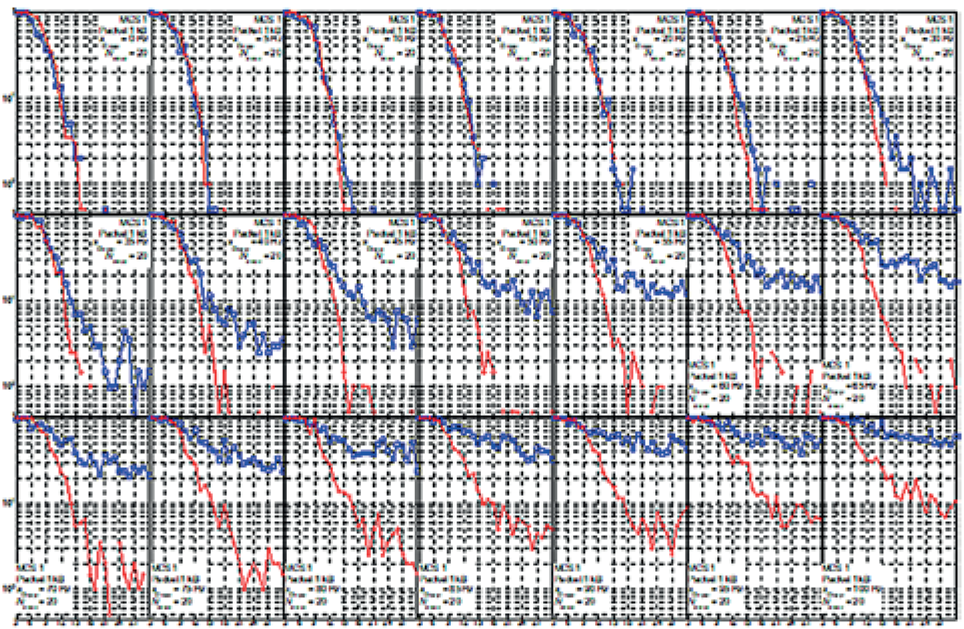


Fig. 19. The PER versus SNR (in dB) for QPSK with the coding rate of 1/2 (802.11p 802.11a) by transmitting 1 KB in the packet

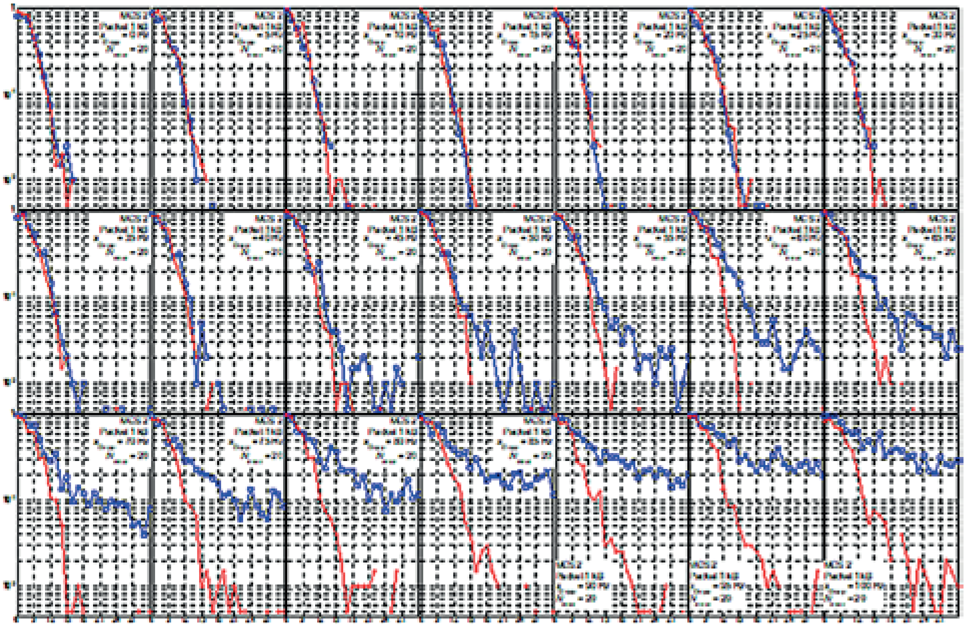


Fig. 20. The PER versus SNR (in dB) for QPSK with the coding rate of 3/4 (802.11p 802.11a) by transmitting 1 KB in the packet

