Modified TFRI Channel Estimation Scheme in OFDM-IM for 802.11p

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***Abstract*—IEEE 802.11p is developed to support cooperative intelligent transport systems. In such systems, channel estimation is a challenging problem due to the channel's double dispersive nature. This paper proposes a modified time domain reliable test frequency domain interpolation (M-TFRI) scheme for 802.11p orthogonal frequency division multiplexing with index modulation (OFDM-IM) systems is proposed. Unlike OFDM, OFDM-IM can achieve better performance in vehicular communication environments. However, due to the in-active subcarriers, channel estimation for OFDM-IM is more difficult than OFDM. Inspired by the OFDM TFRI and the structure of OFDM-IM, the proposed M-TFRI utilizes preambles and least square (LS) methods to fill in the missing channel information on in-active subcarriers, reducing the serious performance degradation caused by the conventional TFRI used in OFDM-IM. Simulation results show that the proposed M-TFRI achieves a similar estimation performance as that of the OFDM TFRI. Moreover, the proposed M-TFRI significantly outperforms the existing channel estimation performance designed for OFDM-IM systems.**

***Index Terms*—Orthogonal frequency division multiplexing (OFDM), index modulation (IM), test frequency domain interpolation (TFRI), least square (LS), IEEE 802.11p standard, vehicular channels..**

I. Introduction

To realize the cooperative intelligent transportation system (C-ITS), IEEE 802.11p standard has been proposed to develop the physical layer of the wireless access in vehicular environments [1]. Since the channel in such environments is usually doubly selective, the conventional orthogonal frequency division multiplexing (OFDM) modulation suffers serious performance degradation. OFDM with index modulation (OFDM-IM) [2], which is a new concept inspired from spatial modulation (SM), has been proposed recently to alleviate the drawbacks suffered by OFDM. In OFDM-IM, part of information are indicated by the status of subcarriers and the rest of information are carried by modulated subcarriers. Compared with the conventional OFDM, the in-active subcarriers of OFDM-IM makes it more capable of combating inter carrier interference (ICI) which makes OFDM-IM attractive [3]. Therefore, OFDM-IM is a very promising technique which may be considered for the next generation communications.

Despite the advantages of OFDM-IM aforementioned, there are still problems in the practical applications of OFDM-IM in wireless communications, especially in vehicular environments. OFDM-IM receivers need to detect the indices of active subcarriers by utilizing different detection methods. Most literatures implements such detections by assuming the receiver has perfect channel state information, which is impossible in practical cases. Some channel estimation schemes for OFDM-IM systems have been proposed [4]–[6]. In [4], an least square (LS) channel estimation scheme for OFDM-IM is proposed by utilizing the in-active subcarriers for pilots. Channel estimation schemes utilizing Zadoff-Chu sequence and linear minimum mean squared error (LMMSE) algorithm are proposed in [5] and [6], respectively. Nevertheless, there is currently no corresponding solution for OFDM-IM channel estimation in vehicular environments.

For OFDM, several channel estimation schemes have been proposed for IEEE 802.11p standard, such as spectral temporal averaging (STA) [7], constructed data pilot (CDP) [8], and time domain reliable test frequency domain interpolation (TFRI) scheme [9]. It has been recognized that STA and CDP schemes hardly meet the requirements of advanced V2X use cases [10]. TFRI algorithm that performs well in OFDM provides a good candidate for OFDM-IM channel estimations. However, it is known that the vehicular channel is usually time-varying, but the in-active subcarriers of OFDM-IM make channel tracking uneasy, which bring serious performance degradation when conventional TFRI scheme is applied in OFDM-IM. To solve this problem, in this paper, a modified TFRI (M-TFRI) is proposed for vehicular channel estimation in OFDM-IM systems. The proposed M-TFRI utilizes LS scheme to obtain the indices of in-active subcarriers. Then, the proposed M-TFRI utilizes preambles and previous channel estimate to obtain the corresponding channel frequency responses (CFR) on the in-active positions. To the best of authors' knowledge, this is the first paper regarding to the estimation method for OFDM-IM under vehicular channels. Simulations results show that the proposed M-TFRI achieves significant better estimation performance than that of the conventional LS scheme. Moreover, the proposed M-TFRI also achieves a similar performance as that of the TFRI scheme in OFDM systems.

The remainder of this paper is organized as follows: Section II describes the system model, including the OFDM-IM with 802.11p standard, and the conventional LS scheme. Section III provides the concept of the proposed M-TFRI scheme, which performance are verified by the simulation results in Section IV. The conclusion is given in Section V.

