Pilot Insertion with Index Modulation for OFDM-Based Vehicular Communications

Qiang Li, Miaowen Wen, Yuekai Zhang,
Jun Li, Fangjiong Chen, and Fei Ji

South China University of Technology
HUAWEI Technologies Co., Ltd
Guangzhou University

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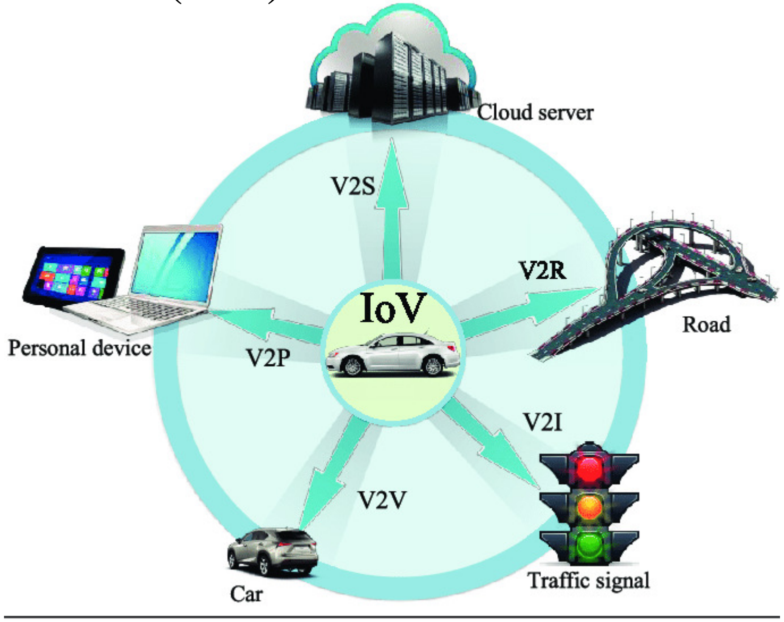
Background

- **Vehicular Communications**

Vehicular communications play a vital role in the realization of Internet of Vehicle (IoV).

Various vehicular communication solutions have been developed throughout the world.