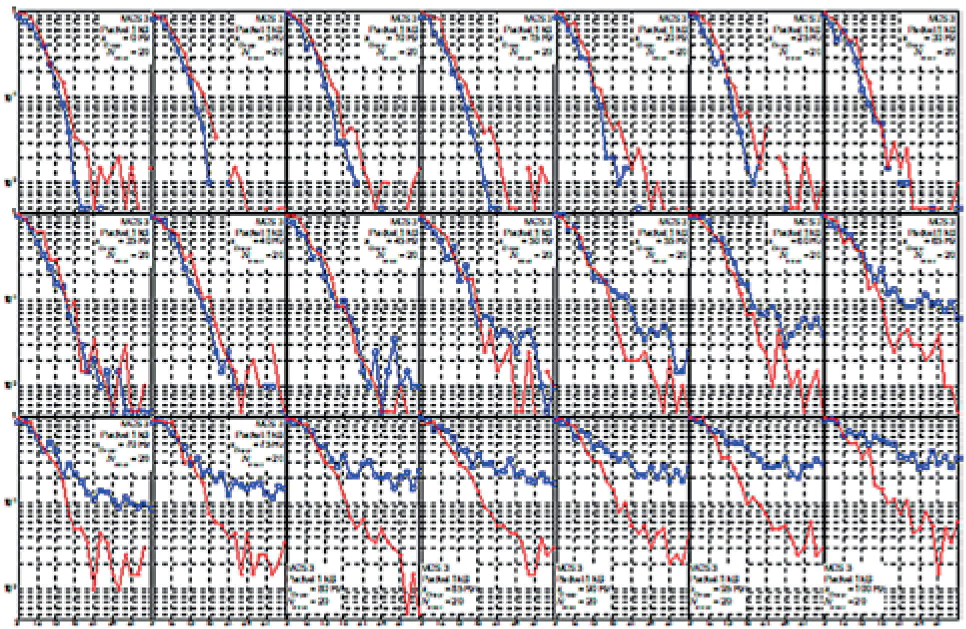


Fig. 21. The PER versus SNR (in dB) for 16-QAM with the coding rate of 1/2 (802.11p 802.11a) by transmitting 1 KB in the packet

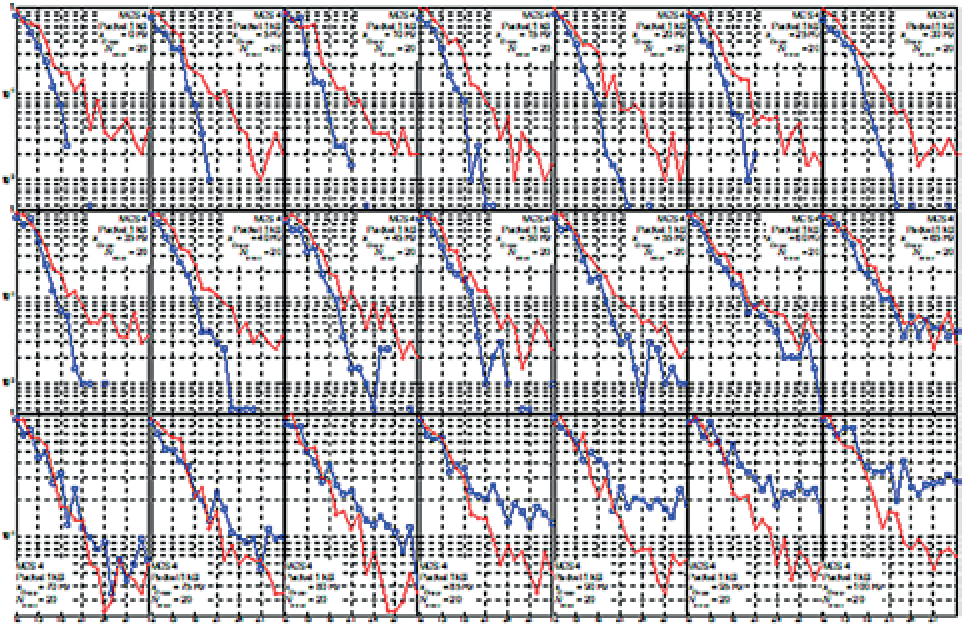


Fig. 22. The PER versus SNR (in dB) for 16-QAM with the coding rate of 3/4 (802.11p 802.11a) by transmitting 1 KB in the packet

