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On 20 MHz Channel Spacing for V2X Communication based on 802.11 OFDM

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***Abstract*—In this semi-tutorial paper, we will examine the use of a larger channel spacing than 10 MHz for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, collectively referred to as V2X communication, based on the IEEE 802.11 OFDM physical layer. The main advantage of shifting to 20 MHz channel spacing is reduced congestion, which will reduce, or even eliminate, the need for congestion control algorithms. The tutorial parts of the paper will review basic OFDM design rules, summarize the reported values of important V2X channel properties (path-loss, delay spread, Doppler spread), and explain the current frequency allocation in Europe and the US. The novel parts of the paper will verify that the OFDM design rules are satisfied and quantify the performance of 10-MHz and 20-MHz systems through computer simulations. It is shown that a 20-MHz system will outperform a 10-MHz system.**

I. Introduction

Advanced sensor systems and vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication are enabling technologies for these future traffic safety and efficiency applications. With V2V and V2I communication, we mean direct communication between road vehicles (cars, trucks, motorcycles, etc.) and road vehicles and roadside infrastructure (e.g., traffic light, traffic signs, etc.), respectively, without involving a central control unit (basestation or access point). We will collectively refer to V2V and V2I communication as V2X communication.

The current standards for V2X communication have adopted the medium access control (MAC) and physical (PHY) layers of IEEE 802.11p[1] [2], [3]. To be more precise, the PHY layer is regular 802.11 OFDM with the 10-MHz channel spacing option, while most common option for Wi-Fi is 20 MHz. Hence, there is no special adaptation of the PHY layer to fit the V2X channel. The standard transmission rate of traffic safety messages is 6 Mbit/s.

The MAC adopted for V2X communication is standard 802.11 carrier-sense multiple access (CSMA) with enhanced distributed channel access (EDCA). The collective useful data rate that the V2X nodes will experience will be significantly less than 6 Mbit/s, due to the inability of CSMA to perfectly coordinate transmissions. In fact, it is well-known that CSMA does not scale well when the number of nodes increases. This has motivated an increased interest in distributed congestion control algorithms, i.e., methods for reducing the network load by controlling, e.g., the transmit power or offered traffic [4].

[1]802.11p was approved in 2010 and is now absorbed into 2012 version of 802.11 [1]

TABLE I: 802.11 OFDM parameters [1, Tables 18-4, 18-5]

Parameter	20 MHz	10 MHz
Sample Duration: T_s	0.05 μs	0.1 μs
Channel Spacing: $\Delta_F = 1/T_s$	20 MHz	10 MHz
Subcarrier Spacing: $\Delta_f = \Delta_F/64$	312.5 kHz	156.25 kHz
Orthogonality Duration: $T = 1/\Delta_f$	3.2 μs	6.4 μs
Cyclic Prefix (Guard Interval): $T_{\text{GI}} = T/4$	0.8 μs	1.6 μs
OFDM Symbol Duration: $T_{\text{SYM}} = T + T_{\text{GI}}$	4 μs	8 μs
MCS(QPSK, 1/2)	12 Mbit/s	6 Mbit/s
MCS(16-QAM, 1/2)	24 Mbit/s	12 Mbit/s

In this paper, we suggest an alternative solution to mitigating congestion, namely to increase the data rate by increasing the channel spacing to 20 MHz. This, seemingly trivial, approach offers several advantages, as will be detailed below.

The main contribution of this paper is a rather detailed discussion about the advantages and disadvantages of 10 and 20 MHz channel spacing for 802.11 OFDM PHY transmission over V2X channels and how a 20-MHz system can be implemented with current spectrum regulation in Europe. Moreover, the OFDM design rules are reviewed and are verified to be satisfied by a 20-MHz system, and results from extensive computer simulations quantify the gains we can expect by switching to 20 MHz system.

II. 802.11 OFDM PHY layer

All timing and bandwidth parameters for the 802.11p PHY layer can be derived from the sample time $T_s \in \{0.05, 0.1, 0.2\}$ μs, see Table I.

Current V2X standardization use the 6 Mbit/s data rate option for transmission of safety-related messages (CAM: cooperative awareness message and DENM: decentralized environmental notification message in Europe and BSM: basic safety message in the US). CAM/BSM messages are transmitted periodically with 10 Hz and typical messages lengths are approximately 400 bytes. Hence, the collective data rate of 6 Mbit/s will support a maximum of approximately $6 \times 10^6/(400 \times 8 \times 10) \approx 187$ vehicles, if the transmissions are perfectly coordinated. In practice, the 802.11 MAC will support significantly fewer transmitters.