II. System Model

A. 802.11p with Index Modulation

IEEE 802.11p is an amendments rooted from IEEE 802.11a standard. IEEE 802.11p includes some enhancements required to support C-ITS applications, which includes data exchange between vehicles and between vehicles and infrastructures. IEEE 802.11p utilizes 10MHz bandwidth. Due to narrower bandwidth, all parameters of 802.11p are doubled compared to 802.11a. 802.11p also utilizes OFDM with 64 subcarriers. 52 subcarriers in the range from -26 to 26 are employed for information transmission. Subcarriers with index -21, -7, 7, 21 are utilized for pilots, and the other subcarriers are used for information transmission.

Compared to OFDM, OFDM-IM utilizes subcarrier status (active or inactive) to indicate information bits, which makes trade-off between spectral and energy efficiency. The flexibility and superior performance make OFDM-IM a potential candidate for vehicular communications [11]. In an OFDM-IM system, m bits $\mathbf{B}$ are split into G groups. Each group $\mathbf{B}_g$ contains p bits. K subcarriers are divided into G subblocks, each contains k subcarriers, thus $m = pG$ and $K = kG$. p bits in each subblock are divided into p_1 and p_2 bits. $p_1 = \lfloor \log_2 C_k^u \rfloor$ bits are employed to choose u active subcarriers from k subcarriers, where C_a^b represents the binomial coefficient. Here we write the indices of u active subcarriers in the g^{th} subblock as: $I_g = \{i_{g,1}, i_{g,2}, ..., i_{g,u}\}$, where $i_{g,\gamma} \in \{1, 2, ..., u\}$ for $1 \le g \le G$ and $1 \le \gamma \le u$. Then, the $p_2 = u\log_2 M$ bits are mapped to M-ary constellations and modulated on the u active subcarriers according to the first p_1 bits. The g^{th} block of symbols are written as $\mathbf{S}_g = [S_g(1), S_g(2), ..., S_g(u)]$, where $S_g(\gamma) \in \chi_s$ and χ_s is the constellations. Considering I_g and $\mathbf{S}_g$ for all G subblocks, a complete OFDM-IM sequence can be written as: $\mathbf{X} = [X(1), X(2), ..., X(K)]^T$, where $X(\alpha) \in \{0, \chi_s\}$, for $\alpha = 1, 2, ..., K$ and T denotes the transpose. Then, similar to OFDM, the baseband-equivalent OFDM-IM symbols are generated by applying the inverse fast Fourier transform (IFFT) operations. At OFDM-IM receiving side, p_1 bits need to be recovered at first through ML or LLR detection by deciding the status of subcarriers. Then, the rest of p_2 bits can be recovered. We note that due to space limitations, readers who are interested in OFDM-IM can refer to [2].

Fig.1 illustrates an IEEE 802.11p subcarriers arrangement when OFDM-IM is applied. Compared to IEEE 802.11p subcarriers arrangement with OFDM modulation, the corresponding OFDM-IM version has in-active subcarriers which are usually 0s. However, different from the null positions in the conventional OFDM IEEE 802.11p frame, the in-active subcarriers in the frame structure of the OFDM-IM version implicitly conveys p_1 bits information through its position indices. The receiving side can recover the corresponding p_1 bits information by detecting these inactive carriers.

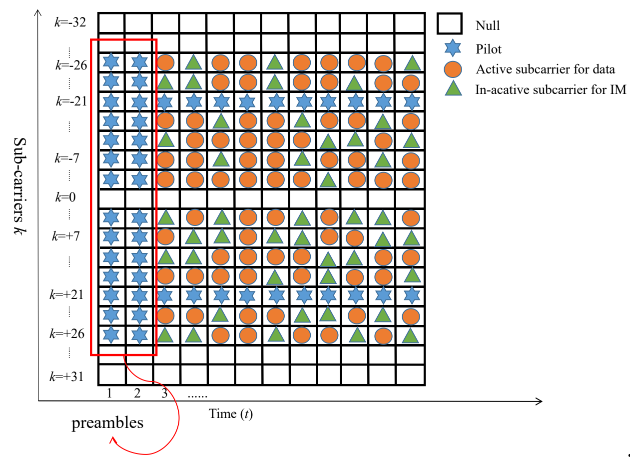

Fig. 1. IEEE 802.11p subcarriers arrangement

B. Conventional LS Channel Estimation Scheme

Let A_{on} be the set of non-blank subcarriers (the colored part of Fig.1), the input-output relation between the transmitted and received OFDM-IM block ($A_{on} \times T$) can be written as:

$$\mathbf{Y}[\alpha, t] = \tilde{\mathbf{H}}[\alpha, t]\mathbf{X}[\alpha, t] + \mathbf{N}[\alpha, t], \alpha \in A_{on}, \quad (1)$$