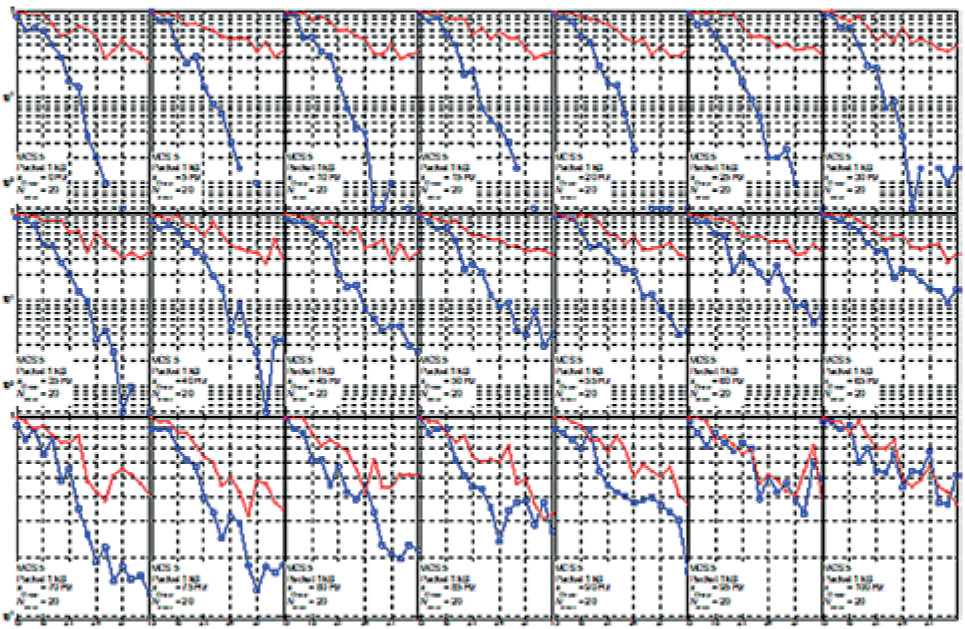


Fig. 23. The PER versus SNR (in dB) for 64-QAM with the coding rate of 2/3 (802.11p 802.11a) by transmitting 1 KB in the packet

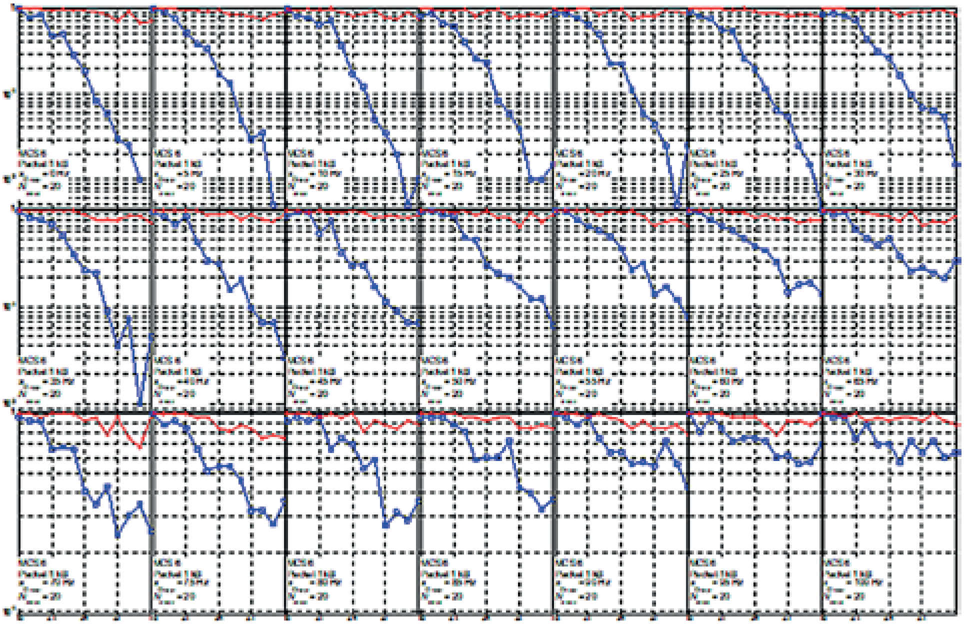


Fig. 24. The PER versus SNR (in dB) for 64-QAM with the coding rate of 3/4 (802.11p 802.11a) by transmitting 1 KB in the packet