IEEE 802.11p-based

LTE-V2X-based

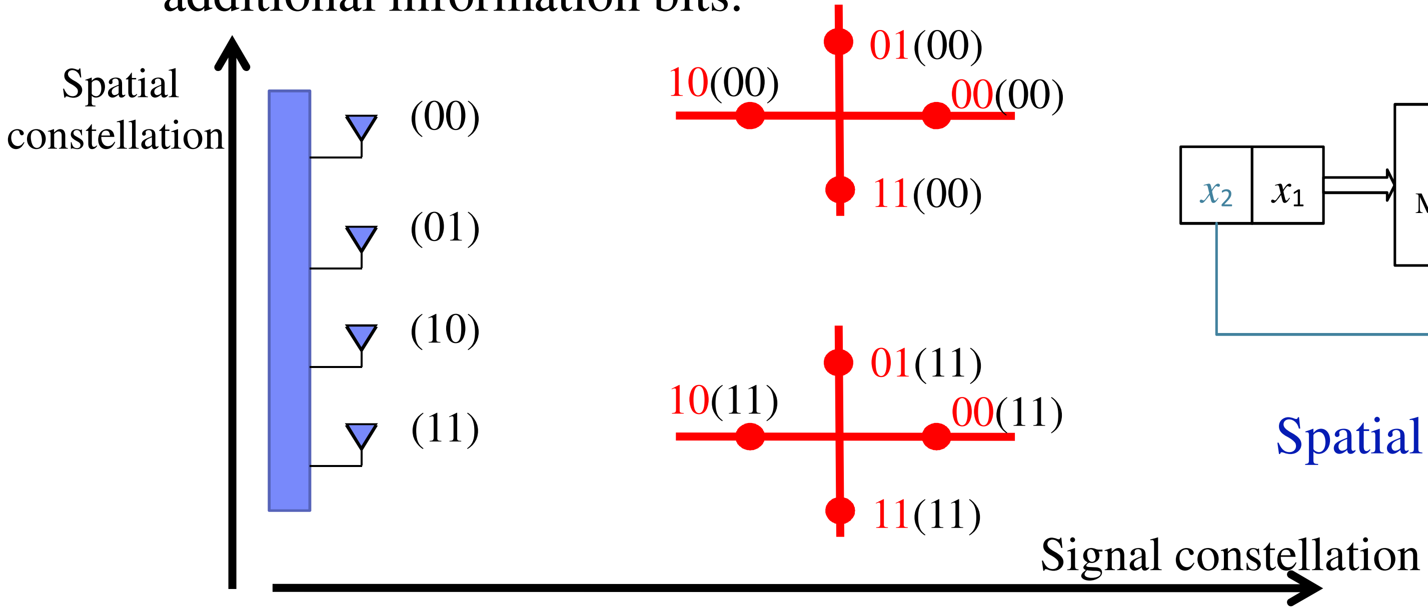
OFDM

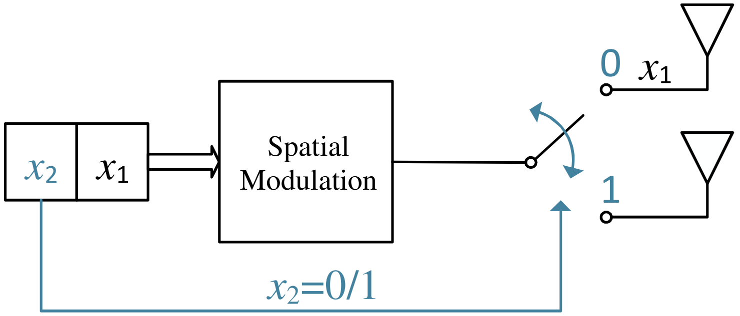
Waveform

Background

- **Index Modulation**

Index modulation (IM) is a kind of digital modulation technique that utilizes the index(es) of building block(s) of a communication system to convey additional information bits.





Spatial Modulation (SM)

