# Tentpoles Scheme: A Data-Aided Channel Estimation Mechanism for Achieving Reliable Vehicle-to-Vehicle Communications

Zheng Li, *Member, IEEE*, Fan Bai, Joseph A. Fernandez, *Member, IEEE*, and B. V. K. Vijaya Kumar, *Fellow, IEEE*

***Abstract*—IEEE 802.11p-based Dedicated Short Range Communications (DSRC) is considered a promising wireless technology for enhancing transportation safety and improving highway efficiency. One major challenge of IEEE 802.11p technology development ensuring its communication reliability in highly dynamic Vehicle-to-Vehicle (V2V) environments. In this paper, by investigating the characteristics of V2V channels through empirical measurements, we show that the decreased reliability of V2V communication is because the IEEE 802.11p design does not have sufficient number of training symbols in time domain and pilot subcarriers in frequency domain to enable estimation of the fast-changing V2V channels accurately. To tackle this challenge, we propose a new approach called Tentpoles scheme, which utilizes a small subset of data symbols and subcarriers protected by a strong Error Correction Code (ECC) to track and estimate V2V channel variations. Since this subset of data symbols and subcarriers provide dual-use, our Tentpoles scheme not only improves the accuracy of channel estimation and communication reliability, but has only a small impact on effective throughput. Through extensive simulations in synthetic V2V channels and emulation experiments using empirical measurements, our proposed Tentpoles scheme is shown to significantly outperform other V2V channel estimation and equalization methods in terms of communication reliability, at the cost of only moderate loss of throughput.**

***Index Terms*—Vehicle-to-Vehicle communications, IEEE 802.11p, Error correction codes, DSRC, Channel estimation.**

## I. Introduction

THE EMERGENT IEEE 802.11p-based Dedicated Short Range Communication (DSRC) standard provides a new approach for enabling Vehicle-to-Vehicle (V2V) communication. Among other V2V use cases, cooperative safety system is the most important application: one vehicle can warn another about impending road hazards, adverse weather, an upcoming traffic jam, or another vehicle in its blind spot. As a result, the U.S. National Highway Traffic Safety Administration recently announced that it is to begin taking steps to enable the deployment of V2V technology in all new cars and trucks [1].

To realize the full potential of V2V, one major technical challenge is to ensure that the reliability of such mission-critical communication systems is adequate. V2V wireless channel is indeed an extremely challenging signal propagation environment: (1) vehicle-level mobility leads to a short channel coherence time; and (2) the presence of mobile and stationary scatterers results in a narrow coherence bandwidth. The most recent channel sounding measurements indicate that coherence bandwidth is about 410–820 KHz and coherence time is about 0.3–1.0 ms in V2V channels [2], which are in direct contrast to benign static indoor environments (a coherence time of 25 ms [3] and coherence bandwidth of 1–3 MHz [4]). Since the V2V channel changes dramatically over the course of one packet, channel estimation and corresponding equalization process is significantly challenging, leading to degraded communication reliability [8]. The key reasons for the degraded performance of IEEE 802.11p standard in V2V channels are two-fold:

- Due to the fast time-varying nature of the V2V channels, coupled with the fact that the 802.11p standard does not restrict packet length (the only restriction is a maximum of 4095 bytes per packet), the channel estimate obtained at the beginning of each packet becomes quickly outdated;
- The 4 pilot subcarriers regulated in IEEE 802.11p standard are not spaced closely enough in frequency to capture the channel variation in the frequency domain.

Therefore, the primary challenge that we face is to develop an accurate means of updating the channel estimate over the course of a packet length, *while* adhering to two critical structural requirements of IEEE 802.11p standard (i.e., OFDM and convolutional code). By improving the performance at the physical layer, we reduce packet error rate (PER) and make each link in the vehicular network more reliable. We argue that this improvement will trickle its way up the communication stack, improving performance at all layers and leading to a better performing network.

In this paper, we propose a new approach called Tentpoles scheme to achieve this goal. Our major contributions are listed as follows:

- We show that the low reliability of V2V communication is mainly due to the fact that the IEEE 802.11p design is not fully customized to V2V channel, i.e., IEEE 802.11p does not have sufficient number of training symbols in

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Z. Li is with Coats & Bennett PLLC, Cary, NC 27518 USA (e-mail: zhengli.hust@gmail.com).

F. Bai is with General Motors Corporation, Detroit, MI 48232-5170 USA (e-mail: fan.bai@gm.com).

J. A. Fernandez is with Northrop Grumman Corporation, Falls Church, VA 22042 USA (e-mail: joseph.anthony.fernandez@gmail.com).

B. V. K. Vijaya Kumar is with the Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213-3890 USA (e-mail: kumar@ece.cmu.edu).

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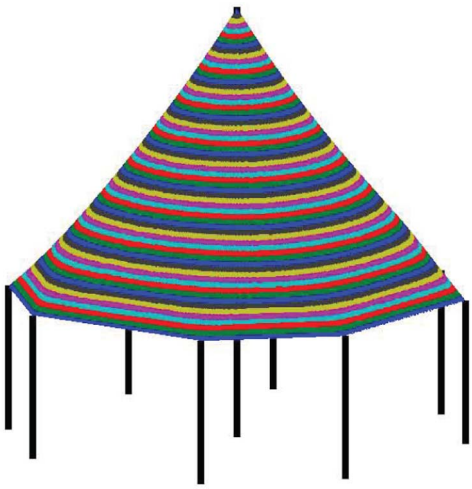


Fig. 1. A graphic illustration of Tentpoles Scheme. In the scheme, a small subset of data symbols and subcarriers (protected by strong Error Correction Code) are able to improve the accuracy of overall channel estimation, in a similar way that a few tentpoles are able to support the whole tent.

time domain and pilot subcarriers in frequency domain to track highly dynamic V2V channels;

- Having realized the root cause of unreliable V2V communication is the poor estimation of the underlying fast-varying channel, we propose a new channel estimation approach called Tentpoles scheme to improve channel estimation accuracy. In this proposed scheme, at the transmitter, a small subset of data symbols and data subcarriers are further protected by strong Error Correction Codes (ECC), as tentpole symbols/subcarriers to track and estimate V2V channel variations; therefore, the receiver has sufficient information to perform accurate channel estimation and corresponding equalization. A graphical illustration of Tentpoles Scheme is given in Fig. 1. The novelty of our Tentpoles scheme lies on the fact that tentpole symbols/subcarriers provide dual-use: they are used to enhance channel estimation as virtual training symbols or virtual pilots subcarriers, but they still carry user data;
- Through extensive simulations and emulations using both synthetic V2V channels and empirical measurements, we show that the performance (in terms of Packet Error Rate) could be significantly improved from 40% (using a simple Least Squares Estimator) to $<10\%$ by using our Tentpoles scheme in real-world empirical measurements, at the cost of moderate loss in throughput. We also conduct extensive sensitivity study to explore different design options and find some interesting observations. For instance, our analysis reveals that Tentpoles scheme in frequency domain gives the best performance because V2V channel is a fast fading channel.

The rest of the paper is organized as follows. We summarize the relevant literature in Section II. We give the background of IEEE 802.11p standard and motivate our work in Section III. After presenting the vision of our scheme in Section IV, we present the design of Tentpoles scheme at both the transmitter and the receiver in Section V and Section VI, respectively. We then present simulation results in synthetic channels in Section VII and present emulation results using empirical measurements in Section VIII. We conclude the paper in Section IX.

## II. Related Work

In recent years, there have been extensive research efforts on V2V communications:

**V2V Channel Measurements and Modelling**. In [8], the authors conducted a series of empirical experiments and analyzed V2V channel characteristics under freeway, rural, suburban and open field environments. Impacts of various factors including distance, velocity, transmission power and modulation rate were tested and analyzed. These empirical experiments provided a comprehensive understanding of the real V2V channel characteristics. A V2V channel model through parametric method is proposed in [9], which is shown to be more accurate than the classical Jake's channel model. Furthermore, a series of empirical experiments were conducted in [10], which is the foundation for the six V2V channel models used in our simulation studies. The focus of our work is on channel estimation and equalization, while we explicitly make use of the channel models in [10] to emulate our proposed Tentpoles scheme in different V2V scenarios.

**Channel Estimation in Fast Fading Channels**. In [11], the authors proposed to insert additional training symbols to help channel estimation. These additional training symbols were used purely for channel estimation and cannot carry any user information. In contrast, our scheme uses tentpole symbols/subcarriers as additional virtual training symbols or pilot subcarriers, which helps to better track channel variation. At the same time, these tentpole symbols/subcarriers could still carry user information though the data rate is slightly reduced. An iterative channel estimator by using generalized discrete prolate spheroidal sequence was proposed in [13]. With either a small coherence bandwidth or a small coherence time, the computational complexity of this iterative channel estimator will significantly increase, making it unsuitable for V2V channels. Our proposed Tentpoles scheme, instead, is particularly designed for V2V channels with small coherence bandwidth and short coherence time, so that the computational complexity is acceptable.