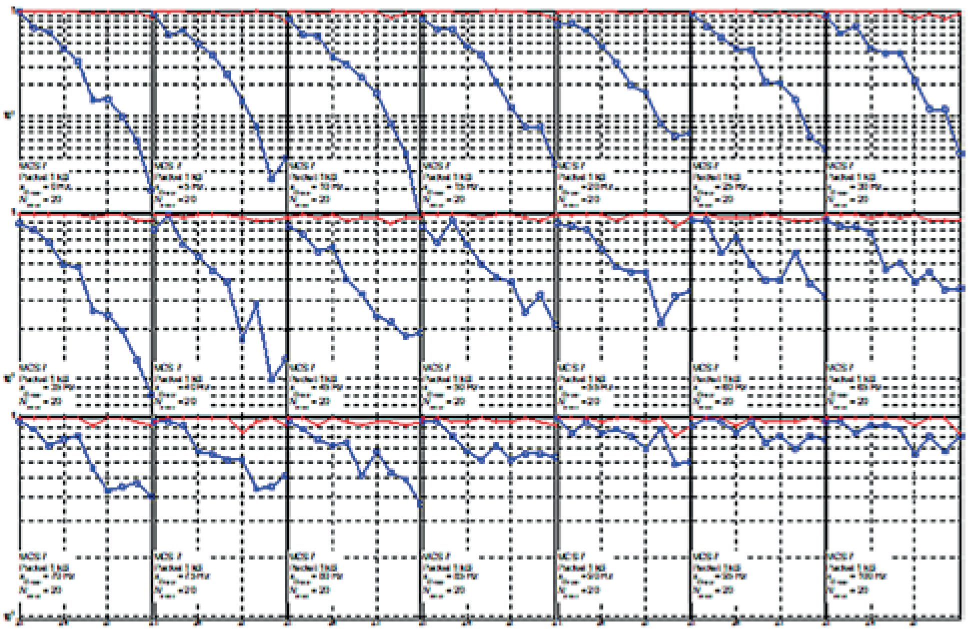


Fig. 25. The PER versus SNR (in dB) for BPSK with the coding rate of 1/2 (—□—802.11p —+—802.11a) by transmitting 1 KB in the packet ($N_{error} = 100$)

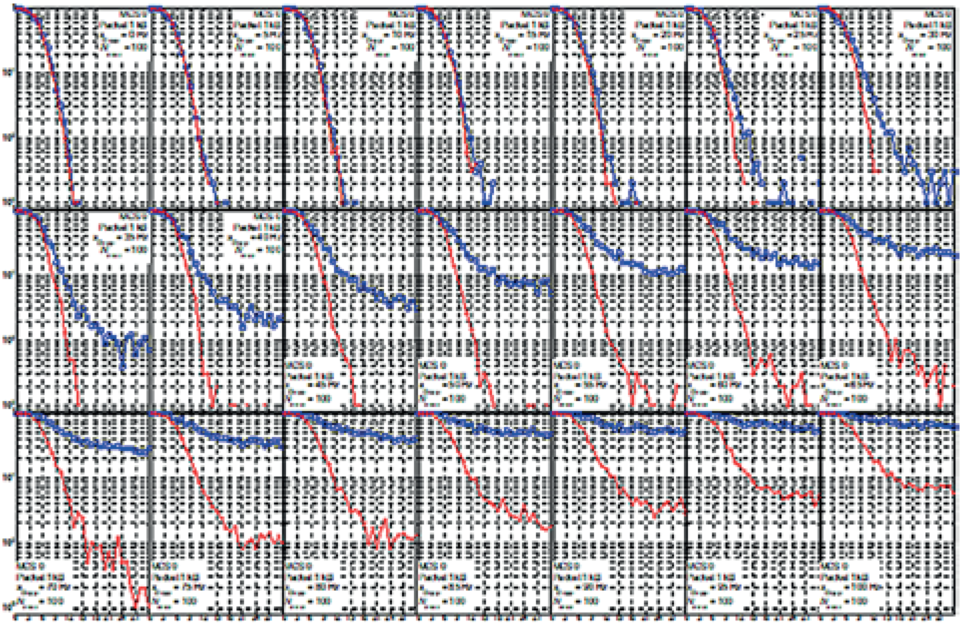


Fig. 26. The PER versus SNR (in dB) for BPSK with the coding rate of 3/4 (—□—802.11p —+—802.11a) by transmitting 1 KB in the packet ($N_{error} = 100$)