To limit the impact of congestion, we can either employ congestion control algorithms that adjust, e.g., message rates, transmit power, packet lengths, or data rates. In this context, data rates are adjusted by changing the modulation and coding scheme (MCS), which we denote by MCS(*mod*, *rate*), where *mod* is the modulation and *rate* is code rate. For example, we can double the data rate by shifting from MCS(QPSK, 1/2) to MCS(16-QAM, 1/2), see Table I. However, MCS(16-QAM, 1/2) requires approximately 5 dB more received power than MCS(QPSK, 1/2) [1, Table 18-14], which will reduce the transmission range.

Another alternative to increase the data rate is to keep MCS(QPSK, 1/2) and increase the channel spacing to 20 MHz, which will require approximately 3 dB more received power [1, Table 18-14]. However, if the spectrum regulation can be interpreted as a spectrum mask, i.e., a constraint on the transmitted power spectral density, we are allowed to double the transmit power when doubling the bandwidth and thereby compensating for the increased received power requirement. The spectrum allocation will be discussed further below in Sec. IV-B.

Hence, this first-order analysis implies that there is no loss in transmission range when switching to a 20 MHz channel spacing. On the contrary, since a 20 MHz-system is more robust against channel time-variations and has the potential to collect more frequency diversity, the transmission range might even improve.

One could also imagine using carrier aggregation to transmit two parallel 10 MHz 802.11 OFDM frames with MCS(QPSK, 1/2) on adjacent frequency channels. This would also double the data rate, but the OFDM symbol length would remain the same and robustness against time-variations would be worse compared to 802.11 with 20 MHz channel spacing.

Finally, as explained in Sec. IV-B, we might even argue that the extra 10 MHz bandwidth needed to switch from 10 MHz to 20 MHz can be found without extra cost.

To summarize, it is our contention that we can increase the data rate, and thereby reduce the congestion, essentially without paying for this in transmit range or spectrum by switching from 10 MHz to 20 MHz channel spacing. This, of course, is only true if the 802.11 OFDM PHY will perform well over 20 MHz V2X channels. The remainder of this paper is mainly devoted to showing that is indeed the case.

III. OFDM DESIGN RULES

Intercarrier interference (ICI) occurs when the received subcarriers are not orthogonal. To avoid ICI, the OFDM symbol should be very small compared to the channel coherence time, T_c, which justifies the OFDM design rule 1:

$$T_{\text{SYM}} \ll T_c \approx \frac{1}{B_D} \Rightarrow B_D T_{\text{SYM}} \ll 1, \tag{1}$$

where B_D is the Doppler spread.

Intersymbol interference (ISI) occurs when OFDM symbols overlap in time at the receiver. To avoid ISI, the cyclic prefix (guard interval) should exceed the channel maximum delay spread T_m, i.e., $T_{\text{GI}} > T_m$. Since, $T_m \approx \sigma_{T_m}$, where σ_{T_m} is the RMS delay spread, this justifies the OFDM design rule 2:

$$T_{\text{GI}} > \sigma_{T_m}. \tag{2}$$

As we increase the channel spacing in 802.11 OFDM, all timing parameters, including T_{GI} and T_{SYM} are reduced. Hence, the PHY layer becomes more robust against Doppler spread, but less robust against delay spread.

TABLE II: Reported V2V channel parameters

Parameter	Highway	Rural	Suburban	Urban
RMS delay spread [ns]	40–400	20–60	104	40–300
Doppler spread [Hz]	100-1000	100-800	missing	30–350

IV. V2X RADIO CHANNELS

A. Channel characterization

Radio channels are typically characterized by three effects: path loss, large-scale fading (shadow fading), and small-scale fading. These characteristics will depend on the environment (e.g., urban, suburban, rural) and if V2V or V2I channels are considered. Path-loss is typically modeled as following a log-distance law, i.e., that the received power (in dB-scale) at distance d can be computed as

$$P_r(d) = P_0 - 10\beta \log_{10}(d/d_0), \tag{3}$$

where P_0 is the received power (in dB-scale) at distance $d = d_0$ and β is the path-loss exponent. In some environments, the received power follows (3) in a piece-wise linear manner, e.g., the pathloss exponent is different for different distance intervals. The pathloss exponent is important, since it will dictate how the communication range will change as a function of the transmit power.

The large-scale fading is typically modeled as a log-normal random variable. However, we will not discuss it further here, since we assume that it will not depend on the channel spacing, and can therefore be absorbed into P_0 in (3).