**Performance of IEEE 802.11p standard**. In [15], the authors analyzed the performance of IEEE 802.11p standards through real-world experiments, which included both Line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. Several equalization methods were designed to improve the performance of IEEE 802.11p standard in [16]. The method in [12] is substantially similar to the STA method proposed in [16]. The idea is to update channel estimation from symbol to symbol with only 2 training symbols at the beginning of each packet (see section 3.A of [12]). The only difference is that [12] uses reduced FFT for channel smoothing while STA uses weighted moving averaging for channel smoothing. [14] investigates the downstream performance of measured IEEE 802.11p infrastructure-to-vehicle links. However, [14] does not investigate V2V channels. Empirical measurement results in both [15] and [16], though conducted in different countries,

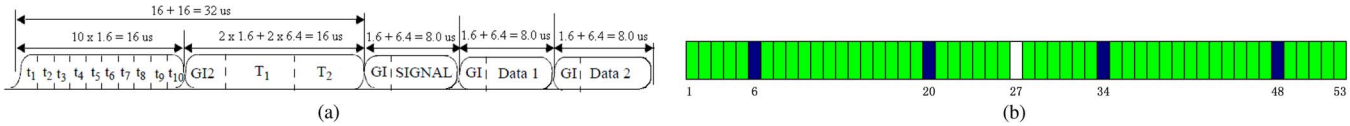



Fig. 2. The packet structure and symbol structure of IEEE 802.11p packet. (a) The IEEE 802.11p physical-layer packet structure; (b) the IEEE 802.11p OFDM symbol structure. Pilot subcarriers are labeled as blue and data subcarriers are labled as green.

showed high packet error rate across a variety of realistic driving scenarios, indicating that there is a strong need for a new channel estimation and equalization algorithm to improve the performance of IEEE 802.11p standard. Our work is motivated by these two pieces of research. Unlike other channel estimation approaches which are of receiver-centric nature, our work advocates a transmitter-centric approach in which extra ECC protection is carefully placed on a subset of data symbols and data subcarriers on the transmitter side.

## III. Background and Motivation

In this section, after introducing IEEE 802.11p standard, we analyze why existing IEEE 802.11p transceiver technique faces significant challenges in providing reliable V2V communication.

### A. IEEE 802.11p Standard

The IEEE 802.11p standard follows the same Orthogonal Frequency Division Multiplexing (OFDM) modulation as the IEEE 802.11a/g standard. OFDM is a multicarrier modulation technology that transmits data by spreading it over multiple orthogonal subcarriers; this way, each narrowband subcarrier only experiences flat fading although the overall spectrum is frequency selective fading.

Fig. 2(a) illustrates the structure of IEEE 802.11p physical-layer packet [6]. After the first ten short synchronization symbols ($t_1$ through $t_{10}$), two identical symbols ($T_1$ and $T_2$) are used as training symbols to enable the receiver to estimate the wireless channel for the entire packet. Then, a number of data symbols are sent while the channel estimation obtained using the training symbols at the beginning of the packet is used to equalize data symbols at the receiver. Fig. 2(b) illustrates the OFDM symbol structure: there are 52 subcarriers in each OFDM symbol for IEEE 802.11p standard. Among them, 4 pilot subcarriers (subcarriers 6, 20, 34 and 48) are used for tracking channel variations in frequency domain while the remaining 48 subcarriers are used for transmitting user data information.

**IEEE 802.11p-compliant Equalization Scheme**: To obtain correct data packets, the receiver must perform channel estimation and equalization to reduce Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI).

The IEEE 802.11p standard mechanism heavily relies on the initial 2 training symbols ($T_1$ and $T_2$) of each packet to estimate the channel. In particular, the default Least Squares (LS) equalization scheme [6] extracts the transmitted symbol from the received symbol as $X_i(k) = \frac{Y_i(k)}{H_0(k)}$, where $Y_i(k)$ is the $i$-th received data symbol at subcarrier $k$ and $X_i(k)$ is the corresponding estimated transmitted data symbol. Here, $H_0(k)$ is the initial channel estimate obtained using these 2 training symbols and $H_0(k)$ will not be further updated through the entire packet. Similarly, in each symbol, the 4 pilot subcarriers are the only mechanism used to correct frequency offsets. Because of its loose tracking capability, as reported in [16], even with the most reliable modulation option (BPSK with 1/2 coding rate), the observed Packet Error Rate (PER) of LS scheme could reach 40%, which is obviously much higher than the reliability requirement of commercial WiFi chipsets [6].

TABLE I
V2V Channel Characteristics

| Parameter | Suburban | Highway | Rural |
|---|---|---|---|
| Coherence Time | 1.0ms | 0.3 ms | 0.4ms |
| Coherence Bandwidth | 820 KHz | 410 KHz | 420 KHz |

To address this issue, an advanced equalization scheme called Spectral-Temporal Averaging (STA) [16] was proposed to continuously update channel estimation at the receiver. In particular, once the $i$-th data symbol $X_i(k)$ is successfully demodulated at the receiver, an updated channel estimate of subcarrier $k$ is obtained as $H_i(k) = \frac{Y_i(k)}{X_i(k)}$. To reduce the impact of channel fluctuation, $H_i(k)$ is further averaged in both frequency domain and time domain through a low-pass filter (e.g., weighted moving average) before it is used to demodulate the $i+1$-st symbol as $X_{i+1}(k) = \frac{Y_{i+1}(k)}{H_i(k)}$. By tracking time-domain and frequency-domain variation of V2V channel more closely, STA and its enhancement, ESTA [17], were shown to significantly outperform the default LS scheme, reducing PER values from 40% to 20% (for STA), and 40% to 15% (for ESTA), respectively.

In vehicular environments, there are two channel impairment factors that degrade the performance of OFDM schemes: Multi-path fading (caused by environments) and Doppler effect (caused by mobility). These two factors could be quantified by two channel characteristics—channel coherence time and channel coherence bandwidth. In this section, by analyzing these two channel characteristics in real-world environments, we not only understand how V2V channel characteristics affect channel estimation, but also reveal potential solution to improve the accuracy of channel estimation in highly dynamic V2V environments.

### B. Vehicular Wireless Channel Characteristics

Table I presents the key vehicular wireless channel characteristics across a variety of V2V environments (suburban, highway and rural), which was obtained through extensive channel sounding measurement experiments in Pittsburgh, Pennsylvania, USA [2]. We observe that both coherence time and coherence bandwidth in V2V channel are much smaller than their counterparts in stationary indoor WiFi channel. For example, the coherence time is about 0.3–1.0 ms in V2V

channel while indoor environments enjoy longer coherence time (i.e., 25 ms [3]); the coherence bandwidth in V2V channel is about 410–820 KHz while typical value of coherence bandwidth in an indoor environment is in the range 1–3 MHz [4].

To achieve reliable wireless communication, accurate channel estimation—either through training symbols in time domain or through pilot subcarriers in frequency domain—plays a critical role in equalization process.

In time domain, channel estimates are obtained from initial training symbols in the packet header and are used for the remainder of packet. Therefore it is vital to ensure that the packet duration is smaller than the coherence time for the channel estimates and thus the corresponding equalization to remain valid. In V2V environments, it takes 1.5–4.5 ms for a packet of 500–1500 bytes to be transmitted at a data rate of 3 Mbps, while the channel coherence time is only 0.3–1 ms. That is to say, the initial channel estimate provided by IEEE 802.11p design is outdated quickly, which clearly indicates that the IEEE 802.11p design is inadequate to track channel variation in time domain. Similarly, in frequency domain, channel estimation is performed by using pilot subcarriers. It is therefore important to ensure that the spacing of pilots must be smaller than the channel coherence bandwidth. However, in current IEEE 802.11p design, the pilot subcarrier spacing (2.1875 MHz) is significantly larger than V2V channel coherence bandwidth (410–820 KHz), which indicates that the 4 pilot subcarriers are inadequate to track the frequency-domain variation as well.

We believe that the insufficient number of training symbols (in time domain) and pilot subcarriers (in frequency domain) is the root cause of inaccurate channel estimation, which leads to less reliable wireless communication in V2V environments. Motivated by this observation, in this paper, we propose a new approach called the Tentpoles scheme which virtually increases the number of training symbols and pilot subcarriers to improve the channel estimation accuracy.

## IV. Tentpoles Scheme in a Nutshell

Having realized that the insufficient channel tracking structure of existing IEEE 802.11p standard is the fundamental reason for inaccurate channel estimation in V2V communication scenarios, we believe that an enhanced channel tracking capability will help to improve the communication reliability of IEEE 802.11p standard. Specifically, there are three different options to achieve this goal:

1) The first approach is to explicitly insert a number of extra training symbols in the middle of each packet (in time domain) or insert extra pilots in each OFDM symbol (in frequency domain);
2) The second approach is to implicitly utilize all the data symbols or all the data subcarriers as if they were additional training symbols or pilot subcarriers.
3) The last approach is to implicitly utilize a small portion of selected data symbols as additional *pseudo training symbols* in time domain, or use a small portion of data subcarriers as additional *pseudo pilot subcarriers* in frequency domain, or a combination of both approaches, to enhance channel estimation;

The first option ensures that the receiver has sufficient information in both time domain and frequency domain to estimate the channel accurately. On the other hand, however, these extra training symbols and pilot subcarriers do not carry user information, resulting in more overhead and reducing data transmission efficiency. The second option treats all data symbols and data subcarriers with equal importance; as shown later in Section VII, our experiments demonstrate that this option tends to add more redundancy than needed, rendering a less effective solution.