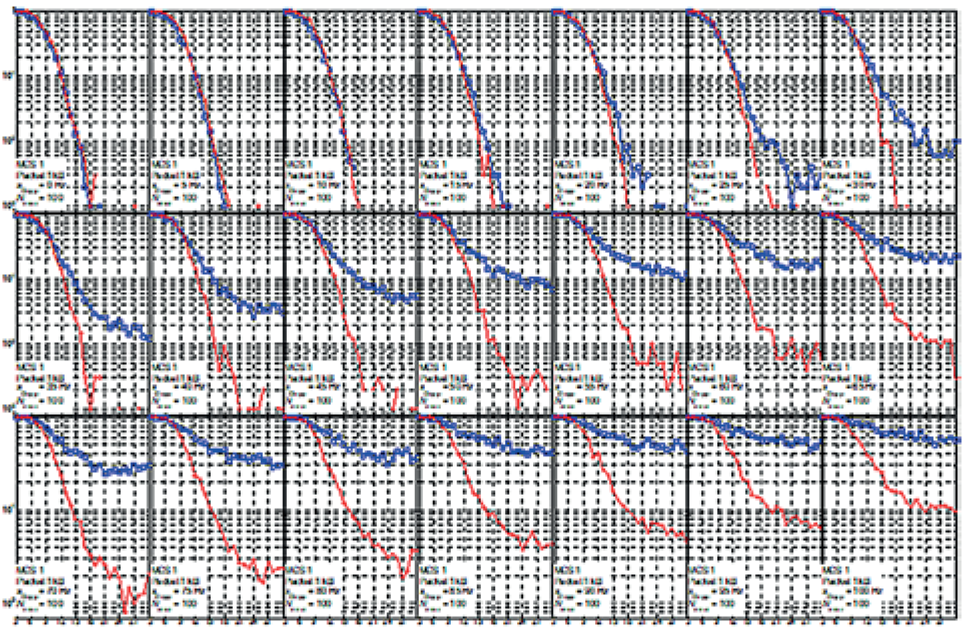


Fig. 27. The PER versus SNR (in dB) for QPSK with the coding rate of 1/2 (—▫— 802.11p —+— 802.11a) by transmitting 1 KB in the packet (N_{error} = 100)

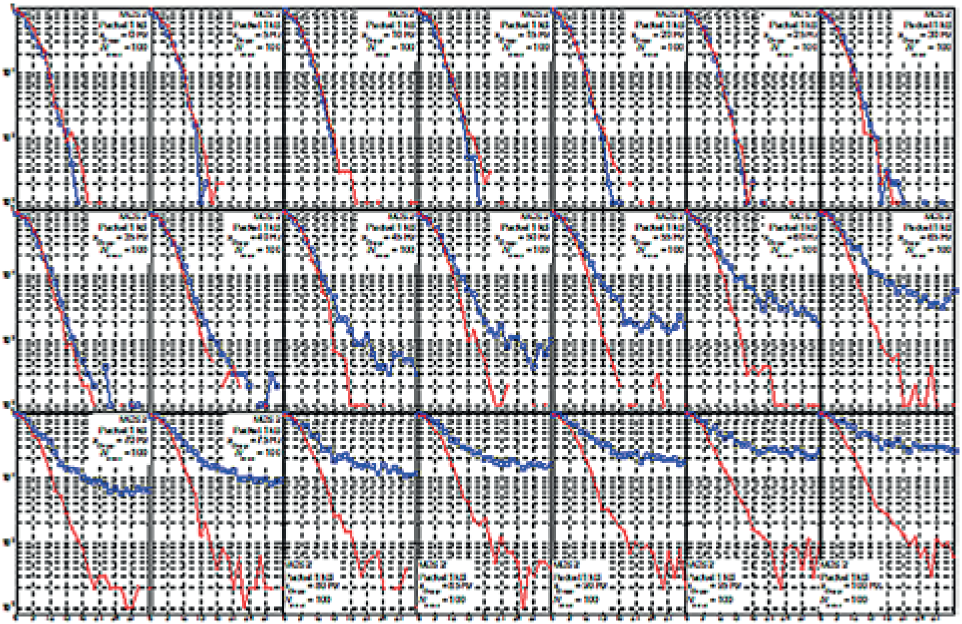


Fig. 28. The PER versus SNR (in dB) for QPSK with the coding rate of 3/4 (—▫— 802.11p —+— 802.11a) by transmitting 1 KB in the packet (N_{error} = 100)

