Hindawi Publishing Corporation
Research Letters in Communications
Volume 2008, Article ID 485013, 5 pages
doi:10.1155/2008/485013

*Research Letter*

# Iterative Channel-Tracking Techniques for 5.9 GHz DSRC Applications

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Received 25 November 2007; Accepted 15 January 2008

Recommended by N. Sagias

This letter proposes a novel channel-tracking scheme to improve the performance of the dedicated short-range communication (DSRC) systems affected by rapid fluctuations in channel envelopes. The proposed technique is called "iterative (turbo) compensation." It utilizes additional information extracted from the receivers output to further improve the accuracy of the channel estimation. Simulation results show that the iterative scheme performs better than noniterative techniques in higher constellation modulations at high vehicle speeds.

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## 1. Introduction

Dedicated short-range communication (DSRC) was established at a 5.9 GHz band for services involving vehicle-to-vehicle and vehicle-to-roadside communications [1–3]. The physical layer design of DSRC was adopted from the popular wireless local area network (WLAN) standard IEEE 802.11a [4] with high delay spread due to mobility in particularly urban canyons [5]. It was shown in [6] that conventional channel tracking, which is based solely on the known preamble of each packet, is highly sensitive to velocity, data rate, and the packet length, and that conventional channel estimation is not feasible for DSRC applications. A new channel-tracking technique, called the first-order channel tracking, was investigated in [7, 8] for highly mobile orthogonal frequency division multiplexing (OFDM) systems based on different reference signals. The first-order channel-tracking technique was more effective in combating with channel impurities than conventional techniques where only preamble was used in channel estimation. Similar studies in [9, 10] had also showed improvement in mobile environments by utilizing first-order decision-aided schemes along with numerous other studies outlined in [7]. The benefits of these schemes can be applied to other OFDM applications that involve mobility. The ultimate goal is to maximize the data throughput by minimizing packet retransmission via reduction of the packet error rate (PER).

In this paper, a novel iterative channel-tracking technique is proposed to further enhance the packet error performance at high velocities. The performance of the iterative technique is compared to conventional channel estimation and the first-order scheme in a DSRC system under varying signal-to-noise ratio (SNR), velocity, and modulation schemes.

## 2. Background on DSRC

The DSRC physical layer utilizes OFDM [11]. OFDM can be realized in baseband with inverse discrete Fourier transforms (IDFTs). Note that a transmitted OFDM symbol, $\mathbf{X_n} = [X_{n,0}, X_{n,1}, \ldots, X_{n,N-1}]$, is a vector consisting of $N$ parallel data symbols in frequency domain, where $n$ is the symbol index. DSRC uses 64 frequency subcarriers with only 52 subcarriers actually used for signal transmission. Of the 52 subcarriers, 4 are pilot channels and they are used for phase tracking, while the remaining 48 subcarriers are used for data carriers. Each DSRC packet consists of two preambles. The first preamble consists of ten short training symbols for packet detection, frequency offset estimation, and symbol timing. The second preamble, consists of two identical training symbols, ($x_{\text{train}}$), used for channel estimation subsequent to a long guard interval of length $G_{CE} = 3.2\,\mu$s. The data rate is then determined only by selecting a modulation scheme and coding rate. The transmission mode and packet length is determined adaptively based on SNR, but the preamble is always modulated with binary phase-shift keying (BPSK).

The channel is modeled using statistical models presented in [12]. *Rayleigh fading* channels are used to represent 2D isotropic scattering environments to consider the worst-case performance of the receiver.