In this paper, we take the third approach and propose a new packet structure called *Tentpoles scheme* to improve channel tracking and estimation. In our proposed scheme, in addition to default 2 training symbols and 4 pilot subcarriers, a small number of extra training symbols (in time domain) and/or pilot subcarriers (in frequency domain) are implicitly designated as psuedo training symbols and psuedo pilot subcarriers. We call these psuedo training symbols and psuedo pilot subcarriers as tentpole symbols and tentpole subcarriers. Note that these tentpole symbols and tentpole subcarriers offer dual-use: on one hand, they still carry user information just as other data symbols and subcarriers do; on the other hand, they are implicitly used to enhance channel estimation as virtual training symbols or pilot subcarriers, in addition to regulated 2 training symbols and 4 pilot subcarriers in the standard IEEE 802.11p packets. These tentpole symbols and subcarriers can offer such dual use because the Tentpoles scheme protects the tentpole symbols and subcarriers with a stronger error correction code (ECC), thus ensuring that after decoding, the transmitted data corresponding to the tentpole symbols and subcarriers is known at the receiver with very high probability. With extra tentpole symbols and tentpole subcarriers providing better tracking capability, the receiver closely tracks channel variation and performs accurate channel estimation. As shown in Fig. 3, Tentpoles scheme could be achieved either in time domain, or in frequency domain, or in a combination of both.

The key novelty of our proposed Tentpoles scheme lies on the following two aspects:

1) The 'dual-use' property of Tentpoles scheme is realized by using stronger Error Correction Code (ECC) to further protect the selected subset of tentpole symbols and tentpole subcarriers. This approach offers substantial benefits in terms of communication reliability and communication efficiency than existing IEEE 802.11p default schemes.
2) In our design, we ensure that the spacing between tentpole symbols $\Delta T_{tentpoles}$ should be smaller than the coherence time $T_c$ (i.e., $\Delta T_{tentpoles} \leq T_c$), and the spacing between tentpole subcarriers $\Delta f_{tentpoles}$ should also be smaller than the coherence bandwidth $B_c$ ($\Delta f_{tentpoles} \leq B_c$). This ensures that tentpole scheme accurately tracks V2V channel dynamics in both time domain and frequency domain.

Our proposed Tentpoles scheme requires changes at both transmitter side and receiver side. We describe the design and

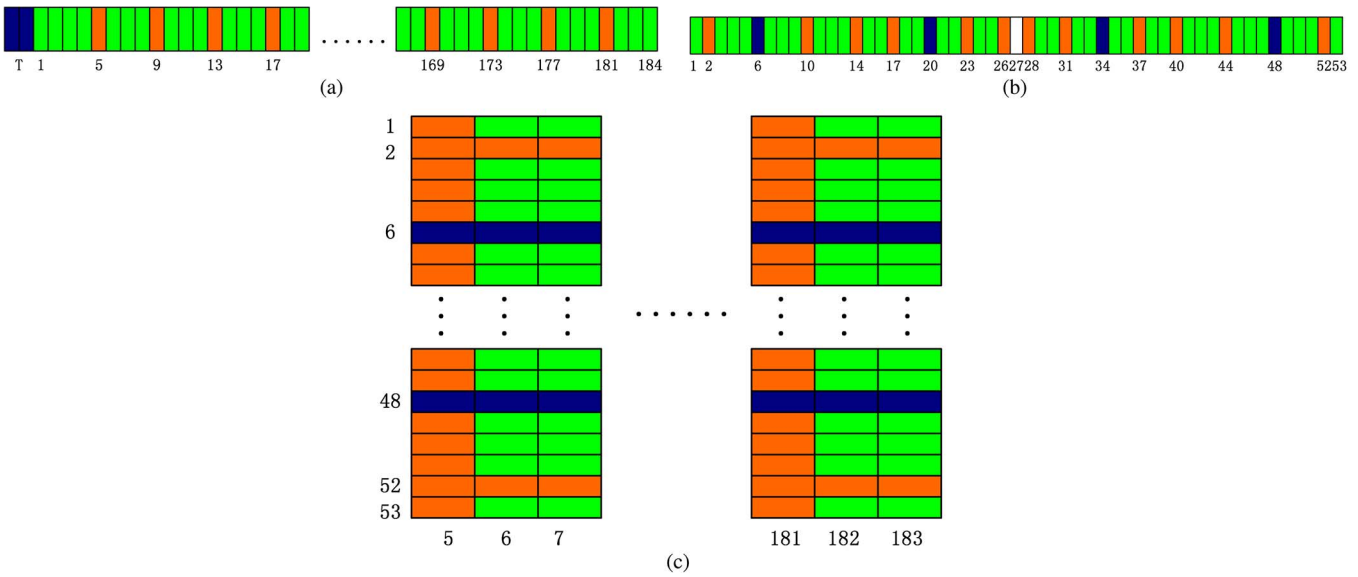



Fig. 3. The proposed tentpoles scheme of IEEE 802.11p packet. (a) Tentpoles scheme in time domain. Data symbols are labeled as green, pilot subcarriers are labeled as blue, and tentpole symbols are labeled as orange. A packet with 184 data symbols is shown as an example. (b) Tentpoles scheme in frequency domain. Data subcarriers are labeled as green, pilot subcarriers are labeled as blue, and tentpole subcarriers are labeled as orange. (c) Tentpoles scheme in both time and frequency domain. Data symbols/subcarriers are labeled as green, pilot subcarriers are labeled as blue, and tentpole symbols/subcarriers are labeled as orange.

the rationale behind the design of both transmitter and receiver in the next two sections.

## V. Transmitter Design for Tentpoles Scheme

In this section, we describe the design and implementation of Tentpoles scheme at the transmitter. Our design is still compatible with the overall framework of 802.11p standard, because our tentpole scheme is built upon OFDM and convolutional code. The key novelty of our proposed Tentpoles scheme is on the transmitter side.

### A. Time Domain

First, we discuss the Tentpoles scheme in the time domain. By leveraging tentpole symbols being placed across the entire packet (in addition to 2 initial training symbols), we are able to better track the channel variation over time since every tentpole symbol periodically updates the channel estimation. During our design process, we attempt to answer the following three questions: (1) how should the tentpole symbols be distributed? (2) how many tentpole symbols should be used? and (3) what type and level of ECC protection should be used?

Inspired by the packet structure design philosophy of Long-Term Evolution (LTE) standard [19], we advocate that tentpole symbols should be evenly distributed throughout the packet, to track time-domain channel variations. Specifically, the spacing between tentpole symbols $\Delta T_{tentpoles}$ should be smaller than the coherence time $T_c$.

The number of tentpole symbols is determined by both packet duration and channel coherence time. Assuming that each packet has overall $M$ OFDM symbols. Among them, $m$ symbols are tentpole symbols $(m < M)$, then the lower bound of $m$ value is $\lceil \frac{T_p}{T_c} \rceil$ (where $T_p$ is packet transmission duration). As $m$ value increases, the channel estimation becomes more accurate and the communication reliability (in terms of PER) improves, even though the benefits of further increasing $m$ gradually become marginal.

Finally, in the 802.11p standard, all data symbols are equally protected by convolutional codes with the same coding rate. In our Tentpoles scheme, we apply stronger ECC to $m$ tentpole symbols while the remaining $M - m$ data symbols are still protected by the standard convolution code. There are many options for the stronger ECC to be used on tentpole symbols including (1) a different class of ECC codes (e.g., LDPC code), (2) a stronger convolutional code with lower code rate, and (3) a non-convolutional type ECC with lower code rate.

An example is presented in Fig. 3(a) to demonstrate the Tentpoles scheme in time domain. For a packet with 184 OFDM data symbols (1.5 ms transmission duration), in addition to 2 training symbols (blue color), there are 45 tentpole symbols (orange color) evenly placed across the entire packet, with separation of 4 data symbols (green color).

### B. Frequency Domain

In frequency domain, Tentpoles scheme utilizes $n$ dual-use tentpole subcarriers (which are protected by strong ECC) to track channel variations. Again, following the practice used in time domain, our principle is to evenly place $n$ tentpole subcarriers (together with 4 pilot subcarriers regulated by IEEE 802.11p standard) across the entire frequency bandwidth. In particular, the spacing between tentpole subcarriers $\Delta f_{tentpoles}$ should also be smaller than the coherence bandwidth $B_c$, suggesting that there should be at least one tentpole subcarrier within the coherence bandwidth.

In the case of frequency domain, the number of tentpole subcarriers is determined by both frequency bandwidth and channel coherence bandwidth. The lower bound of $n$ value is $\lceil \frac{B_s}{B_c} - 4 \rceil$ (where $B_s$ is bandwidth used by IEEE 802.11p

standard (i.e., 10 MHz), while 4 is due to the fact that IEEE 802.11p standard already has 4 pilot subcarriers). The higher $n$ value is, the more reliable communication is.

Fig. 3(b) shows an example of Tentpoles scheme in frequency domain. In this particular example, we provide 12 tentpole subcarriers (orange color) (subcarriers 2, 10, 14, 17, 23, 26, 28, 31, 37, 40, 44, and 52) among the 52 subcarriers; at the same time, our Tentpoles scheme still exploits the existing 4 pilot subcarriers (blue color).