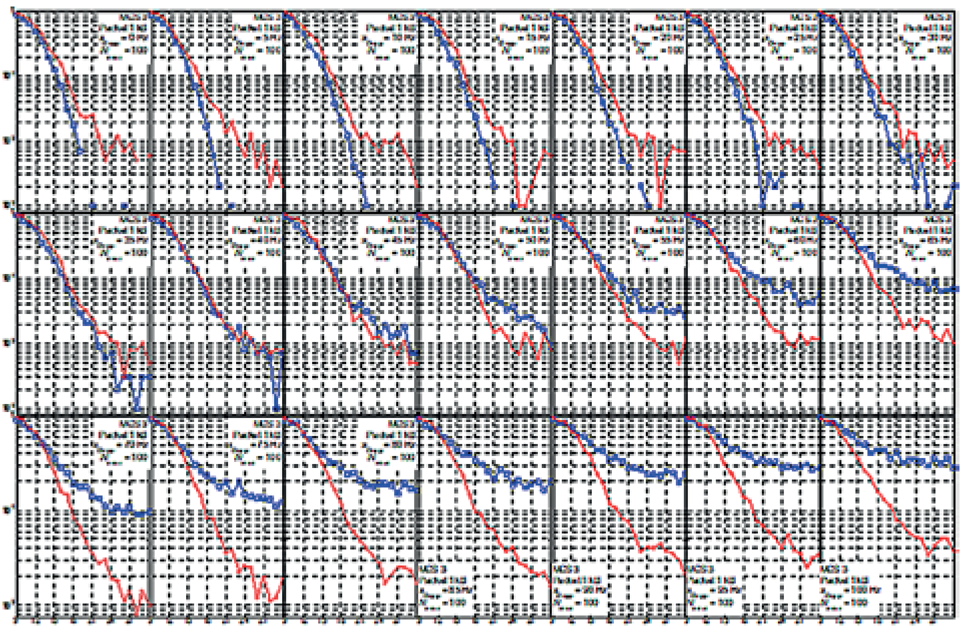


Fig. 29. The PER versus SNR (in dB) for 16-QAM with the coding rate of 1/2 (—□— 802.11p —+— 802.11a) by transmitting 1 KB in the packet ($N_{error} = 100$)

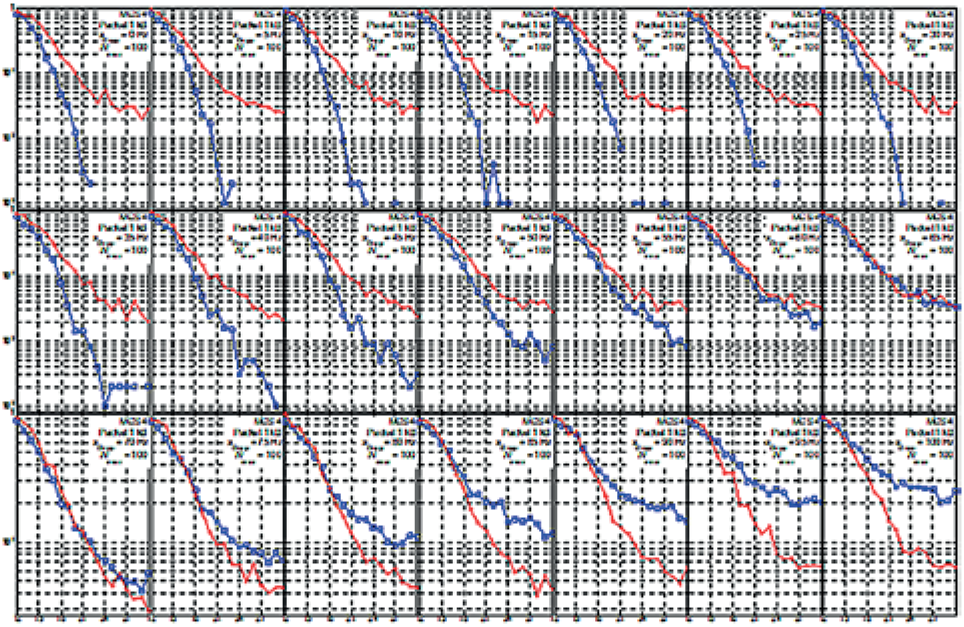


Fig. 30. The PER versus SNR (in dB) for 16-QAM with the coding rate of 3/4 (—□— 802.11p —+— 802.11a) by transmitting 1 KB in the packet ($N_{error} = 100$)