Proposed Scheme

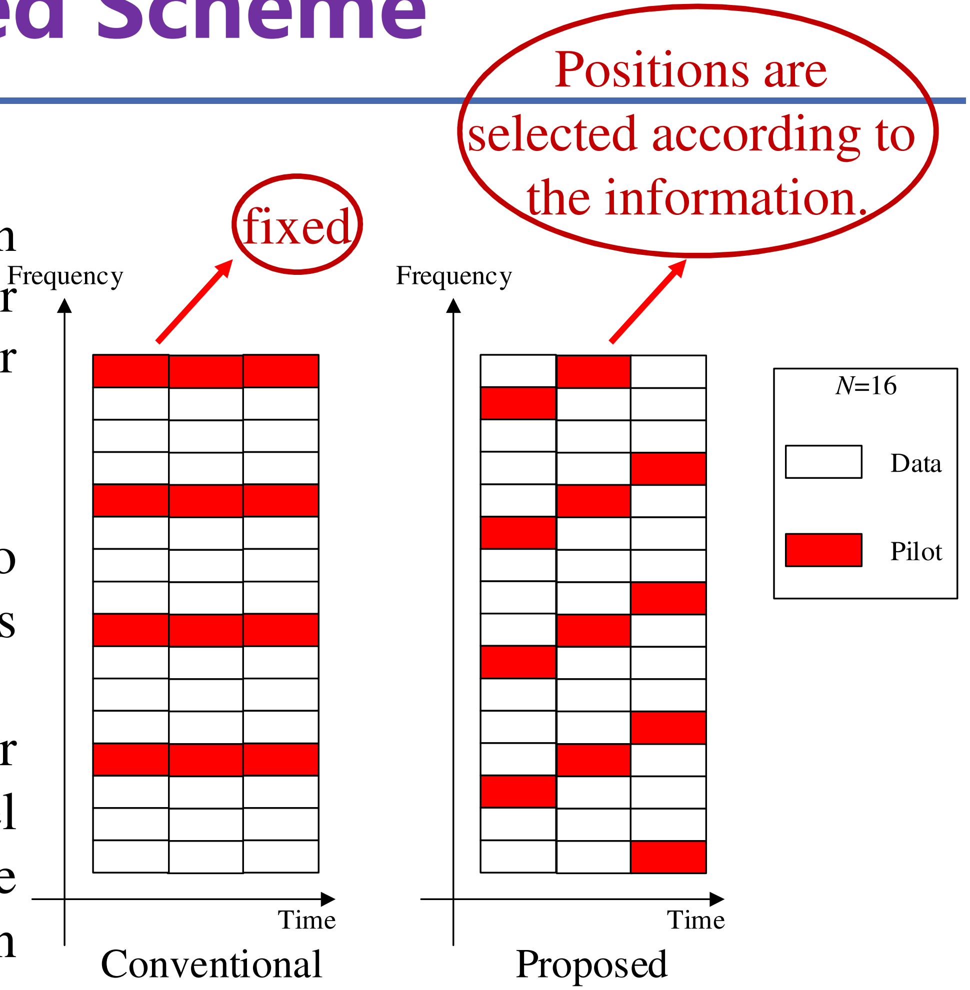
- **Motivation**

  The positions of pilots are fixed in current OFDM-based vehicular communications. This overhead lower the system spectral efficiency (SE).

- **Idea**

  To utilize the indices of pilots to carry additional information, thus improving the SE.

  The pilots can be used for either carrier phase tracking or channel estimation purpose. Carrier phase tracking is taken as an example in this talk.



fixed

Positions are selected according to the information.

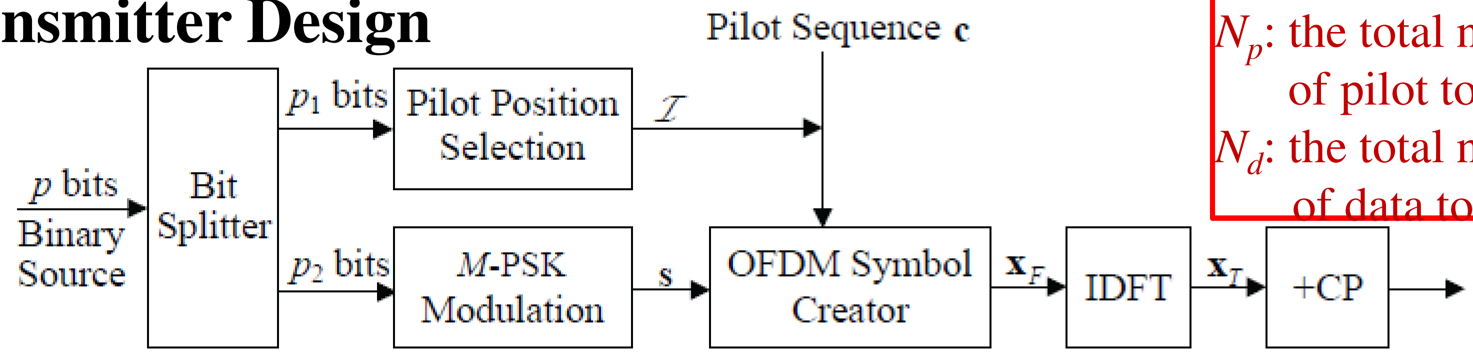
Conventional

Proposed

Proposed Scheme

N: the total number of subcarriers
N_p: the total number of pilot tones
N_d: the total number of data tones

- **Transmitter Design**



The process of p_1 bits:

☐ *Equal-spaced pilot position selection* (PPS), PPS-I

The spacing between any two adjacent pilot tones is $n=N/N_p$.

$$p_1 = \lfloor \log_2(n) \rfloor \Longrightarrow \mathcal{I} = \{d_0, n+d_0, \ldots, (N_p-1)n+d_0\}, \; d_0 \in \{0, 1, \ldots, n-1\}$$