### C. Time and Frequency Domain

In our design, Tentpoles scheme could be used in time domain and frequency domain simultaneously. For a packet with overall $M$ symbols, we first put $m$ $(m < M)$ tentpole symbols in time domain; for each of the remaining $M - m$ data symbols, we further put $n$ $(n < 48)$ extra tentpole subcarriers in frequency domain.

An example of Tentpoles scheme using both time- and frequency-domain mechanisms is shown in Fig. 3(c). Here, the vertical direction shows frequency domain (with 52 subcarriers) and the horizontal direction represents time domain (in this particular case, 184 data OFDM symbols are used). To avoid an overly congested figure, we only show 6 OFDM symbols (symbols 5, 6, 7, 181, 182 and 183) in time domain, and a portion of subcarriers (subcarrier 1–8 and 46–54) in frequency domain. To be consistent with the examples used in Section V-A and Section V-B, we place 45 tentpole symbols (with a separation of 4 data symbols between two adjacent tentpole symbols) in time domain and 12 tentpole subcarriers (with a separation of 3 data subcarriers between two adjacent tentpole subcarriers).

### D. Error Correction Codes for Tentpoles Scheme

All data symbols in the IEEE 802.11p packets are protected by a standard convolutional code. The three options are: 1/2 code rate, 2/3 code rate, and 3/4 code rate. In our proposed scheme, tentpole symbols and/or tentpoles subcarriers should be further protected by even stronger ECC, to handle highly dynamic and unpredictable V2V channels. There are three different approaches to achieve this goal:

- Stronger ECC code with the same code rate as IEEE 802.11p standard, e.g., LDPC code with 1/2 code rate.
- Convolutional code with lower code rate, e.g., convolutional code with 1/4 code rate.
- Stronger ECC code with lower code rate, e.g., LDPC code with 1/4 code rate.

Stronger ECC code, like LDPC code, offers strong protection for tentpole symbols and/or tentpole subcarriers, but at the cost of significantly increased system complexity to support both convolutional and LDPC encoder/decoder at the same time. To avoid this drawback, in this paper, we choose not to use LDPC code; instead, we take the approach of using convolutional code with lower coding rate, which is compatible with the overall IEEE 802.11p standard framework. A comparison of LDPC and Turbo codes is important and will be considered in our future research works. Our initial conjecture is that the performance of our tentpoles scheme will be further improved when using more capable codes such as LDPC codes.

In standard-compliant convolutional code, lower code rate can be implemented through using a combination of 3 default options provided by IEEE 802.11p standard so that the system complexity could be reduced; 1/4 rate convolutional code, for instance, is simply implemented by applying 1/2 rate convolutional code twice. Although lower code rate leads to increased rate loss, our scheme will cause only a moderate overall rate loss since only tentpole symbols/subcarriers (which is a small portion of data symbols/subcarriers) are subject to the lower rate convolutional code.

In our design, OFDM symbols as well as channel subcarriers in each symbol are split into two groups: the first group includes all tentpole symbols (or tentpole subcarriers), which are protected by convolutional code with lower code rate; the second group includes all the remaining data symbols (or data subcarriers), which are still protected by convolutional code with default code rate.

### E. Major Questions for Transmitter Design

In our design process, we are interested in understanding the impact of the following design options on our proposed Tentpoles scheme:

- In which domain should we perform Tentpoles scheme: time domain, frequency domain, or a combination of both?
- If in time domain, how many tentpole symbols should be used?
- If in frequency domain, how many tentpole subcarriers should be used?
- What ECC options should be used?
- Is Tentpoles scheme sufficiently robust to various V2V environments?

To answer these questions, in this paper, by using both a set of synthetic V2V channels and real-world measurements, we conduct extensive simulation and emulation study to evaluate the performance of Tentpoles scheme. We also attempt to delve deeper through a careful analysis to reveal the fundamental reason why (or why not) Tentpoles scheme works in harsh V2V environments.

## VI. Receiver Design for Tentpoles Scheme

After introducing the design of Tentpoles scheme at the transmitter in Section V, in this section, we describe how the receiver should function in our Tentpoles scheme.

### A. Two-Phase Decoding Process

At transmitter side, Tentpoles scheme places extra tentpole symbols and/or tentpole subcarriers. As shown in Fig. 4, the receiver performs a two-phase channel estimation and decoding process, to separately handle tentpole symbols/subcarriers and data symbols/subcarriers.

**Tentpoles Decoding (Phase 1)**: The first phase of decoding process focuses on tentpole symbols/subcarriers in the packet. Relying on 2 initial training symbols and 4 pilot subcarriers of

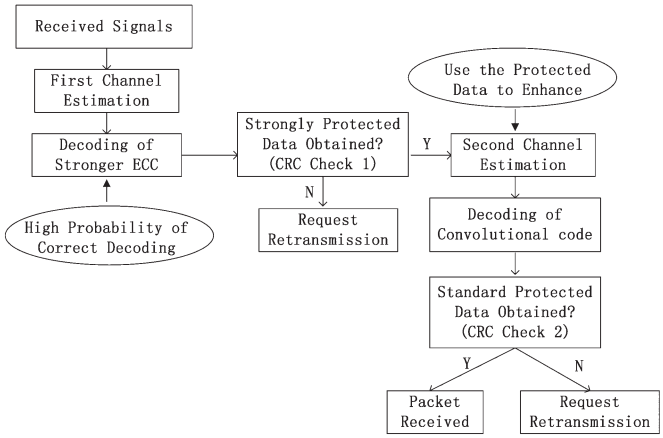



Fig. 4. Receiver procedure of tentpoles scheme.

each packet, the receiver obtains a channel estimate and uses that estimate for equalization only on tentpole symbols using existing schemes (e.g., LS [6], STA [16] or ESTA [17], we use ESTA in our implementation). Even though this initial channel estimate may not be sufficiently accurate, these tentpole symbols/subcarriers are more robust to channel estimation error because they are protected by stronger ECC code; as a result, these tentpole symbols could be decoded successfully with a high probability.

If these tentpole symbols have been correctly decoded and pass the CRC check, the receiver will perform phase 2 operation to decode remaining data symbols; However, if phase 1 operation fails, in our implementation, for the sake of avoiding unnecessary system complexity, we simply discard the whole packet. As shown later in Section VII, our simulation study reveals that failure probability of phase 2 decoding is about 98.4% if phase 1 operation is not successful.

**Data Decoding (Phase 2)**: Once Tentpoles decoding (phase 1) operation succeeds, these tentpole symbols and/or tentpole subcarriers are available for the receiver. Then the receiver utilizes these tentpole symbols/subcarriers as additional training symbols or pilot subcarriers to perform channel estimation and equalization. Since more symbols and subcarriers are now available for channel estimation, the accuracy of the channel estimate will be higher than that obtained in Phase 1. With a significantly improved channel estimation capability, the receiver can perform convolutional decoding on the remaining data symbols and data subcarriers, even though the default convolutional code itself might not be strong enough to handle channel errors by itself. If the phase 2 operation fails, an error signaling mechanism will be called to notify MAC layer for necessary actions.

We believe that the receiver-end operations for Tentpoles scheme are light-weight. First, in our implementation, we intentionally choose lower rate convolutional code as strong ECC to protect tentpole symbols/subcarriers, so that the system complexity is manageable. To be specific, the computational complexity of convolutional decoding is determined by trace-back length of the Viterbi decoder; in IEEE 802.11p standard, Viterbi decoder only has a trace-back length of 7. Moreover, we also do not expect that tentpole code demands extra storage capacity, since the total number of transmitted coded bits per packet, in both Tentpoles scheme and in standard scheme, is the same. Finally, due to the 2-phase decoding procedure, we do expect that the decoding latency will increase slightly.

In our simulations, we do not consider time delay. The tentpoles scheme has the disadvantage of increased decoding latency due to the use of stronger ECC. However, our proposed scheme has its advantage of reducing the number of retransmissions also because of the use of stronger ECC. The time delay of the scheme is a combination of increased decoding latency and reduced number of retransmissions. Analyzing the time delay involving both the increased decoding latency and the reduced number of retransmissions is a complex problem that depends on implementation details such as various parametric choices, which merits an independent study.

### B. Discussion

To further quantify the performance of Tentpoles scheme at the receiver end, we can express the PER at the receiver as

$$PER_{Tentpoles} = PER_{p1} + (1 - PER_{p1})PER_{p2} \tag{1}$$

where $PER_{Tentpoles}$ is the PER experienced by receiver using Tentpoles scheme, while $PER_{p1}$ is the PER of phase 1 (tentpoles decoding) operation and $PER_{p2}$ is the PER of phase 2 (data decoding). Using Tentpoles scheme, we expect that $PER_{p1}$ should be reasonably small because tentpole symbols/subcarriers are protected by strong ECC; similarly, we also expect that $PER_{p2}$ is small as well thanks to the more accurate channel estimation provided by Tentpoles scheme in phase 1 operation. As a result, we believe that overall PER performance experienced by Tentpoles scheme should be significantly low when compared to other schemes.

## VII. Simulation in Synthetic V2V Channels

In this paper, we use a combination of simulation study and real signal based emulation experiments to investigate the performance of our proposed Tentpoles scheme. On one hand, simulation allows us to evaluate our designed systems with more control but might suffer from a challenge as to whether the simulated signals accurately represent the real environments; on the other hand, hardware-based emulation platform provides better realism, but are tightly constrained by the physical environment and circumstances under which experiments are carried out. In this study, by using both of them, we intend to validate Tentpoles scheme in a flexible, controllable and comprehensive manner, while still testing it in real-world scenarios.