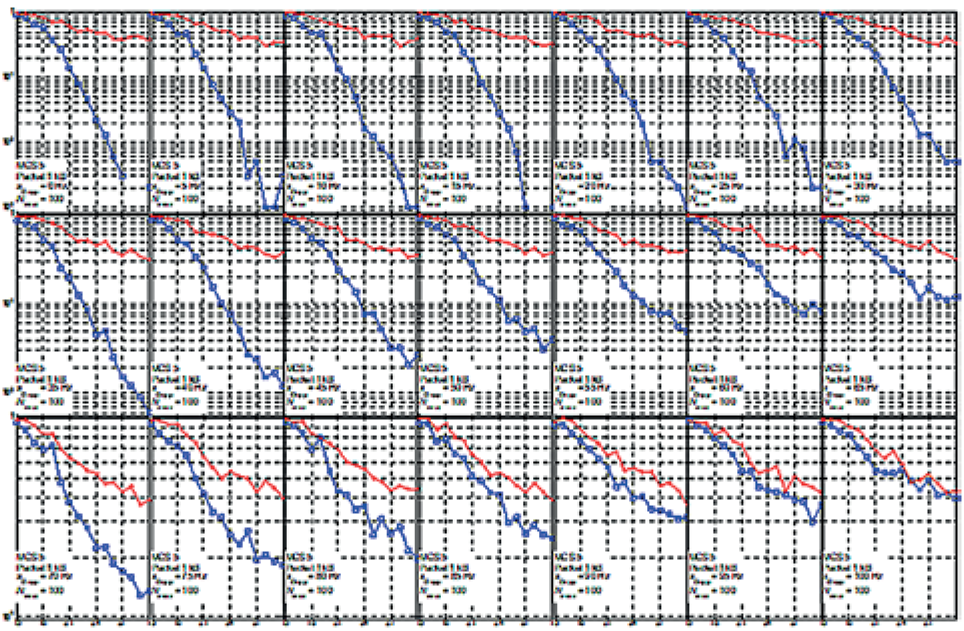


Fig. 31. The PER versus SNR (in dB) for 64-QAM with the coding rate of 2/3 (—▫— 802.11p —+— 802.11a) by transmitting 1 KB in the packet ($N_{error} = 100$)

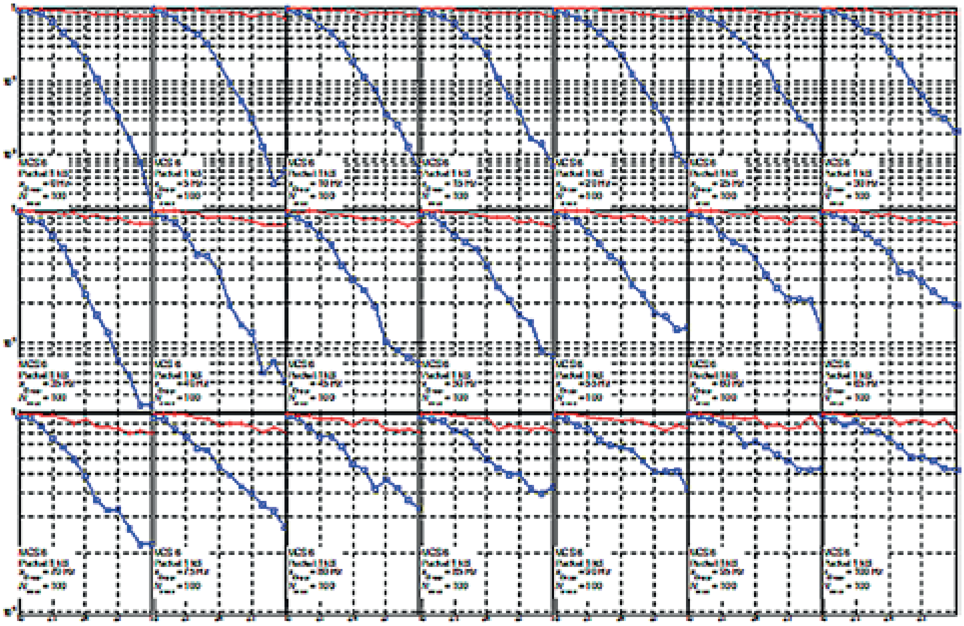
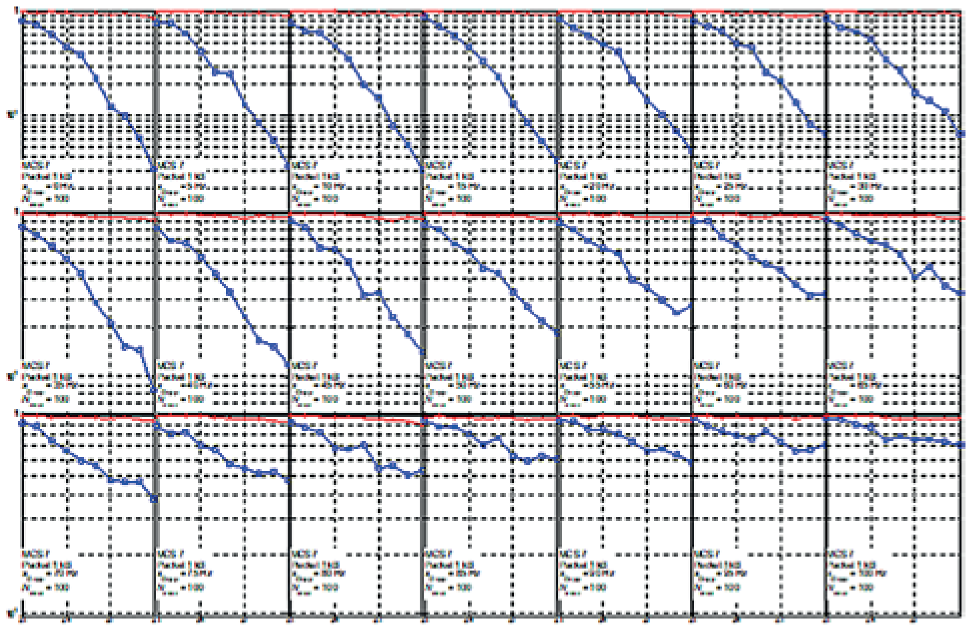