☐ *Unequal-spaced PPS*, PPS-II

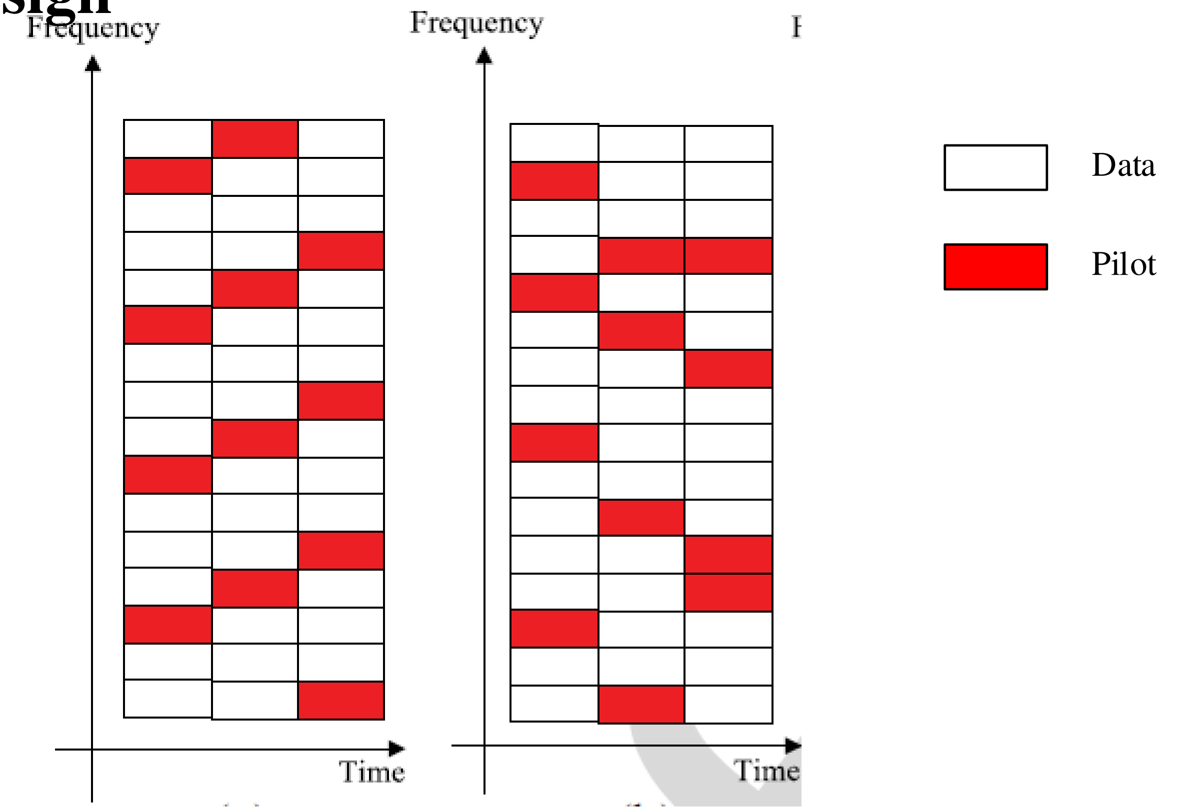
Divide both the N subcarriers and p_1 bits into N_p sub-blocks, and select one pilot within n subcarriers for each sub-block.

$$p_1 = N_p \lfloor \log_2(n) \rfloor \Longrightarrow \mathcal{I} = \left\{ d^{(0)}, n + d^{(1)}, \ldots, (N_p - 1)n + d^{(N_p-1)} \right\}$$

Proposed Scheme

- **Transmitter Design**

Pilot patterns with
$N=16$ and $N_p=4$



Equal-spaced PPS (PPS-I) *Unequal-spaced* PPS (PPS-II)

Proposed Scheme

- **Transmitter Design**

$$p_2 = N_d \log 2(M) \text{ bits} \xrightarrow{M\text{-PSK constellation } \mathcal{S}} \mathbf{s} = [S_0, S_1, \ldots, S_{N_d-1}]^T$$

$$\left.\begin{array}{l} \text{Data symbols } \mathbf{s} = [S_0, S_1, \ldots, S_{N_d-1}]^T \\ \text{Pilot sequence } \mathbf{c} = [C_0, C_1, \ldots, C_{N_p-1}]^T \end{array}\right\} \xrightarrow{\mathcal{I}=\{i_0,\, i_1,\, \ldots,\, i_{N_p-1}\}}$$

the frequency-domain block $\mathbf{x}_F = [X_0, X_1, \ldots, X_{N-1}]^T$

where $X_m = \begin{cases} C_k, & \text{for } m = i_k, k \in \{0, 1, \ldots, N_p - 1\}, \\ S_\kappa, & \text{for } m = \bar{i}_\kappa, \kappa \in \{0, 1, \ldots, N_d - 1\}. \end{cases}$

$\{\bar{i}_0, \bar{i}_1, \ldots, \bar{i}_{N_d-1}\} \triangleq \bar{\mathcal{I}} = \mathcal{N} \backslash \mathcal{I}$ are the indices of data symbols.