### 2.1. Conventional receiver and channel estimation

At the conventional receiver, the guard interval is removed from the received signal, then the received data is converted to parallel form, which is denoted as $y_{n,k}$. At this point, $y_{n,k}$ is demultiplexed into the fast Fourier transform (FFT), yielding the following output in the frequency domain:

$$\mathrm{FFT}[y_{n,k}] = Y_{n,k} = H_{n,k} \cdot X_{n,k} + W_{n,k}, \tag{1}$$

where $H_{n,k}$ denotes the channel frequency response at the $n$th symbol index of the $k$th subcarrier, $W_{n,k}$ represents the additive white Gaussian noise (AWGN), and $X_{n,k}$ is related to data that used to be the input to the inverse FFT (IFFT) of the transmitter. If it is assumed that $X_{n,k}$ is known, then the channel response can be solved from (1) as follows:

$$H_{n,k} = \frac{Y_{n,k} - W_{n,k}}{X_{n,k}} = \frac{Y_{n,k}}{X_{n,k}} - \frac{W_{n,k}}{X_{n,k}} = \hat{H}_{n,k} + \psi_{n,k}, \tag{2}$$

where $\hat{H}_{n,k}$ is the estimated channel response based on the least-square (LS) method with an error component of $\psi_{n,k}$ due to the AWGN. Therefore, the accuracy of the channel estimation decreases with noise power. This effect is known as *noise enhancement*. In order to reduce the effect of noise enhancement, the channel estimator employs the second preamble, which consists of two identical training symbols. The estimated channel response is computed as the average channel response over the first and second received OFDM symbols $Y_{-1,k}$ and $Y_{-2,k}$:

$$\hat{H}_{0,k} = \frac{Y_{-2,k} + Y_{-1,k}}{2 \cdot X_{\mathrm{train},k}}. \tag{3}$$

In conventional channel estimation, it is assumed that the channel $\hat{H}_{n,k}$ exhibits time-invariant fading, and can be approximated as $\hat{H}_{0,k}$ for the duration of the packet. Then the received data is compensated as follows:

$$\hat{Y}_{n,k} = \frac{Y_{n,k}}{\hat{H}_{0,k}}. \tag{4}$$

That has shown to be not effective [6] and the following sections will investigate alternative approaches that are necessary to improve receiver performance in DSRC.

### 2.2. First-order channel tracking

Adaptive signal processing concepts can be considered for tracking the channel variation by updating the estimated channel response $\hat{H}_{n,k}$ for $n = 1, 2, \ldots, N-1$ [13]. The receiver block diagram that enables the channel tracking is shown in Figure 1. The initial channel estimate, $\hat{H}_{0,k}$, is obtained based on the training data. Assume that the first received symbol $Y_{0,k}$ is compensated by the initial channel estimate, that is,

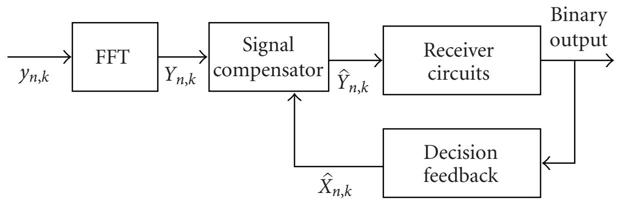



Figure 1: Receiver block diagram.

$$\hat{Y}_{0,k} = \frac{Y_{0,k}}{\hat{H}_{0,k}}. \tag{5}$$

After the received symbol is compensated, the desired signal, $\hat{X}_{1,k}$, is produced from the feedback circuit and the rest of the packet duration. The desired data, $\hat{X}_{n,k}$, is used to update the channel estimate symbol-by-symbol. Preliminary channel estimate obtained by feedback loop in the receiver, denoted as $\tilde{H}_{n,k}$, is obtained by the LS method:

$$\tilde{H}_{n,k} = \frac{Y_{n,k}}{\hat{X}_{n,k}}. \tag{6}$$

In this process, *noise enhancement* caused by the error components can be reduced by introducing a "forgetting factor," ($\gamma$), which is a constant to balance between $\tilde{H}_{n,k}$ and $\hat{H}_{n,k}$. The latter estimate is obtained recursively from $\hat{H}_{0,k}$ by introducing the channel estimate error $\Delta H_{n,k}$ defined as

$$\Delta H_{n,k} = \tilde{H}_{n,k} - \hat{H}_{n,k}. \tag{7}$$

Hence, the recursive equation can be put in the form

$$\begin{aligned}\hat{H}_{n+1,k} &= \hat{H}_{n,k} + \gamma \cdot \Delta H_{n,k} \\ &= (1-\gamma) \cdot \hat{H}_{n,k} + \gamma \cdot \tilde{H}_{n,k}.\end{aligned} \tag{8}$$

Forgetting factor $\gamma$ gets its values between 0 and 1 with an optimal value depending on the time invariant properties of the channel such as velocity, SNR, and the modulation scheme.