We model the radio channel as a random, time-varying linear filter with impulse response $h(\tau, t)$. We will assume that the channel is wide-sense stationary (WSS) uncorrelated scattering (US). This assumption is shown to be reasonable for time intervals less than 40 ms and frequency intervals less than 40 MHz in [5], which is sufficient for our purposes. The time-varying frequency response $H(f, t) = \int_{-\infty}^{\infty} h(\tau, t) \exp(-j2\pi f\tau)\, d\tau$ for a WSS-US channel is wide sense stationary in both time and frequency, i.e., the autocorrelation function $R_H(f, f + \Delta_f; t, t + \Delta_t) \triangleq \mathrm{E}[H^*(f, t)H(f + \Delta_f, t + \Delta_t)]$ is only a function of Δ_f and Δ_t. With some abuse of notation, we will in the following write $R_H(\Delta_f, \Delta_t)$ rather than $R_H(f, f + \Delta_f; t, t + \Delta_t)$. The coherence time T_c and coherence bandwidth B_c are measures on the smallest time and frequency spacing for which the channel decorrelates, i.e., $|R_H(0, \Delta_t)|$ is small for $\Delta_t \geq T_c$ and $|R_H(\Delta_f, 0)|$ is small for $\Delta_f \geq B_c$. In this paper, we do not specify exactly what is meant by "small" is this respect, since we will not need the exact numerical values of the coherence time or coherence bandwidth.

The coherence time and coherence bandwidth are inversely proportional to the delay spread T_m and Doppler spread B_D, respectively. We will not specify the proportionality factor, since it depends on detailed features of R_H and since it is not needed for our analysis.

A summary of reported values for RMS delay and Doppler spreads for measured V2X channels is found in Table II, see [6] and the references therein. It should be noted that reported values varies quite a lot in the literature. For instance, the RMS delay spread has been observed to be as large as 2 μs is some extreme situations [7]. However, the values in Table II are representative of average values of the measured Doppler and delay spreads, and we therefore consider them in the following discussion. Clearly, the V2X channel with highest Doppler and delay spread is the V2V highway one. However, we note from Tables I and II that the OFDM design rules (1) and (2) are satisfied for both the 10 and 20 MHz channel spacing options.

B. Spectrum allocation

The ITS spectrum allocation in Europe is described in the ETSI standards EN 302 571 [8] and EN 302 663 [9]. The safety related messages will be transmitted in the ITS-G5A band: 5.875–5.905 GHz. Similar spectrum bands have been allocated in the US, 75 MHz in the range 5.850–5.925 GHz and in Japan, 80 MHz in the range 5.770–5.850 GHz [10].

Four specific bands are defined in [9]: ITS-G5A, from 5.875 to 5.905 GHz, dedicated to ITS for safety related applications; ITS-G5B, from 5.855 to 5.875 GHz, dedicated to ITS non-safety applications; ITS-G5D, from 5.905 to 5.925 GHz, which is reserved for future use for ITS road traffic applications; and ITS-G5C, from 5.470 to 5.725 GHz, which is a Radio Local Area Network (RLAN) band that can be used also for ITS applications.

The channel spacing in ITS-G5A, ITS-G5B, and ITS-G5D is set to 10 MHz, which is the same spacing as in WAVE [3]. Hence, there is room for seven channels in these bands: one control channel, G5CCH, and six service channels, G5SCH1–G5SCH6 [9], see Fig. 1.

As seen from in Fig. 1, the spectrum mask (thick solid line) is not used to its maximum emission limit, presumably to limit interference into the important control channel and to adhere to the strict out-of-band emission limits into the CEN-DSRC band, which is located at 5 795–5 805 MHz.

The current approach is to transmit CAM and DENM messages in the control channel (G5CCH). To the best of the author's knowledge, there are no concrete plans for what the service channels in ITS-G5A will be used for. Hence, to form a 20 MHz channel by combining, e.g., G5CCH and G5SCH2, would not cost anything in terms of bandwidth, in the sense that no current or planned service must be moved from G5SCH2.

Moreover, the spectrum mask indicates that a 20 MHz system is allowed to transmit with 3 dB more power than a 10-MHz system. The power allocation in G5SCH2 should be possible to change by updating ETSI EN 302 571 [8], i.e., no new spectrum regulation should be required.

V. Numerical Results

To verify the approximative analysis above, we have conducted computer simulations to estimate the frame error probability for different fading channel conditions, frame lengths, channel spacing, and channel estimation approaches. The modulation and coding scheme is 802.11 OFDM with MCS(QPSK, 1/2), see [1, Table 18.4].