Finally, the time-domain transmit vector

$N \times N$ DFT matrix

$$\mathbf{x}_T = [x_0, x_1, \ldots, x_{N-1}]^T = \frac{1}{\sqrt{N}} \mathbf{F}_N^H \mathbf{x}_F,$$

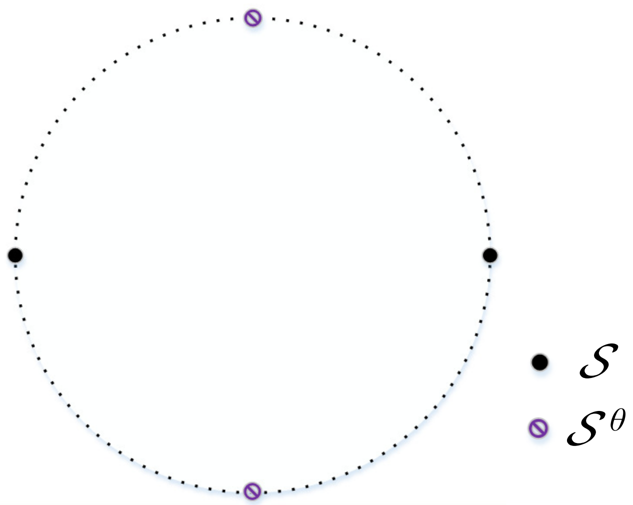
Proposed Scheme

- **Transmitter Design**

Pilot symbols selection

To facilitate pilot position detection (PPD), the pilot symbols are required to be distinguishable from the data symbols as much as possible. Hence, in this paper, C_k, $k \in \{0, 1, . . . ,N_p - 1\}$ is equiprobably drawn from a rotated constellation $\mathcal{S}^{\theta}$ that is derived by rotating $\mathcal{S}$ with angle θ, where θ is selected as $\theta = \pi/M$.

For example, M=2



Proposed Scheme

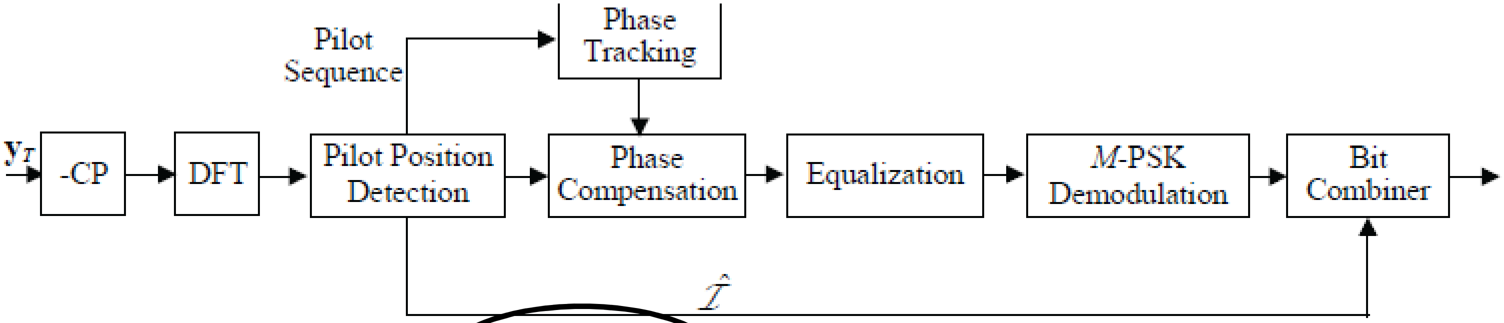
- **Receiver Design**

The *m*-th tone of the γ-th received OFDM symbol in the frequency domain

$$R_m^{(\gamma)} \approx H_m^{(\gamma)} X_m^{(\gamma)} e^{j\varphi_\gamma} + V_m^{(\gamma)}$$

phase error for the γ-th OFDM symbol

Matrix form: $\mathbf{r}_F = [R_0, R_1, \ldots, R_{N-1}]^T = \mathbf{X}\mathbf{h}_F e^{j\varphi} + \mathbf{v}$