## 3. Iterative channel tracking

Although first-order scheme performed better than conventional approach [7, 8], in this section further improvement, called iterative channel tracking, will be investigated. This iterative technique utilizes additional information to further improve the accuracy of the tap weight estimates with additional complexity. The iterative technique is derived based on (8). Recall that $\tilde{H}_{n,k}$ is the channel response based on the LS estimate in (6). In (5), the received data,

**procedure** ITV. CH. TRAKING($X_{\text{train},k}$, $Y_{n,k}$, $\gamma$)
  Compute $\hat{H}_{0,k}$ ▷ estimate based on preamble
  Compute $\hat{Y}_{0,k}$ ▷ compensate first received symbol
  Generate $\hat{X}_{1,k}$
  Select $\gamma$
  $\hat{H}_{1,k} = \hat{H}_{0,k}$
  **for** $n = 1 : (N-1)$ **do**
    **for** $i = 0 : 1$ **do**
      Compute $\tilde{H}_{n,k}^{(i)}$ ▷ Estimate
      Compute $\hat{H}_{n,k}^{(i)}$ ▷ Update
      Compute $\hat{Y}_{n,k}^{(i)}$ ▷ Compensate
      Generate $\hat{X}_{n,k}^{(i)}$
    **end for**
    $\hat{Y}_{n,k} = \hat{Y}_{n,k}^{(1)}$
    $\hat{H}_{n+1,k} = \hat{H}_{n,k}^{(1)}$
  **end for**
**end procedure**

Figure 2: Iterative channel-tracking technique's pseudocode.

$Y_{n,k}$, is compensated by the channel estimate, $\hat{H}_{n,k}$. The current desired signal is used to estimate the current channel response which is $\tilde{H}_{n,k}$. The updated estimated channel response, $\hat{H}_{n+1,k}$, is used to compensate the next received data, $Y_{n+1,k}$. Recall that at high velocities, the channel may exhibit fast-fading characteristics, which means that there may be a substantial change in the channel response during the symbol duration. Therefore, by the time the next symbol is received, the estimated channel response may be slightly outdated.

The proposed solution to this problem is to iterate the compensation of the received symbol with the next channel estimate. This technique involves *iterative tracking*, where the knowledge of an additional feedback is used to improve the current channel estimate, and hence improve the overall system performance to better track the rapid channel variations. Such iterative schemes like *Turbo Decoding* are known to be very effective in improving performance of communication systems [14].

The technique is derived as follows. First, $Y_{n,k}$ is received and compensated by $\hat{H}_{n,k}$ to be demapped, deinterleaved, and decoded. The Viterbi decoder in the receiver circuit reduces errors that are due to outdated channel estimates and produces the desired signal, $\hat{X}_{n,k}^{(0)}$. This desired data is used to estimate the preliminary channel estimate $\tilde{H}_{n,k}^{(0)}$, using the least-square method in the following relation:

$$\tilde{H}_{n,k}^{(0)} = \frac{Y_{n,k}}{\hat{X}_{n,k}^{(0)}}. \tag{9}$$

The next step is to obtain a first channel estimate using the following relation:

$$\hat{H}_{n,k}^{(0)} = (1-\gamma)\cdot\hat{H}_{n,k} + \gamma\cdot\tilde{H}_{n,k}^{(0)}, \tag{10}$$

where $0 < \gamma < 1$ is the forgetting factor which is selected based on simulation practice. At this point, the received symbol $Y_{n,k}$ is compensated a second time with the current channel estimate, $\hat{H}_{n,k}^{(0)}$. After decoding the compensated data, a new desired signal is produced, $\hat{X}_{n,k}^{(1)}$. Again, the new desired data is used to estimate the next preliminary channel estimate:

$$\tilde{H}_{n,k}^{(1)} = \frac{Y_{n,k}}{\hat{X}_{n,k}^{(1)}}. \tag{11}$$

The channel response is finally estimated based on the recursion in (10) using the new estimate:

$$\hat{H}_{n,k}^{(1)} = (1-\gamma)\cdot\hat{H}_{n,k}^{(0)} + \gamma\cdot\tilde{H}_{n,k}^{(1)}, \tag{12}$$

where $\hat{H}_{n,k}^{(0)}$ is obtained from (10). The recursive channel update is then simplified as follows:

$$\begin{aligned}\hat{H}_{n,k}^{(1)} &= (1-\gamma)\cdot\left[(1-\gamma)\cdot\hat{H}_{n,k} + \gamma\cdot\tilde{H}_{n,k}^{(0)}\right] + \gamma\cdot\tilde{H}_{n,k}^{(1)}\\ &= \left(1-2\cdot\gamma+\gamma^2\right)\cdot\hat{H}_{n,k} + \left(\gamma-\gamma^2\right)\cdot\tilde{H}_{n,k}^{(0)} + \gamma\cdot\tilde{H}_{n,k}^{(1)}\\ &= \gamma^2\cdot\left(\hat{H}_{n,k}-\tilde{H}_{n,k}^{(0)}\right)+\gamma\cdot\left(\tilde{H}_{n,k}^{(1)}+\tilde{H}_{n,k}^{(0)}-2\cdot\hat{H}_{n,k}\right)+\hat{H}_{n,k}.\end{aligned} \tag{13}$$

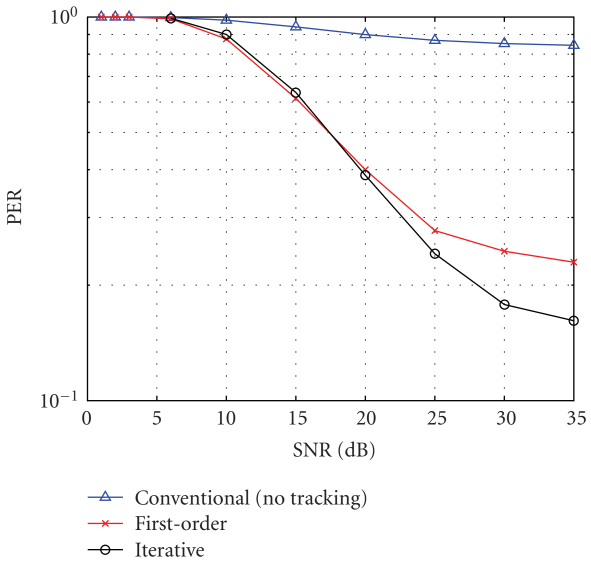
Finally, the second channel estimate is used at the next symbol index:

$$\hat{H}_{n+1,k} = \hat{H}_{n,k}^{(1)}, \tag{14}$$

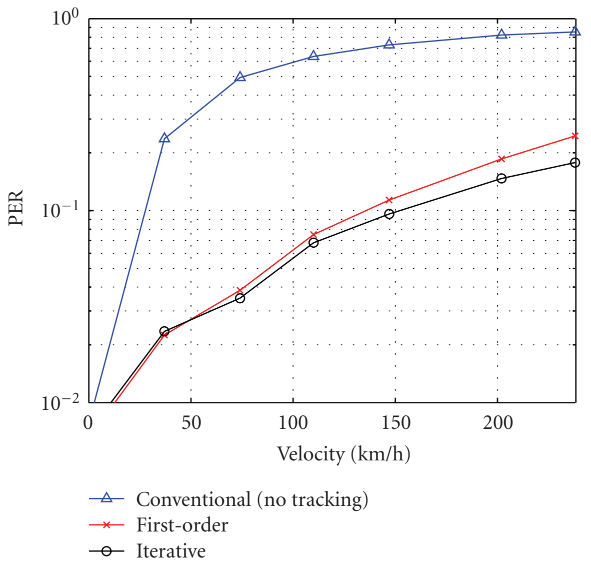
where $\hat{H}_{n+1,k}$ is used to compensate the next symbol $Y_{n+1,k}$, which then will produce a new desired signal $\hat{X}_{n+1,k}^{(0)}$ and so on. This continues until the last symbol of the packet. The pseudocode for the technique is given in Figure 2. In the case of fast-fading channels, the second compensation is crucial since there may be a substantial change in the channel response during a symbol interval. As a result, the iterative tracking will reduce the packet error rate at high velocities.