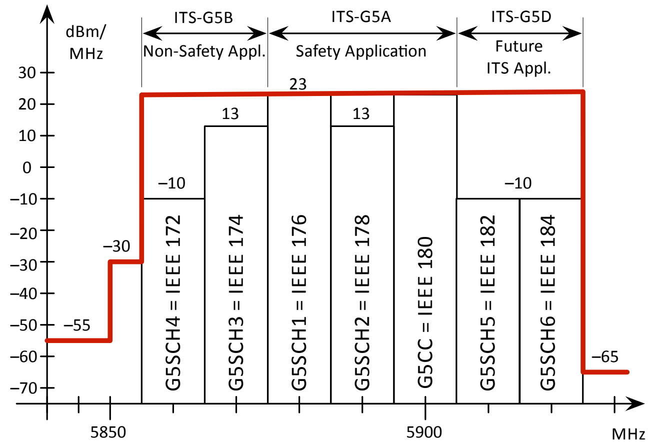

Fig. 1: Channel allocation and spectrum mask for ITS-G5A, ITS-G5B, and ITS-G5D channels.

The channel is modeled as an L-tap tapped-delay line with impulse response $h(\tau, t) = \sum_{\ell=0}^{L-1} h_\ell(t)\delta(t - \tau_\ell)$, where $h_\ell(t)$ and τ_ℓ are the gain and delay of the ℓth tap, respectively. We assume that $\{h_\ell(t)\}_{\ell=0}^{L-1}$ are iid zero-mean circular complex Gaussian random processes (Rayleigh-fading) with Clarke's (or Jakes') power spectrum, i.e., the autocorrelation function for $h_\ell(t)$ is $\mathrm{E}[h_\ell^*(t)h_\ell(t + \Delta_t)] = J_0(2\pi f_D \Delta_t)$, where J_0 is the zeroth order Bessel function of the first kind and f_D is the maximum Doppler shift. For a uniform scattering environment and two-dimensional propagation, which is the physical motivation for Clarke's power spectrum, we have that $f_D = v/\lambda$, where v is the speed and λ is the wavelength. We assume that $\lambda = c/f_c$, where c is the speed of light in vacuum and $f_c = 5.9$ GHz. Although V2V channels typically do not experience the scattering environments that result in Clarke's power spectra, we will use it here since it is well-known and easily parameterized. In the plots in Figs. 2 and 3, the Doppler spread is indicated by the (virtual) speed v.

With the above modeling, we can approximate the Doppler spread with the maximum Doppler shift and the RMS delay spread by the maximum delay spread, i.e., $B_D \approx f_D$ Hz and $\sigma_{T_m} \approx (L-1)/10$ μs, respectively.

For simplicity, we assume that the channel is static over one sample duration T_s and that the tap delays are integer multiples of 0.1 μs, i.e., $\tau_\ell = \ell \times 10^{-7}$ s for $\ell = 0, 1, \ldots, L-1$. However, the channel is allowed to vary over an OFDM symbol, which will result in intercarrier interference.

The received signal is $r(t) = s(t) * h(\tau, t) + n(t)$, where $n(t)$ is additive white complex Gaussian noise with power spectral density N_0. The receiver is a standard OFDM receiver. Hence, the signal sampled is with rate $1/T_s$, the cyclic prefix is removed, and data is found by soft Viterbi decoding.

We model channel estimation in two ways, long training (LT) based or perfect. With "perfect" we mean that the receiver can compute the true channel frequency response $H(f, t)$. In the decoding of nth OFDM symbol, the receiver uses the channel frequency response averaged over the corresponding

OFDM symbol duration, i.e., the "perfect" channel estimate is

$$\hat{H}_{\mathrm{p}}(f,n) \triangleq \frac{1}{T_{\mathrm{SYM}}} \int_{nT_{\mathrm{SYM}}}^{(n+1)T_{\mathrm{SYM}}} H(f,t)\,dt, \quad n=0,\ldots,n_F-1,$$

where n_F is the number of OFDM symbols that carries the data part of the frame.

In practice, channel estimation is often based on the long training (LT) sequence that prepends the data symbols in a 802.11 OFDM frame. The channel estimate is then kept fixed during the frame. We model such a receiver by the channel estimate $\hat{H}_{\mathrm{LT}}(f,n) = \hat{H}_{\mathrm{p}}(f,0)$ for $n = 0,1,\ldots,n_F-1$. We note that both the "perfect" and "LT" channel estimators are idealized since they are not affected by channel noise.