where $\mathbf{Y}[\alpha, t], \mathbf{X}[\alpha, t], \mathbf{N}[\alpha, t]$ denote the transmitted OFDM-IM symbol, the received signal, and the noise of the α^{th} subcarrier in the t^{th} OFDM-IM symbol, respectively. Then, the transmitted symbols and the transmitted preambles can be written as follows:

$$\mathbf{y}_t[\alpha] = \tilde{\mathbf{h}}_t[\alpha]\mathbf{x}_t[\alpha] + \mathbf{n}_t[\alpha], \alpha \in A_{on}, \quad (2)$$

$$\mathbf{y}_t^{(p)}[\alpha] = \tilde{\mathbf{h}}_t[\alpha]\mathbf{p}[\alpha] + \mathbf{n}_t^{(p)}[\alpha], \alpha \in A_{on}, \quad (3)$$

where $\mathbf{x}_t[\alpha]$ and $\mathbf{p}[\alpha]$ are the t^{th} transmitted OFDM-IM symbol and the transmitted preamble, respectively.

LS channel estimation algorithm is a classical scheme which has been discussed in a number of articles [4]–[6]. LS is also a basic solution for channel estimation in IEEE 802.11p OFDM-IM systems. In LS scheme, two received long preambles $\mathbf{y}_1^{(p)}[\alpha]$ and $\mathbf{y}_2^{(p)}[\alpha]$ are required to obtain the CFR, which can be written as follows:

$$\hat{\tilde{\mathbf{h}}}_{LS}[\alpha] = \frac{\mathbf{y}_1^{(p)}[\alpha] + \mathbf{y}_2^{(p)}[\alpha]}{2\mathbf{p}[\alpha]}, \quad (4)$$

where $\mathbf{p}[\alpha]$ is the pre-known pilot symbols on the α^{th} subcarriers of the long preambles, and $\hat{\tilde{\mathbf{h}}}_{LS}[\alpha]$ is the corresponding CFR on the α^{th} subcarriers. LS algorithm assume time is invariant, thus the estimation accuracy degrades with the increase of index t of the OFDM-IM symbols. Therefore, the conventional LS algorithm is not suitable for vehicular channel environments and the requirement of IEEE 802.11p standard.

III. The Proposed M-TFRI Channel Estimation Scheme

TFRI scheme is based on the frequency domain interpolation of the reliable constructed data pilot. For the proposed M-TFRI scheme, the indices of in-active subcarriers need to be detected at first based on LLR calculations. For the t^{th} OFDM-IM symbol, the LLR of the α^{th} subcarrier can be written as follows:

$$\lambda(\alpha)=\ln(\sum_{s=1}^{M}\exp(-\frac{1}{N_{0,F}}|\mathbf{y}_t[\alpha]-\hat{\hat{\mathbf{h}}}_{LS}[\alpha]\chi_s|^2)), \quad (5)$$

a larger $\lambda(\alpha)$ value means it is more probable that index is selected by the index selector at the transmitter, i.e., it is active.

After obtaining the in-active subcarriers' positions, the initial channel estimate needs to be calculated. The corresponding steps for initial channel estimation is expressed as follows:

1) The t^{th} OFDM-IM symbol is obtained based on the estimated channel last time, which is written as:

$$\mathbf{y}_{eq_t}[\alpha]=\frac{\mathbf{y}_t[\alpha]}{\hat{\hat{\mathbf{h}}}_{Initial_{t-1}}[\alpha]},\hat{\hat{\mathbf{h}}}_{Initial_0}[\alpha]=\hat{\hat{\mathbf{h}}}_{LS}[\alpha]. \quad (6)$$

2) Next, subcarriers $\mathbf{y}_{eq_t}[\alpha]$ needs to be de-mapped to a data $\mathbf{d}_t[\alpha]$, which is used for initial channel estimate. The active subcarriers can be de-mapped to the nearest constellation. In OFDM-IM system, there is no data at the in-active position. Therefore, in the M-TFRI method, to obtain the initial channel estimates of the corresponding in-active positions, the data on the in-activated carrier is set to zero. Moreover, the pilot subcarriers are set to the predefined symbols in the standard. The $\mathbf{d}_t[\alpha]$ obtaining procedure for subcarriers $\mathbf{y}_{eq_t}[\alpha]$ can be expressed as follows:

$$\mathbf{d}_t[\alpha]=\begin{cases}\underset{\chi_s}{\operatorname{argmin}}(|\mathbf{y}_{eq_t}[\alpha]-\chi_s|) & \text{if } \mathbf{y}_t[\alpha] \text{ is active}\\ 0 & \text{if } \mathbf{y}_t[\alpha] \text{ is in-active}\\ \mathbf{p}_t[\alpha] & \text{if } \mathbf{y}_t[\alpha] \text{ is pilot}\end{cases} \quad (7)$$