### A. Methodology

We first conduct extensive simulations under synthetic V2V channels. Among the six synthetic tapped-delay line channel models [10] extracted from empirical channel sounding measurements in real-world vehicular environments, in our study, we focus on 3 channel models directly related to V2V

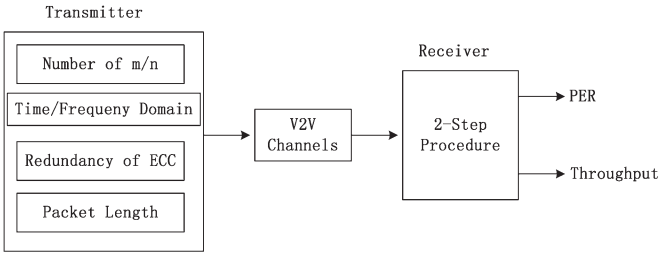



Fig. 5. Simulation framework of tentpoles scheme.

communication and implement them into a Matlab-based customized simulator: *V2V expressway oncoming*, *V2V expressway same direction*, and *V2V urban canyon oncoming*. The detailed parameters of the 3 channel models are listed in Table 2 in [10]. We believe that these 3 synthetic models are reasonable approximation to capture the channel variation in both time domain and frequency domain. Among these 3 V2V channel models, *V2V expressway oncoming* model is believed to create the most challenging scenario for V2V communication [10], so that we use this model as our default model throughout our study, except that in Section VII-E where we present a sensitivity study on channel models.

In each scenario, we generate synthetic V2V channels with different SNR values, ranging from 10 dB to 20 dB. The range of 10 dB to 20 dB represents typical channel conditions in real-world IEEE 802.11 WiFi networks [20]. For each SNR value, we generate 5,000 samples of synthetic channels and then calculate the PER. In our simulation, we use BPSK modulation for both tentpole and data symbols/subcarriers; for data symbols/subcarriers, we use 1/2 rate convolutional code. We intentionally choose BPSK modulation and 1/2 rate convolutional code since both are default options of IEEE 802.11p standard. In particular, we use polynomial (8,[357,251,233]) for 1/3 rate convolutional code, polynomial (7,[133,171,117,165]) for 1/4 rate convolutional code and polynomial (8,[363,351,331,265,257,237]) for 1/6 rate convolutional code. For all convolutional codes, we use 4-bit quantization and the decoding depth is 60.

In this section, we first investigate if Tentpoles scheme has advantages over existing solutions in terms of communication reliability and data throughput efficiency. Then, as shown in Fig. 5, we vary different design options to study how these options could impact the performance of Tentpoles scheme for a variety of SNR values. We finally conduct sensitivity study to examine if Tentpoles scheme is robust to external factors, which are either given by environments (e.g., V2V channel models) or dictated by application requirements (e.g., packet length).

### *B. An Overview of Performance Results*

We first compare the PER of our proposed Tentpoles scheme and other solutions, including LS [6] and ESTA [17]. LS and ESTA schemes are using IEEE 802.11p standard compliant frame format and they do not use tentpoles symbols in their implementation. At the same time, we also examine in which domain (time-domain, frequency-domain, or both time- and frequency-domain) Tentpoles scheme delivers the best performance. Using a packet with 184 data symbols and a data rate of 3 Mbps (BPSK with 1/2 code rate) as an example, we have three roughly equivalent options for Tentpoles scheme[1]:

- In time domain, we use 1/4 rate convolutional code to protect about 25% (i.e., 45 out of 184) of data symbols;
- In frequency domain, we use 1/4 rate convolutional code to protect 25% (i.e., 12 out of 48) of subcarriers;
- In both time and frequency domain, we use 1/4 rate convolutional code to simultaneously protect about 10% (19 out of 184) of data symbols and about 15% (i.e., 8 out of 48) of data subcarriers.

In these three options, about 1/4 of data symbols and/or data subcarriers are protected by 1/4 rate convolutional code, leading to an overall rate loss of 1/8 for the default data rate 3 Mbps. Therefore, the effective data rate for all these options is $3 \times (1-\frac{1}{8}) = 2.625$ Mbps. Note that in the third option, the ratio of protected symbols and subcarriers can be calculated as $(\frac{19}{184} + \frac{(184-19)/6}{184}) \approx 0.25$.

As shown in Fig. 6(a), LS scheme has the worst performance among all the options because it lacks sufficient capability to track highly dynamic V2V channels; ESTA mechanism provides improved performance but it is still outperformed by our proposed Tentpoles scheme. The advantage of our Tentpoles scheme is larger at higher SNRs.

More interestingly, we also observe that Tentpoles scheme in frequency domain appears to have the best performance, when compared to the other two Tentpoles schemes. This is somewhat different from our initial expectation, since we initially thought that these three options should have the same performance. After our analysis, we realize that we could attribute this somewhat surprising observation to the unique characteristics of V2V channel—V2V channel is a fast fading channel in time domain [6]. To handle this fast fading channel, tracking channel dynamics in time domain is more difficult than tracking it in frequency domain, because the channel estimation obtained via frequency domain is robust to channel variation in time domain. Therefore, with the same rate loss, we believe that it is better to track channel variation using frequency-domain Tentpoles scheme. Though used for other scenarios, similar observations that frequency-domain channel estimation is proper for fast fading channels was also reported in [21] and [22].

Given that Tentpoles scheme in frequency domain has the best performance in V2V channels, we will mainly focus on frequency-domain in the remaining part of this paper. We denote Tentpoles scheme by $\langle R_{ECC}, m(n), r_{loss} \rangle$, where $R_{ECC}$ is the code rate of convolutional code, $m$ (or $n$) is the number of tentpole symbols or tentpole subcarriers, and $r_{loss}$ is the corresponding rate loss caused by ECC. For instance, in the case of 1/4 rate convolutional code to protect 12 tentpole subcarriers, resulting in a rate loss of 1/8 for a data rate of 3 Mbps, we denote it as $\langle \frac{1}{4}, 12, \frac{1}{8} \rangle$.

[1]In our simulations, the total number of transmitted coded bits per packet, in both Tentpoles scheme and in standard scheme, is the same. The packet length, i.e., 184 OFDM symbols, is also the same. The difference is that in tentpoles scheme, the number of information bits carried by the protected data symbols and data carriers is less than that in the standard scheme. Thus, the data rates are different between our tentpoles scheme and the standard scheme.

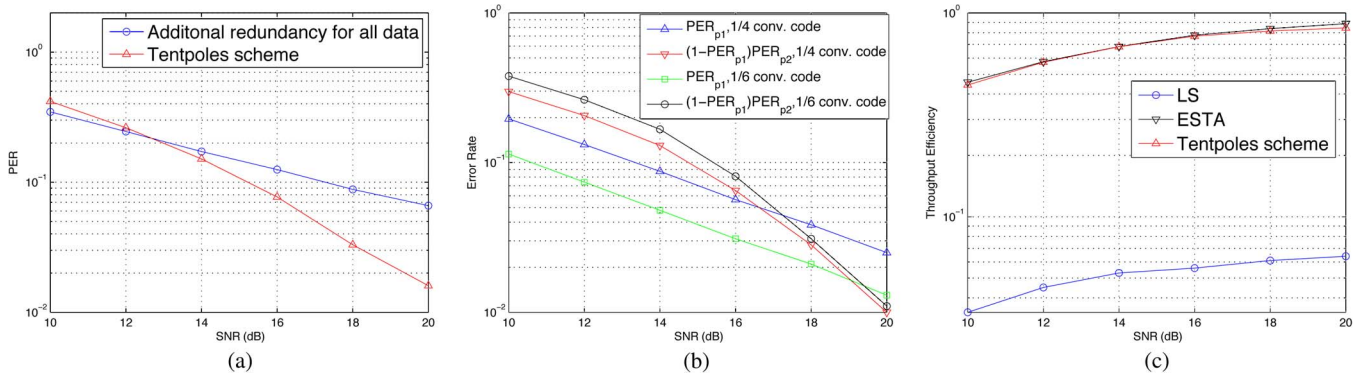



Fig. 6. Overview of the performance of tentpoles scheme. (a) PER of tentpoles scheme and other solutions; (b) detailed analysis of PER at the receiver; (c) throughput.

### C. Detailed Analysis

To better understand the underlying mechanism of Tentpoles scheme and to expose its limitations, we conduct a detailed analysis in this section.

In additions to Tentpoles scheme, we also have an alternative solution in which the same level of ECC protection is uniformly applied to all data symobols and data subcarriers in each packet. This alternative solution is in direct contrast to our Tentpoles scheme, since Tentpoles scheme protects only a small subset of important data symbols or data subcarriers in each packet. To maintain the same level of data rate loss as our Tentpoles scheme, a lower level of ECC protection is needed for this alternative approach. To ensure a fair comparison, both our Tentpoles scheme and this alternative approach have the same data rate.