## 4. Simulation results

The DSRC physical layer was simulated in Matlab. The performance is measured in terms of packet error rate (PER). Conventional, first-order, and iterative channel estimation techniques are compared in a 5.9 GHz DSRC system. Transmissions of 10,000 packets were sent per simulation under varying SNR (0–30 dB) and velocities (0–240 km/h). A velocity of 240 km/h would be the legal maximum of relative vehicular velocity. All simulations were conducted under 1-path Rayleigh fading and had a fixed packet length of $N = 64$ OFDM symbols per packet. The forgetting factors are selected for each modulation scheme based on the simulation practice. Extensive trials were carried out to select a forgetting factor that yields the best overall PER performance. The forgetting factor, $\gamma$, for QPSK, 16- and 64-quadrature amplitude modulation (QAM) selected to be 0.1, 0.4, and 0.5, respectively. These forgetting factors donot necessarily yield the best BER, but they would achieve




(a) PER versus SNR at 238 km/h




(b) PER versus velocity at 30 dB

FIGURE 3: QAM16: first-order versus iterative under rayleigh fading.

the best overall PER over the range of velocity and SNR discussed.

Figure 3 presents results for 16-QAM. More results are reported in [8]. The iterative algorithm outperforms first-order channel estimation method at SNR greater than 20 dB. Figure 3(b) plots the PER versus velocity at a fixed SNR of 30 dB. At relative velocities greater than 75 km/h, iterative channel estimation begins to outperform the first-order method. Notice that the added performance enhancement increases with the increase of velocity. Similar results were obtained for 64-QAM modulations. Iterative technique does not improve QPSK modulation results substantially, but it always performs comparable to the first-order scheme. Therefore, iterative technique is recommended for higher-order modulation schemes at high vehicle velocity operations.

## 5. Conclusion

A novel iterative channel estimation scheme that involves iterative compensation has been proposed and has shown added enhancements to the system through simulation studies that it provided. Substantial improvements are obtained in 16-QAM and 64-QAM transmissions, when the relative velocities are greater than 75 km/h. It is important to note that the results of this are not limited to 5.9 GHz DSRC. There are many different types of OFDM systems that may employ such channel estimation techniques.

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# Special Issue on Physical Layer Network Coding for Wireless Cooperative Networks

## Call for Papers

Cooperative communication is an overwhelming research topic in wireless networks. The notion of cooperative communication is to enable transmit and receive cooperation at user level by exploiting the broadcast nature of wireless radio waves so that the overall system performance including power efficiency and communication reliability can be improved. However, due to the half-duplex constraint in practical systems, cooperative communication suffers from loss in spectral efficiency. Network coding has recently demonstrated significant potential for improving network throughput. Its principle is to allow an intermediate network node to mix the data received from multiple links for subsequent transmission. Applying the principle of network coding to wireless cooperative networks for spectral efficiency improvement has recently received tremendous attention from the research community. *Physical-layer network coding* (PLNC) is now known as a set of signal processing techniques combining channel coding, signal detection, and network coding in various relay-based communication scenarios, such as two-way communication, multiple access, multicasting, and broadcasting. To better exploit this new technique and promote its applications, many technical issues remain to be studied, varying from fundamental performance limits to practical implementation aspects. The aim of this special issue is to consolidate the latest research advances in physical-layer network coding in wireless cooperative networks. We are seeking new and original contributions addressing various aspects of PLNC. Topics of interest include, but not limited to:

- Fundamental limits of relay channels with PLNC
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- Cross-layer design for systems with PLNC
- Joint channel coding, modulation, and PLNC
- PLNC with Turbo/LDPC codes
- PLNC with fountain codes
- Channel estimation and synchronization of PLNC
- Scheduling and resource allocation with PLNC
- PLNC with MIMO and OFDM
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# Special Issue on Interference Management in Wireless Communication Systems: Theory and Applications

## Call for Papers

Interference is a fundamental nature of wireless communication systems, in which multiple transmissions often take place simultaneously over a common communication medium. In recent years, there has been a rapidly growing interest in developing reliable and spectral efficient wireless communication systems. One primary challenge in such a development is how to deal with the interference, which may substantially limit the reliability and the throughput of a wireless communication system. In most existing wireless communication systems, interference is dealt with by coordinating users to orthogonalize their transmissions in time or frequency, or by increasing transmission power and treating each other's interference as noise. Over the past twenty years, a number of sophisticated receiver designs, for example, multiuser detection, have been proposed for interference suppression under various settings. Recently, the paradigm has shifted to focus on how to intelligently exploit the knowledge and/or the structure of interference to achieve improved reliability and throughput of wireless communication systems.

This special issue aims to bring together state-of-the-art research contributions and practical implementations that effectively manage interference in wireless communication systems. Original contributions in all areas related to interference management for wireless communication systems are solicited for this special issue. We are particularly interested in manuscripts that report the latest development on interference channels or cognitive radio channels from the perspectives of information theory, signal processing, and coding theory. Topics of interest include, but are not limited to:

- Information theoretic study of interference channels or cognitive radio channels
- Game theoretical approach to interference management in wireless networks
- Cooperative wireless communication systems
- Relaying in interference networks
- Advanced coding schemes for interference/cognitive radio channels
- Interference channels with confidentiality requirement
- Femtocell networks
- Signal processing algorithms for interference mitigation
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# Special Issue on Signal Processing-Assisted Protocols and Algorithms for Cooperating Objects and Wireless Sensor Networks

## Call for Papers

With the advent of the so-called Internet of Things (IoTs), we will witness an unprecedented growth in the number of networked terminals and devices. In attaining this IoT vision, a class of energy- and, in general, resource-constrained systems like Wireless Sensor Networks (WSNs), networks of cooperating objects and embedded devices such as RFIDs, or networks for Device-to-Device (D2D) and Machine-to-Machine (M2M) communications are to play a fundamental role. The paradigm shift from general-purpose data networks to application-oriented networks (e.g., for parameter or random field estimation, event detection, localization, and tracking) clearly calls for further optimization at the physical, link, and network layers of the protocol stack. Interestingly, the above-mentioned estimation/detection/localization/tracking problems have been addressed for years by the signal processing community, this resulting into a number of well-known algorithms. Besides, some inspiration could be also borrowed from other communication schemes, such as MIMO and beamforming techniques or cooperative communications that were traditionally developed for wireless data networks, or even from other fields such as mathematical biology (e.g., networks of coupled oscillators). However, the challenge now is to enhance such algorithms and schemes and make them suitable for decentralized and resource-constrained operation in networks with a potentially high number of nodes. Complementarily, the vast literature produced by the information theory community, on the one hand, reveals the theoretical performance limits of decentralized processing (e.g., distributed source coding) and, on the other, offers insight on the scalability properties of such large networks and their behavior in the asymptotic regime. Realizing the information-theoretic performance with practical decentralized networking, radio resource management schemes, routing protocols, and other network management paradigms is a key challenge.

The objective of this Special Issue (whose preparation is carried out under the auspices of the EC Network of Excellence in Wireless Communications NEWCOM++) is to gather recent advances in the areas of cooperating objects, embedded devices, and wireless sensor networks. The focus is on how the design of future physical, link, and network layers could benefit from a signal processing-oriented approach. Specific topics for this Special Issue include but are not limited to:

- Decentralized parameter estimation
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- Cooperative event detection
- Data gathering and data fusion
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