In Fig. 2, the frame error rate is plotted versus the SNR per information bit, E_b/N_0, for flat-fading channels, 10 MHz (left column) and 20 MHz (right column) channel spacing, and different frame lengths. The curves in each plot are for "perfect" and "LT" channel estimation and different Doppler spreads.

For flat-fading and "perfect" channel estimation, we expect essentially same performance for all frame lengths. The impact of high Doppler spreads is an increase in intercarrier interference, which is manifested in degraded performance when the Doppler spread increases or when the channel spacing (equivalently, OFDM symbol time) decreases.

For flat-fading and LT channel estimation, we observe, in addition to the above, additional degraded performance as the normalized Doppler spread becomes large, i.e., for longer frames or for larger Doppler shifts.

We can also conclude from Fig. 2, that 20 MHz channel spacing gives better or similar performance compared to 10 MHz channel spacing, when all other parameters are fixed. Indeed, this is the expected result since delay spread is zero for flat-fading channels, and robustness against Doppler is enhanced by increasing the channel spacing (since that implies a decreased OFDM symbol duration for 802.11 OFDM).

Fig. 3 shows similar performance plots as in Fig. 2, but for frequency-selective channels (i.e., for $L = 5$ and uniform power-delay profile). Frequency-selective channels are in general better than flat fading, since the channel coding can exploit the available frequency diversity. This is confirmed by comparing corresponding plots in Figs. 2 and 3 (note the different scales on the vertical axis).

Except for a generally better frame error rate, we note the same relative differences for the frequency-selective channels as for the flat-fading channel.

VI. Conclusions

We conclude that 20 MHz channel spacing is an attractive alternative to 10 MHz channel spacing for V2X communication. The main advantages are due to the shortened OFDM symbol duration which will decrease channel congestion and increase the robustness towards channel time-variations. Hence, the problem with intercarrier interference and outdated channel estimates for long frame lengths will be less for 20 MHz channels compared to 10 MHz channels. Moreover, for the simulated channels in this paper (flat and frequency-selective Rayleigh-fading channels with Clarke's Doppler spectrum and uniform power delay profiles), the 802.11 OFDM PHY layer is able to exploit the frequency selectivity better when using the 20 MHz channel spacing options compared to the 10 MHz channel spacing.

The potential drawback with a shortened guard interval (cyclic prefix), i.e., a reduced robustness towards delay spread, will not be a problem for channels with the delay spreads that corresponds to the reported V2X channel delay spread measurements in Table II. Of course, if the delay spread would be significantly higher than in Table II, this conclusion needs to be re-evaluated.

The comparison is based on the assumption that the transmitted power is constrained by a spectrum mask, implying that the 20 MHz system can use twice as much transmit power as the 10 MHz system. If both systems have the same transmit powers, the 20-MHz transmission range will be approximately 70–80% of the 10-MHz range for path-loss exponents in the interval $\beta \in [2,4]$ (neglecting the changes in robustness to time and frequency variations).