Receiver's Task

- data symbols
- pilot indices

Proposed Scheme

- **Receiver Design**

❑ *Optimal ML Detector*

$$(\hat{\mathcal{I}}, \hat{\mathbf{s}}, \hat{\varphi}) = \arg\min_{\mathcal{I},\mathbf{s},\varphi} \left\| \mathbf{r}_F - \mathbf{X}\mathbf{h}_F e^{j\varphi} \right\|^2$$

high computational complexity

❑ *Near-ML Detector*

For each realization of $\mathcal{I}$, denoted by $(\mathcal{I})\eta$, $\eta \in \{0, \ldots, 2^{p1} - 1\}$, the phase estimate is given by

$$(\varphi)_\eta = \angle\left(\sum_{k=0}^{N_p-1} R_{(i_k)_\eta} (H_{(i_k)_\eta} C_k)^*\right)$$

the k-th entry of $(\mathcal{I})\eta$

Phase compensation $\tilde{\mathbf{r}}_F = \mathbf{r}_F e^{-j(\varphi)_\eta}$

With $(\mathcal{I})\eta$, the metric is $(\Delta)_\eta = \sum\limits_{k=0}^{N_p-1} \left|\tilde{R}_{(i_k)_\eta} - H_{(i_k)_\eta} C_k\right|^2 + \sum\limits_{\kappa=0}^{N_d-1} \left(\min\limits_{S_\kappa \in \mathcal{S}} \left|\tilde{R}_{(\bar{i}_\kappa)_\eta} - H_{(\bar{i}_\kappa)_\eta} S_\kappa\right|^2 \right)$

Finally, we have

$\hat{\eta} = \arg\min\limits_{\eta} (\Delta)_\eta$ and $\hat{S}_\kappa = \arg\min\limits_{S_\kappa \in \mathcal{S}} \left|\tilde{R}_{(\bar{i}_\kappa)_{\hat{\eta}}} - H_{(\bar{i}_\kappa)_{\hat{\eta}}} S_\kappa\right|^2$