As shown in Fig. 6(a), we observe that alternative approach outperforms our Tentpoles scheme if SNR is low (<13 dB) but the advantage of Tentpoles scheme is more obvious when SNR value is high. Our hypothesis is that, when SNR is too low and channel is too noisy, the channel estimates provided by Tentpoles scheme are still not accurate enough. However, as SNR increases, extra tentpole symbols and tentpole subcarriers enhance the accuracy of channel estimation; that is to say, adding strong ECC to just a subset of data symbols and data subcarriers is better than evenly spreading ECC protection over all data symbols and subcarriers. We observe that Tentpoles scheme significantly improves the PER performance for SNRs above 13 dB. Considering that normal operating SNR range of IEEE 802.11 network is between 10 dB and 20 dB, we argue that our Tentpoles scheme effectively improves the performance in the majority of operating SNR range.

**PER Performance at Receiver**: We now examine the PER performance of 2-phase operations at receiver.

The PER of Tentpoles scheme at the receiver is jointly determined by the PER obtained from phase 1 operation (i.e., $PER_{p1}$) and PER obtained from phase 2 operation (i.e., $(1-PER_{p1})PER_{p2}$). As shown in Fig. 6(b), we observe that $PER_{p1}$ smoothly decreases as SNR values increases, because the phase 1 operation purely depends on SNR value of the V2V channel (since only 2 initial training symbols in each packet is used in phase 1 operation). PER value from phase 2 operation $((1-PER_{p1})PER_{p2})$ has a different trend: it is initially high as SNR value is small, but it decreases quickly as SNR value increases. We believe that steep decrease in PER as a function of SNR is due to better channel estimation provided by extra tentpole symbols and tentpole subcarriers as follows. When SNR is low, tentpole symbols or subcarriers still suffer from strong noise, resulting in inaccurate channel estimation; as SNR increases, it is highly likely that tentpole symbols and subcarriers are correctly decoded, rendering a better channel estimate. It is evident that, in Fig. 6(b), when SNR is large, the final PER will be determined by $PER_{p1}$ since $((1-PER_{p1})PER_{p2})$ with different ECC is close to each other. Thus, lower rate convolutional code (i.e., 1/6 rate) has better reliability performance than its counterparts with higher rate convolutional code (i.e., 1/4 rate).

TABLE II
PER OF ENFORCING PHASE 2 OPERATION

| SNR | 1/4 rate conv. code | 1/6 rate conv. code |
|---|---|---|
| 20 dB | 98.4% | 100% |

Also, we test the PER of enforcing phase 2 operation even when phase 1 operation is failed. The results are shown in Table II.

We can see that when phase 1 decoding fails, enforcing phase 2 operation will also fail with high probability. Thus, to avoid unnecessary system complexity, we simply stop the remaining receiving procedure and discard the whole packet when phase 1 decoding fails.

**Effective Throughput**: In addition to communication reliability, we also examine the effective throughput of our proposed Tentpoles scheme. We quantify effective throughput by $(1-PER_{tentpole})\times(1-r_{loss})$, where $r_{loss}$ is the rate loss due to the extra redundancy in tentpole symbols and subcarriers. Following this definition, the effective throughput is maximized if communication is reliable $(PER_{tentpole}=0)$ and no ECC redundancy is introduced $(r_{loss}=0)$.

In Fig. 6(c), we compare the effective throughput of Tentpoles scheme $(\langle\frac{1}{4},12,\frac{1}{8}\rangle)$ with that of LS and ESTA schemes. Again, we find that the default LS scheme in IEEE 802.11p standard has the lowest effective throughput, while our Tentpoles scheme and ESTA scheme have roughly similar performance. The low effective throughput of LS scheme is mainly due to its unreliable communication (i.e., high PER); ESTA

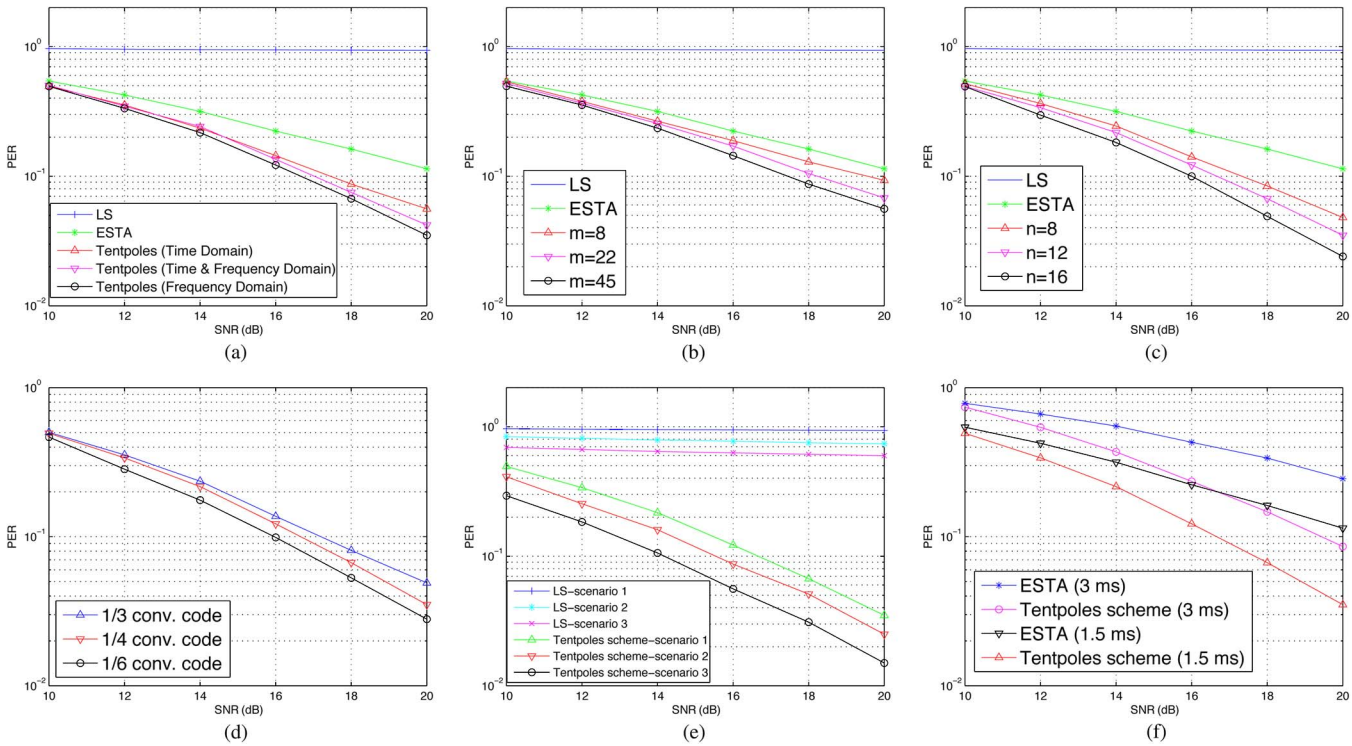



Fig. 7. Sensitivity study of tentpoles scheme in synthetic V2V channels. Here, we investigate how PER is affected by Tentpoles scheme design options (including (a) the choice of time-domain, frequency-domain, or a combination of both, (b) the number of tentpole symbols $m$ in time domain, (c) the number of tentpole subcarriers $n$ in frequency domain, and (d) the ECC options). We also study how Tentpoles scheme is affected by external factors, such as (e) V2V channel models and (f) packet length.

scheme tends to generate higher PER value than our Tentpoles scheme, but on the other hand, the extra redundancy introduced in our Tentpoles scheme also generates extra rate loss while ESTA scheme has no extra rate loss. As a result, ESTA scheme and our Tentpoles scheme have comparable effective throughput.

This observation indicates that our Tentpoles scheme achieves reliable communication at the cost of moderate effective throughput, since extra ECC redundancy is explicitly used to protect critical data symbols and data subcarriers. We believe that our Tentpoles scheme is more proper for PER-sensitive vehicular applications (e.g., cooperative vehicle safety communication), while both receiver-centric ESTA scheme and transmitter-centric Tentpoles scheme are equally suitable for throughput-sensitive applications (e.g., video streaming and file download).

### D. Impact of Design Options on Tentpoles Scheme

In this section, we study how the performance of Tentpoles scheme is affected by different design options. With the insight gained here, we can adjust the parameter settings of Tentpoles scheme to achieve better performance.

**The Number of Tentpole Symbols $m$ and Tentpole Subcarriers $n$**: In time domain, we protect $m$ tentpole symbols in each packet $(m = 8, 22, 45)$, with 1/4 rate convolutional code. As shown in Fig. 7(b), we observe that the channel estimation improves as more tentpole symbols are used, especially in high SNR range. However, considering that more tentpole symboles cause more rate loss, we argue that the benefits of adding more tentpole symbols in time domain will gradually become marginal. As seen in Fig. 7(c), same conclusion could be applied to the case of the number of tentpole subcarriers $n$.

**Strength of ECC**: Here, we study the impact of different convolutional codes on our Tentpoles scheme. We choose the case of frequency-domain Tentpoles scheme with 12 tentpole subcarriers. The 3 Tentpoles schemes used for comparison are $\langle \frac{1}{3}, 12, \frac{1}{12} \rangle$, $\langle \frac{1}{4}, 12, \frac{1}{8} \rangle$ and $\langle \frac{1}{6}, 12, \frac{1}{6} \rangle$, which represent different levels of ECC strength. As shown in Fig. 7(d), we find that Tentpoles scheme with stronger ECC achieves lower PER, since stronger ECC protects tentpole subcarriers more successfully than weaker ECC. Again, considering the increased rate loss caused by strong ECC, we argue that the benefits of using stronger ECC become marginal after a certain threshold.