Acknowledgement

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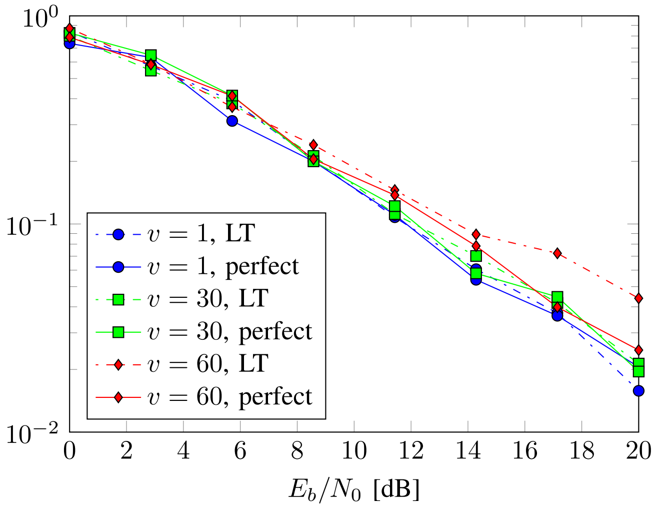
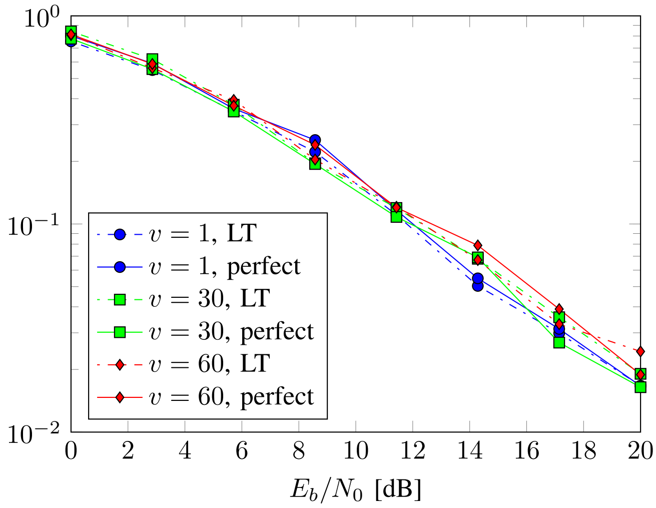
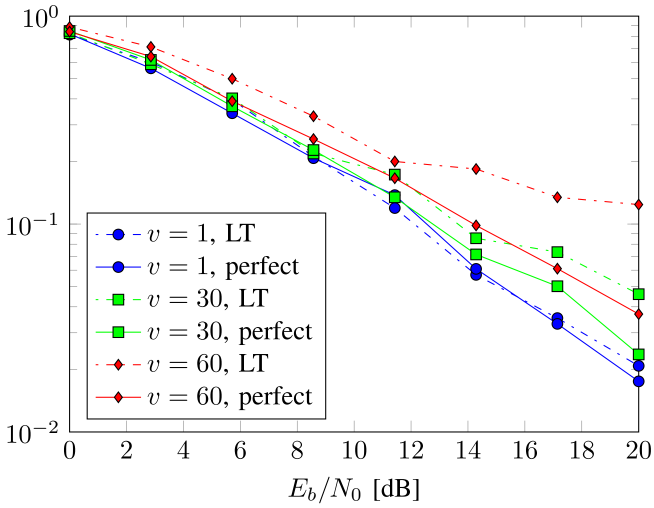


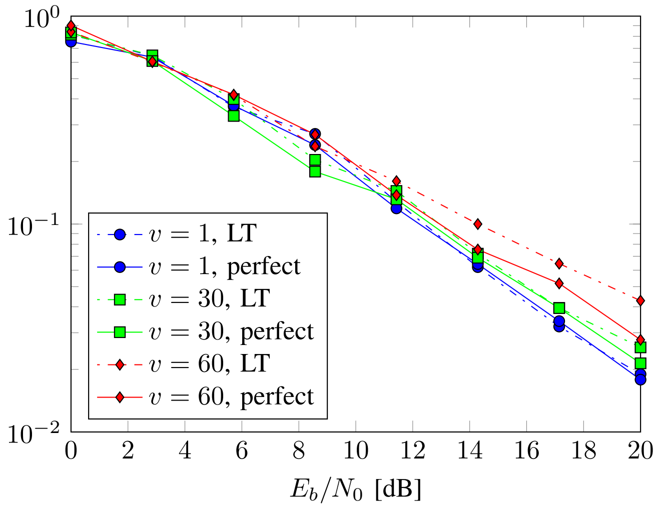
(a) 10 MHz channel spacing, 102 byte frames



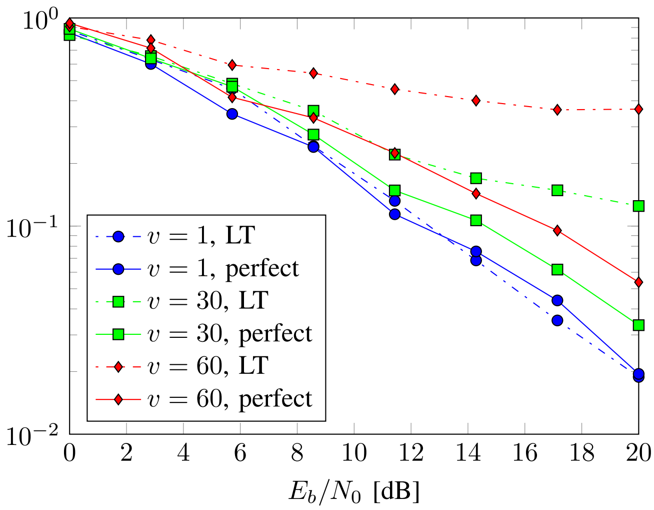
(b) 20 MHz channel spacing, 102 byte frames