Simulation Results

$N = 16;$

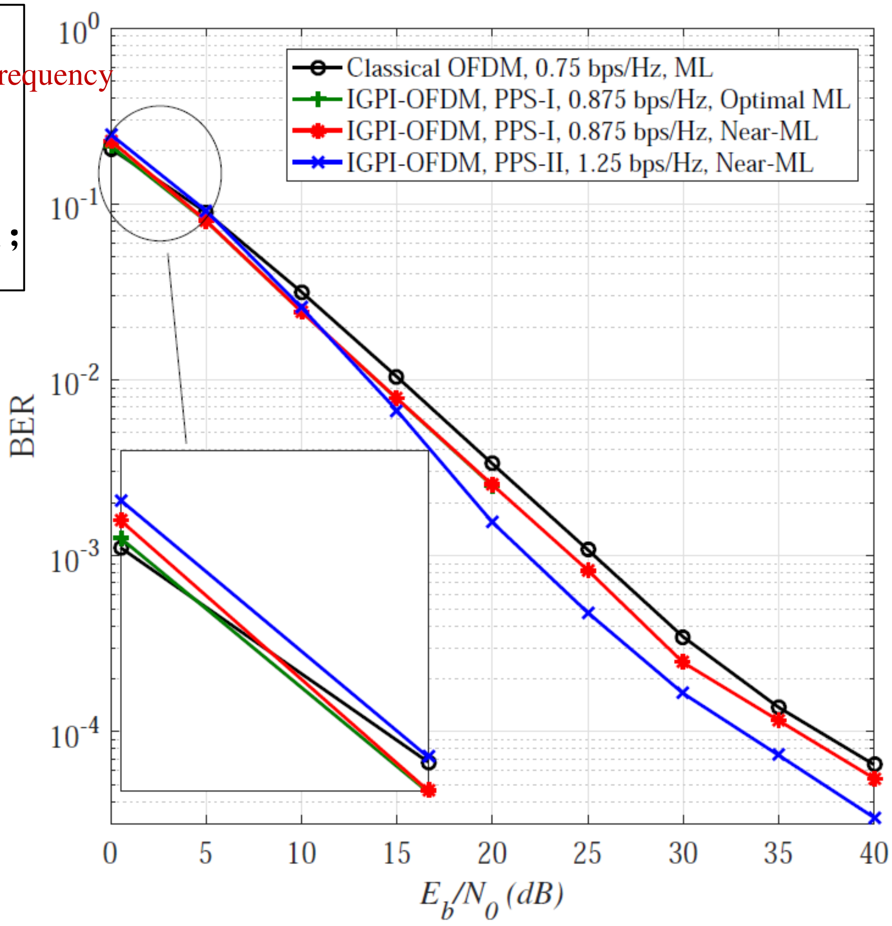
$N_p = 4;$

$M = 2;$

$\varepsilon = \frac{f_\Delta}{f_{sub}} = 0.01;$

carrier frequency offset

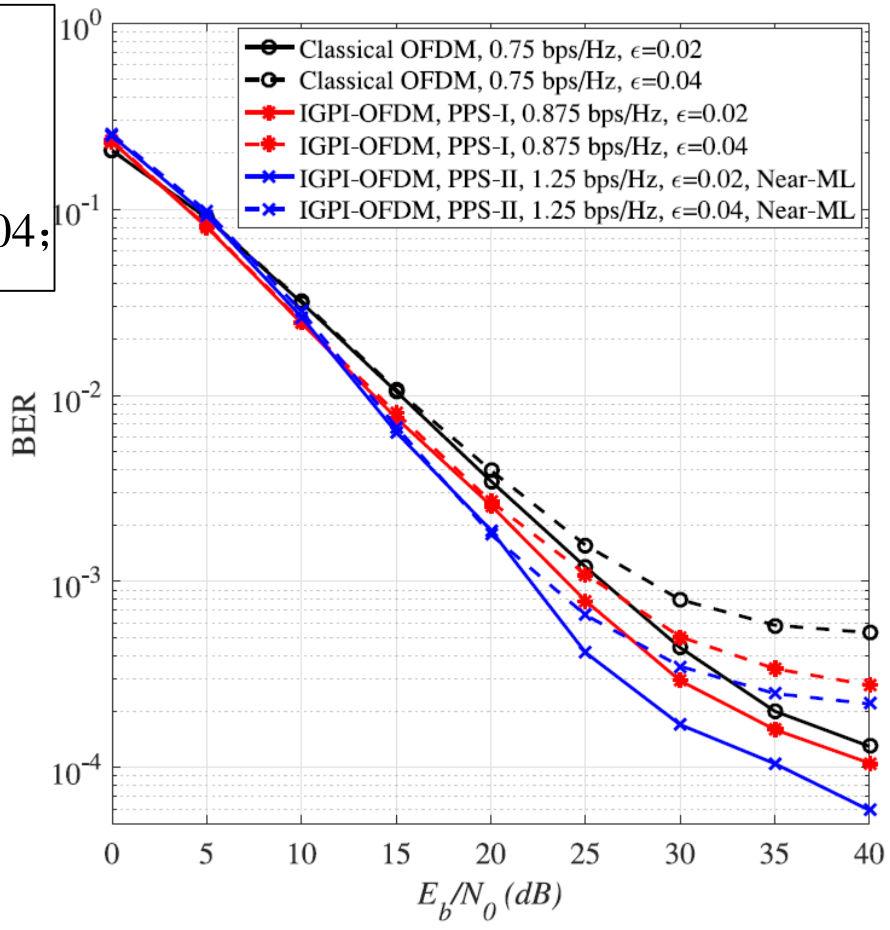
subcarrier spacing



- The BER curve of the near-ML detector almost overlaps that of the optimal ML detector for IGPI-OFDM with PPS-I.
- IGPI-OFDM with PPS-I achieves an SNR gain of about 1 dB over classical OFDM.
- The near-ML detector for IGPI-OFDM with PPS-II achieves SNR gains of about 3 dB over classical OFDM, and about 2 dB over IGPI-OFDM with PPS-I.