### E. Impact of External Factors on Tentpoles Scheme

**Tentpoles Scheme in Various V2V Scenarios**: In addition to *V2V Expressway Oncoming* scenario which represents the harshest V2V channel models in [10], we also look into two other V2V scenarios—*V2V Expressway Same Direction* scenario which represents fast fading channels, and *V2V-Urban Canyon Oncoming* scenario which is featured with low vehicle velocity. We denote the 3 scenarios as scenario 1, 2, 3 respectively.

We simulate frequency-domain Tentpoles scheme $\langle \frac{1}{4}, 12, \frac{1}{8} \rangle$ in all 3 scenarios. As shown in Fig. 7(e), we find that the Tentpoles scheme outperforms LS scheme across all 3 scenarios. More interestingly, we also observe that the differences

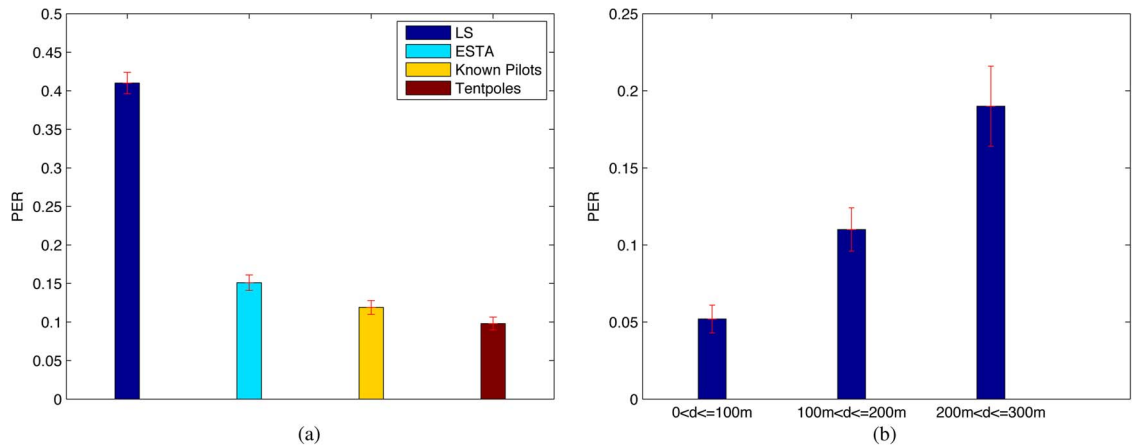



Fig. 8. Performance of tentpoles scheme in real-world environments. (a) PER of different mechanisms; (b) PER vs. distance.

between these three 3 curves are almost constant across different SNR value, which indicates that our Tentpoles scheme is not sensitive to particular V2V mobility channel.

**Impact of Packet Duration**: To understand the impact of packet transmission duration on Tentpoles scheme, we use two types of data packets with different packet length: (1) a 500-byte packet (2 training symbols and 184 data symbols, resulting in a transmission duration of 1.5 ms with 3 Mbps data rate) and (2) a 1,000-byte packet (2 training symbols and 368 data symbols, resulting in a transmission duration of 3 ms with 3 Mbps data rate). In this study, we simulate frequency-domain Tentpoles scheme $\langle \frac{1}{4}, 12, \frac{1}{8} \rangle$ using both packet lengths. We also include the PER results of ESTA for comparison.

From Fig. 7(f), we observe that the PER increases significantly as packet duration increases, for both ESTA and Tentpoles scheme. We also find that Tentpoles scheme still outperforms ESTA scheme when packet length is increased. Moreover, for long packets, the advantage of Tentpoles scheme over ESTA scheme is more.

## VIII. Evaluation in Real Channels

Simulations in synthetic channels show the advantages of Tentpoles scheme. On the other hand, we are also interested in the performance of Tentpoles scheme in realistic on-road scenarios.

### A. Methodology

To evaluate the Tentpoles scheme in real V2V channels, we use a rich set of empirical data (about several hours' experiments) collected from the real-world V2V channels across a number of driving environments (including highway and rural) around Pittsburgh, PA. These experiments consisted of two vehicles being driven, one acting as a transmitter and the other as a receiver.

In these experiments, the transmitter vehicle continuously broadcast IEEE 802.11p packets using an HP E4433B Digital Signal Generator (DSG). The transmitted waveforms used BPSK modulation on each subcarrier, with 1/2 rate convolutional coding. This resulted in the lowest data rate available to the standard (3 Mbps). The packets included 186 OFDM

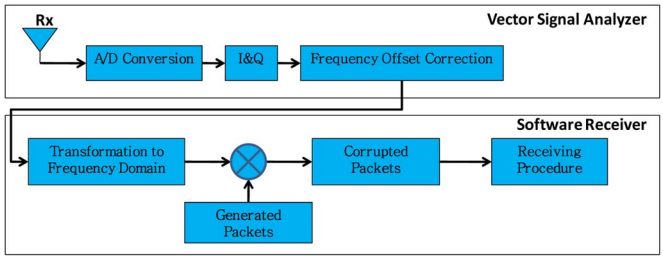



Fig. 9. The software based receiver with real V2V channels.

symbols consisting of 2 training symbols at the beginning of each packet and 184 data symbols (including the SIGNAL field). The duration of each packet was 1.5 ms. The receiver vehicle recorded the time-domain I and Q waveforms using an Agilent 89600 Vector Signal Analyzer (VSA). These digital waveforms were then stored on the computer and transformed into frequency domain. Since transmitted BPSK symbols are known at the receiver, the V2V channels can be extracted directly from the received packets. In each packet, we finally extracted a realization of the frequency domain V2V channels stored as a $53 \times 186$ matrix, because in each packet there are 186 OFDM symbols and each OFDM symbol has 53 subcarriers. Note that among the 53 subcarriers, the 27-th subcarrier is not used for transmission, i.e, zero subcarrier, thus the channel recorded on the 27-th subcarrier is also zero. For more details of the experiments, please refer to [18].

We then use the recorded V2V channels to implement simulations in a software-based receiver built upon a MATLAB emulation platform. The software based receiver is shown schematically in Fig. 9.

The methodology is to artificially generate data packets as $53 \times 186$ matrices with Tentpoles scheme and let the generated packets be corrupted by the recorded real V2V channels, and then try to recover the corrupted packets through the proposed receiving procedure.

The advantage of the methodology is that the performance evaluation can be conducted in empirical V2V channels from real world. However, since the data was collected around Pittsburgh area, it can only reflect the realistic on-road conditions for that specific scenario.

We collected a total of 5000 valid real V2V channels including highway and rural scenarios. In the simulations, we calculate the overall PER because we observe very similar performance in highway and rural scenarios.

The parameter settings of Tentpoles scheme for real V2V channels are the same as for synthetic channels.

### B. Performance Results

We first compare the PER results of Tentpoles scheme with the LS scheme, ESTA scheme and the scheme with additional known pilots. In the scheme with additional known pilots, we use 6 additinal known pilots evenly distributed in frequency domain which corresponds to the same rate loss of 1/8 as the tentpoles scheme ($\langle \frac{1}{4}, 12, \frac{1}{8} \rangle$). We assume that the decoding error probability is a Binomial distribution with 5000 trials (we have collected a total of 5000 real V2V channel samples). We consider the 2-sigma confidence interval (95%). Fig. 8(a) shows the PER results with 95% confidence interval. We see that the performance of Tentpoles scheme surpasses those of the other 3 methods. However, the improvement in real V2V channels is not as significant as in synthetic channels.

The 5,000 real V2V channel samples were collected when the distances between the 2 vehicles are within the range of 0–300 meters. Fig. 8(b) shows the PER vs distances with 95% confidence interval. We use the scheme $\langle \frac{1}{4}, 12, \frac{1}{8} \rangle$. There are three ranges of distances: 0–100 meters (2246 packets), 100–200 meters (1884 packets) and 200–300 meters (870 packets). Clearly, the PER is larger when distance is larger, and the PER in long distance ($>200$ m) is around 4 times the PER in short distance ($<=100$ m). This is because the SNR of the channels is related to the distance. Generally, longer distance means lower SNR. Thus, Tentpoles scheme has different effective areas depending on different PER requirements.

## IX. Conclusion

In this paper, we proposed a novel approach called Tentpoles scheme to accurately estimate the V2V channels to achieve reliable V2V communications. By protecting a subset of data symbols and data subcarriers (called tentpole symbols and tentpole subcarriers) using strong ECC at the transmitter side, our proposed scheme tracks V2V channel variations accurately in both time domain and frequency domain. As a result, the receiver utilizes these tentpole symbols and tentpole subcarriers as additional training symbols or pilot subcarriers to track V2V channel variations accurately. With accurate channel estimation, the receiver equalization is more accurate leading to reliable V2V communications. Through extensive simulations in synthetic V2V channels and emulation using empirical measurements, our Tentpoles scheme is shown to significantly outperform other V2V channel estimation and equalization methods in terms of packet error rates, at the cost of only moderate loss of throughput.