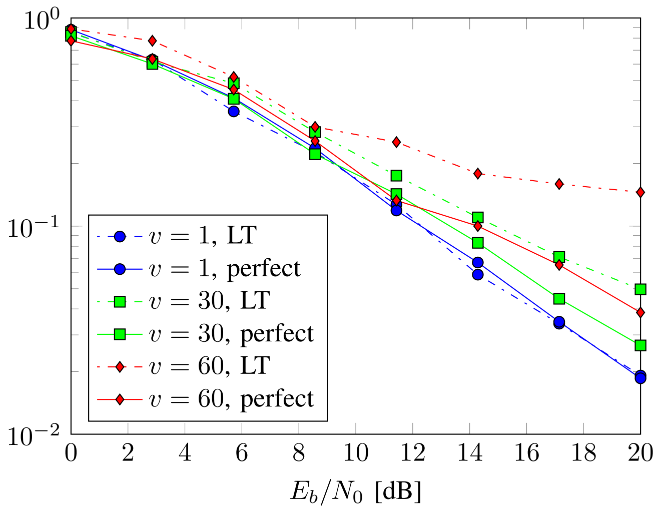
(c) 10 MHz channel spacing, 204 byte frames



(d) 20 MHz channel spacing, 204 byte frames

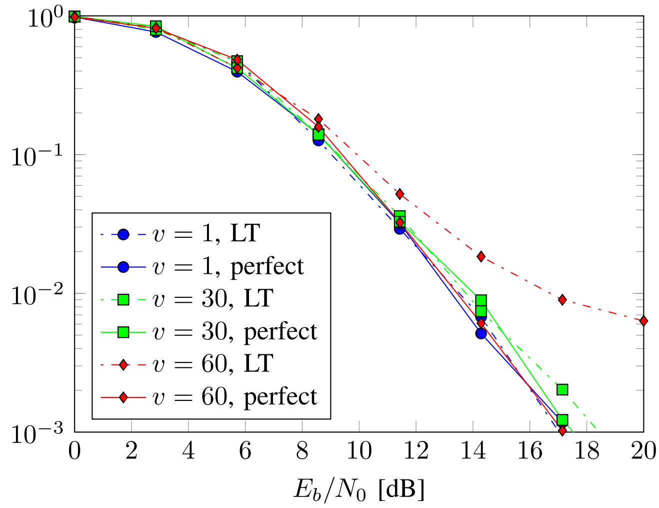


(e) 10 MHz channel spacing, 402 byte frames

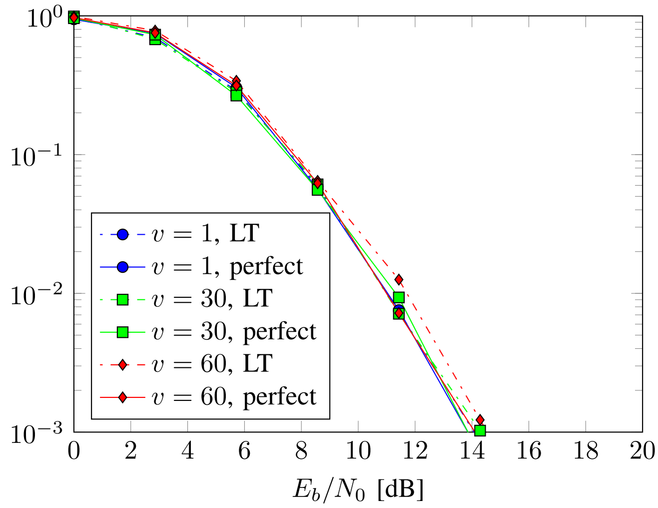


(f) 20 MHz channel spacing, 402 byte frames

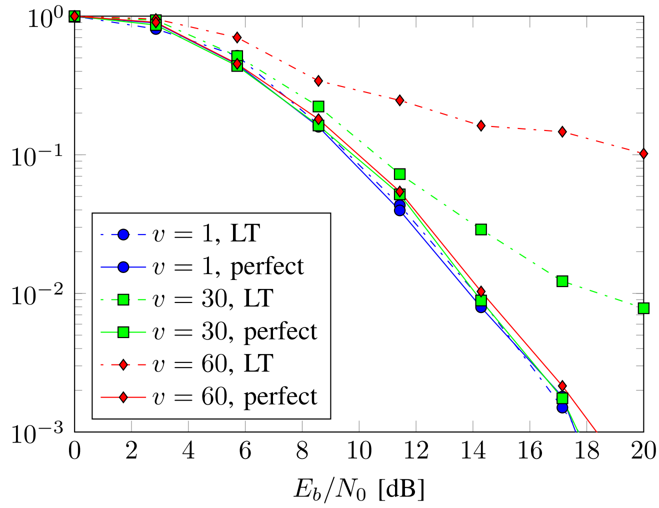
Fig. 2: Frame error probability for 10 MHz (left column) and 20 MHz (right column) channel spacing; 102, 204, and 402 byte frames; "perfect" channel estimation (solid) and LT channel estimation (dash-dotted); flat-fading channel, i.e., $L = 1$.