Simulation Results

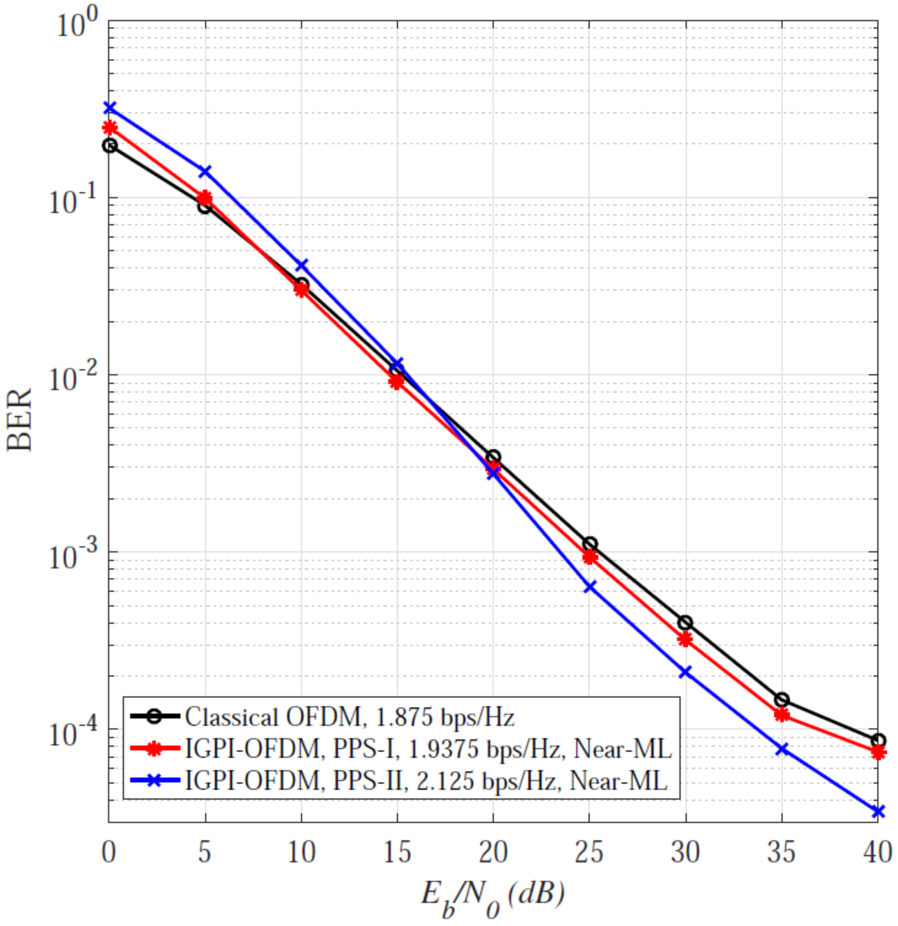
$N = 16$;
$N_p = 4$;
$M = 2$;
$\varepsilon = \dfrac{f_\Delta}{f_{sub}} = 0.02/0.04$;



- Increasing ε deteriorates the performance at high SNR significantly for all schemes.
- At $\varepsilon = 0.02/0.04$, IGPI-OFDM with PPS-I/II performs better than classical OFDM, achieving lower error floors.
- Interestingly, the performance improvement with $\varepsilon = 0.04$ is more notable than that with $\varepsilon = 0.02$.

Simulation Results

$N = 16;$
$N_p = 4;$
$M = 4;$
$\varepsilon = 0.01;$



- IGPI-OFDM with PPS-II performs the best among all schemes when SNR is greater than 19 dB, and about 3 dB SNR gain over IGPI-OFDM with PPS-I is achieved at BER= 2×10^{-4}.

Conclusions

- The information-guided pilot insertion technique is propsoed, which exploits the pilot positions to convey additional information bits, to solve the low SE problem in the current OFDM-based vehicular communications system.
- Two different types of information-guided PPS schemes, which result in the equal-spaced and unequal-spaced pilot patterns, and the corresponding PPD methods have been investigated for carrier phase tracking.
- Simulation results have shown that the proposed IGPI-OFDM outperforms classical OFDM in terms of BER performance significantly.

THANK YOU

Questions?