The proposed tentpoles scheme is not strictly compatible with the 802.11p standard; instead, we believe that a new frame design is necessary to provide reliable Dedicated Short-Range Communications in challenging V2V channels. However, it is desirable that the new frame design should still follow the OFDM-based 802.11 framework so that industry could relatively easily accommodate this new practice. The proposed tentpoles scheme therefore can be a good candidate since it is still within the 802.11 framework. Moreover, the proposed scheme has a flexible choice of the stronger ECC. Thus widely used ECC such as LDPC, Turbo codes and convolution codes all can be applied to the proposed scheme.

## References


[1] U.S. Department of Transportation Announces Decision to Move Forward With Vehicle-to-Vehicle Communication Technology for Light Vehicles. [Online]. Available: http://www.nhtsa.gov/

[2] L. Cheng, B. E. Henty, R. Cooper, D. D. Stancil, and F. Bai, "A measurement study of time-scaled 802.11 a waveforms over the mobile-to-mobile vehicular channel at 5.9 GHz," *IEEE Commun. Mag.*, vol. 46, no. 5, pp. 84–91, May 2008.

[3] H. Jung, T. Kwon, K. Cho, T. Kwon, and Y. Choi, "REACT: Rate Adaptation using Coherence Time in 802.11 WLANs," *Comput. Commun.*, vol. 34, no. 11, pp. 1316–1327, Feb. 2011.

[4] A. Sabharwal, V. Kanodia, and E. Knightly, "MOAR: A multi-channel opportunistic auto-rate media access protocol for Ad Hoc networks," in *Proc. Broadnets*, 2004, pp. 600–610.

[5] G. Karagiannis *et al.*, "Vehicular Networking: A Survey and Tutorial on Requirements, Architectures, Challenges, Standards and Solutions," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 4, pp. 584–616, 2011.

[6] *IEEE802.11p IEEE Standard for Information Technology—Telecommunication and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements. part 11: Wireless LAN MAC and PHY Specifications—Amendment 6: Wireless Access in Vehicular Environments*, Jul. 2010.

[7] A. Molisch, F. Tufvesson, J. Karedal, and C. Mecklenbrauker, "A survey on vehicle-to-vehicle propagation channels," *IEEE Wireless Commun.*, vol. 16, no. 6, pp. 12–22, Dec. 2009.

[8] F. Bai, D. Stancil, and H. Krishnan, "Toward understanding characteristics of dedicated short range communications (DSRC) from a perspective of vehicular network engineers," in *Proc. ACM MobiCom*, Sep. 2010, pp. 329–340.

[9] T. Jiang, H.-H. Chen, H.-C. Wu, and Y. Yi, "Channel modeling and intercarrier interference analysis for V2V communication systems in frequency-dispersive channels," *Mobile Netw. Appl.*, vol. 15, no. 1 pp. 4–12, Feb. 2010.

[10] G. Acosta-Marum and M. Ingram, "Six time- and frequency-selective empirical channel models for vehicular wireless LANs," *IEEE Veh. Technol. Mag.*, vol. 2, no. 4, pp. 4–11, Dec. 2007.

[11] S. I. Kim, H. S. Oh, and H. K. Choi, "Mid-amble aided OFDM performance analysis in high mobility vehicular channel," in *Proc. IEEE Intell. Veh. Symp.*, 2008, pp. 751–754.

[12] A. Bourdoux, H. Cappelle, and A. Dejonghe, "Channel Tracking for Fast Time-Varying Channels in IEEE802.11p Systems," in *Proc. IEEE GLOBECOM*, 2011, pp. 1–6.

[13] T. Zemen, L. Bernado, N. Czink, and A. Molisch, "Iterative Time-Variant Channel Estimation for 802.11p Using Generalized Discrete Prolate Spheroidal Sequences," *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, pp. 1222–1233, Mar. 2012.

[14] A. Paier *et al.*, "Average downstream performance of measured IEEE 802.11p infrastructure-to-vehicle links," in *Proc. IEEE ICC*, 2010, pp. 1–5.

[15] V. Shivaldova *et al.*, "Performance analysis of vehicle-to-vehicle tunnel measurements at 5.9 GHz," in *Proc. URSI Gen. Assem. Sci. Symp.*, Aug. 2011, pp. 1–4.

[16] J. Fernandez, D. Stancil, and F. Bai, "Dynamic channel equalization for IEEE 802.11p waveforms in the vehicle-to-vehicle channel," in *Proc. 48th Annu. Allerton Conf. Commun., Control, Comput.*, 2010, pp. 542–551.

[17] Z. Li, B. V. K. Vijayakumar, and F. Bai, "A double decoding scheme to improve the PER performance of V2V communications," in *Proc. IEEE WCNC*, 2013, pp. 3838–3843.

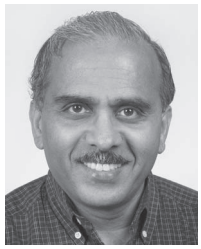
[18] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, and P. Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1501–1516, Oct. 2007.

[19] S. Sesia, I. Toufik, and M. Baker, *LTE-The UMTS Long Term Evolution: From Theory to Practice*. Hoboken, NJ, USA: Wiley, 2011.
[20] R. K. Guha and S. Sarkar, "Characterizing Temporal SNR Variation in 802.11 Networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2002–2013, Jul. 2008.
[21] S. Coleri, E. Ergen, A. Puri, and A. Bahai, "Channel estimation techniques based on pilot arrangement in OFDM systems," *IEEE Trans. Broadcast.*, vol. 48, no. 3, pp. 223–229, Sep. 2002.
[22] M. K. Ozdemir and H. Arslan, "Channel estimation for wireless ofdm systems," *IEEE Commun. Surveys Tuts.*, vol. 9, no. 2, pp. 18–48, 2007.

**Zheng Li** (S'05–M'06) received the B.S. and the M.S. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2003 and 2006, respectively, and the Ph.D. degree in electrical engineering from University of Delaware in 2011. He was a Postdoctoral Researcher at Carnegie Mellon University from 2011 to 2013, where he was working on vehicle-to-vehicle communications for General Motors. Currently, he is a Patent Agent at Coats & Bennett PLLC, a patent law firm located in Cary, NC, USA. He is working on patent applications and prosecutions for major wireless companies. He is registered with the United States Patent and Trademark Office (USPTO). He is also a J.D. candidate at North Carolina Central University School of Law (evening program).

**Fan Bai** received the Ph.D. degree in electrical engineering from the University of Southern California in 2005. He is a Senior Researcher in the Electrical & Control Integration Laboratory, General Motors Corporation. His research is focused on the discovery of fundamental principles and the design of protocols for VANETs, on which he has published over 30 journal and conference papers. He received the Charles L. McCuen Special Achievement Award from GM for his research accomplishments in VANETs.

**Joseph A. Fernandez** (S'07–M'08) received the B.S. degree in electrical engineering from New Mexico Tech in 2008, the M.S. degree in electrical and computer engineering from Carnegie Mellon University in 2010, and the Ph.D. degree from Carnegie Mellon University in 2014. He is currently with Northrop Grumman Corporation in the Future Technical Leaders program. He was awarded the best paper gold award for a student/young researcher at ISPA 2013 for his paper "Zero-Aliasing Correlation Filters." He is a 2010 National Defense Science and Engineering Graduate (NDSEG) Fellow. His research interests include correlation filters, radar signal processing, and wireless communication.



**B. V. K. Vijaya Kumar** (S'78–M'80–SM'90–F'10) received the B.Tech. and M.Tech. degrees in electrical engineering from Indian Institute of Technology, Kanpur and the Ph.D. degree in electrical engineering from Carnegie Mellon University, Pittsburgh, PA, USA. Since 1982, he has been a faculty member in the Department of Electrical and Computer Engineering (ECE) at Carnegie Mellon where he is now a U.A. & Helen Whitaker Professor and the Associate Dean for Graduate and Faculty Affairs for the College of Engineering. He served as the Associate Department Head of the ECE Department from 1994 to 1996 and as the Acting Head of the Department during 2004–2005. His research interests include computer vision and pattern recognition algorithms and applications and coding and signal processing for data storage systems. His publications include the book entitled *Correlation Pattern Recognition* (co-authored with Dr. Abhijit Mahalanobis and Dr. Richard Juday, Cambridge Univ. Press, Nov. 2005), twenty book chapters, 390 conference papers and 190 journal papers. He is also a co-inventor of 10 patents. He served as a Pattern Recognition Topical Editor for the Information Processing division of *Applied Optics* and as an Associate Editor for IEEE TRANSACTIONS ON INFORMATION FORENSICS AND SECURITY. He has served on many conference program committees and was a Co-general Chair of the 2005 *IEEE AutoID Workshop*, a Co-chair of the 2008–2010 SPIE conferences on *Biometric Technology for Human Identification* and a Co-program Chair of the 2012 *IEEE Biometrics: Theory, Applications and Systems* (BTAS) conference. Professor Kumar is a Fellow of SPIE, OSA, and the International Association of Pattern Recognition (IAPR). In 2003, he received the Eta Kappa Nu award for Excellence in Teaching in the ECE Department at CMU and the Carnegie Institute of Technology's Dowd Fellowship for educational contributions and he was a co-recipient of the 2008 Outstanding Faculty Research Award in CMU's College of Engineering.