Fig. 32. The PER versus SNR (in dB) for 64-QAM with the coding rate of 3/4 (—▫— 802.11p —+— 802.11a) by transmitting 1 KB in the packet ($N_{error} = 100$)



Discussion and Conclusion

Table 2 demonstrates that the 802.11p link is completely inefficient by using BPSK, whichever the Doppler shift (the object speed) is. It is also inefficient using QPSK at the coding rate of 1/2 and is partially efficient by QPSK at the coding rate of 3/4 for longer packet transmissions. The 802.11p link is efficient by using QAM. However, as the packet length increases, the margin speed of the object drops. It also drops by increasing the data rate, e.g., the margin speed drops from 16.5 km/hr down to 11 km/hr by increasing the data rate from 18 to 27 Mbps (for 16-QAM and 64-QAM). Therefore, to enable high-quality WAVEs, a combination of the 802.11p and 802.11a links should be used. This combination does not imply assignments of constant weights to the links like a mixed strategy in a game (Hossain & Bhargava, 2007). It is rather a policy of selecting the link type. The selection depends on the object's speed and acceleration. If the object moves not fast with a constant speed, then the 802.11p link is used. As the object accelerates, we have two options: switch it to the shorter packets or QPSK/BPSK (if possible) at the 802.11a link. Otherwise, if the object decelerates, it is recommended to use 802.11p by either QAM (for transmitting packets of any length) or QPSK at the coding rate of 3/4 for 512-bit transmissions and longer. Surely, if the modulation type cannot be changed, then QoS in a QAM system can be ensured only by transmitting packets shorter than 1 KB. In BPSK systems, the 802.11a link is the only alternative. In QPSK systems, the best way to ensure QoS is to use the coding rate of 3/4, at which the data rate is 18 Mbps for 802.11a, where the 802.11p link is turned on at lower speeds.

When the 802.11a link is switched to the 802.11p link, the data rate is decreased twice. Besides, the PER may increase dramatically at higher speeds of moving objects. Then, switching to the lower-data-rate modulation types like BPSK and shorter packets is the only possibility for ensuring stable QoS in WAVEs, although the respective data rate is decreased to 9 Mbps. Therefore, a trade-off herein is a data rate versus margin speed.

Further research is tied to the moving object acceleration. Namely, it is important to understand and study how acceleration influences the QoS in WAVEs and ITS. The matter is that link switching is an inertial process, and plausible delays may have a negative impact on both data rate and PER.

Acknowledgements

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