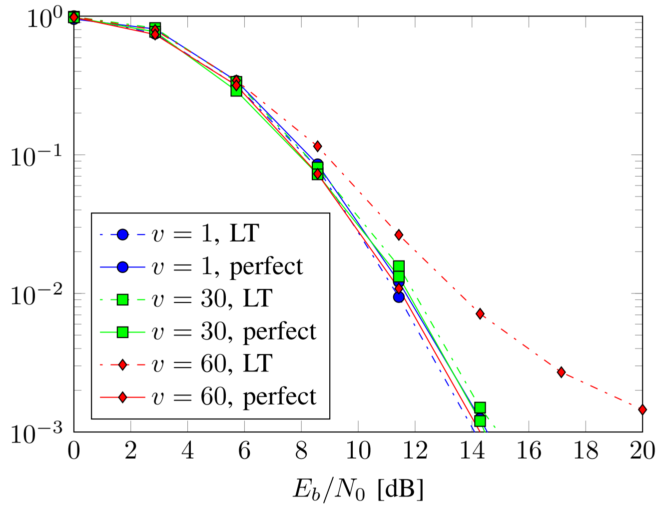
(a) 10 MHz channel spacing, 102 byte frames



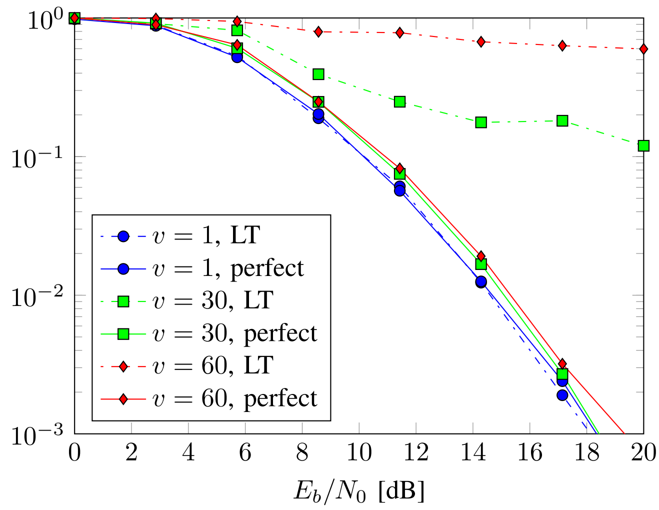
(b) 20 MHz channel spacing, 102 byte frames



(c) 10 MHz channel spacing, 204 byte frames



(d) 20 MHz channel spacing, 204 byte frames



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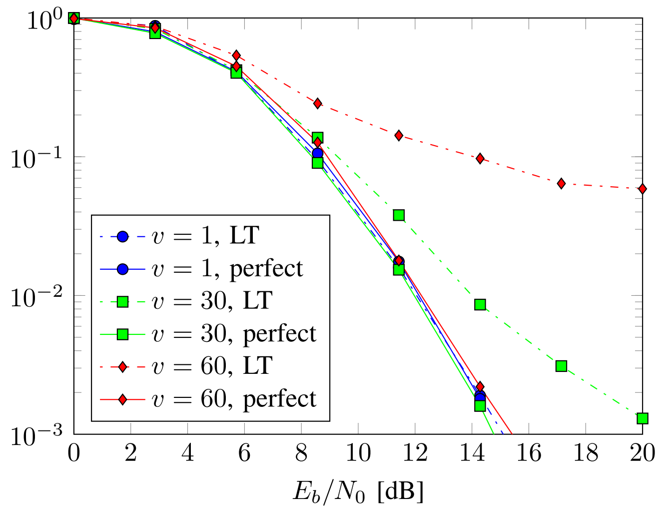

(f) 20 MHz channel spacing, 402 byte frames

Fig. 3: Frame error probability for 10 MHz (left column) and 20 MHz (right column) channel spacing; 102, 204, and 402 byte frames; "perfect" channel estimation (solid) and LT channel estimation (dash-dotted); frequency-selective channel with $L = 5$.