3) Then, the initial channel estimation value needs to be calculated. It should be noted that if α is in-active, the corresponding $\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]$ needs to be replaced by the CFR obtained by TFRI of the previous time:

$$\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]=\begin{cases}\frac{\mathbf{y}_t[\alpha]}{\mathbf{d}_t[\alpha]}\\ \hat{\hat{\mathbf{h}}}_{TFRI_{t-1}}[\alpha],\hat{\hat{\mathbf{h}}}_{TFRI_0}[\alpha]=\hat{\hat{\mathbf{h}}}_{LS}[\alpha]\end{cases}. \quad (8)$$

After obtaining $\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]$, the $(t-1)^{th}$ OFDM-IM symbol is equalized by $\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]$ and $\hat{\hat{\mathbf{h}}}_{TFRI_{t-1}}[\alpha]$ [12],where:

$$\mathbf{y}'_{eq_{t-1}}[\alpha]=\frac{\mathbf{y}_{t-1}[\alpha]}{\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]},\mathbf{y}''_{eq_{t-1}}[\alpha]=\frac{\mathbf{y}_{t-1}[\alpha]}{\hat{\hat{\mathbf{h}}}_{TFRI_{t-1}}[\alpha]}. \quad (9)$$

Then, $\mathbf{y}'_{eq_{t-1}}[\alpha]$ and $\mathbf{y}''_{eq_{t-1}}$ are de-mapped to $\mathbf{d}'_t[\alpha]$ and $\mathbf{d}''_t[\alpha]$ according to (7). M-TFRI utilizes interpolation to obtain the estimated CFR. M-TFRI splits subcarriers into two set. The reliable set (RS) includes pilots and the subcarrier positions that meet $\mathbf{d}'_t[\alpha]=\mathbf{d}''_t[\alpha]$, whereas the rest subcarriers are included in the unreliable set (URS). Then, an interpolation method is implemented by using the channel estimates in RS to fulfill the channel estimates in URS [13]. The corresponding M-TFRI algorithm for OFDM-IM systems can be concluded in Algorithm.1.

Algorithm 1 Modified TFRI Channel Estimation Algorithm

Require: $\hat{\hat{\mathbf{h}}}_{LS}[\alpha]$, $\mathbf{d}_t[\alpha]$ and $\mathbf{y}_t[\alpha]$.
  for $\forall\mathbf{y}_t[\alpha]$ **do**
    Obtaining $\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]$ according to (8).
  end for
  for $\forall\mathbf{y}_t[\alpha]$ **do**
    $\mathbf{y}'_{eq_{t-1}}[\alpha]=\frac{\mathbf{y}_{t-1}[\alpha]}{\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]}$,$\mathbf{y}'_{eq_{t-1}}[\alpha]\rightarrow\mathbf{d}'_t[\alpha]$ according to (7).
    $\mathbf{y}''_{eq_{t-1}}[\alpha]=\frac{\mathbf{y}_{t-1}[\alpha]}{\hat{\hat{\mathbf{h}}}_{TFRI_t}[\alpha]}$,$\mathbf{y}''_{eq_{t-1}}[\alpha]\rightarrow\mathbf{d}''_t[\alpha]$ according to (7).
  end for
  for $\forall\alpha$ on pilot positions **do**
    RS←RS+α
  end for
  for $\forall\alpha$ on information transmission positions **do**
    if $\mathbf{d}''_t[\alpha]==\mathbf{d}'_t[\alpha]$ **then**
      $\hat{\hat{\mathbf{h}}}_{TFRI_t}[\alpha]=\hat{\hat{\mathbf{h}}}_{Initial_t}[\alpha]$
      RS←RS+α
    else
      URS←URS+α
    end if
  end for
  $\hat{\hat{\mathbf{h}}}_{TFRI_t}[URS]$ = cubic Interpolation($\hat{\hat{\mathbf{h}}}_{TFRI_t}[RS]$)

IV. Simulation Result

In this section, normalized mean-squared error (NMSE) is utilized to evaluate the performance of the proposed M-TFRI channel estimation scheme. A $G=16$, $k=4$, and $u=2$ OFDM-IM system with QPSK modulation is considered. The definition of NMSE is given as follows:

$$\text{MSE}_{TFRI}=\frac{1}{N_T}(\sum_{t=1}^{N_t}\tilde{\mathbf{h}}_t-\hat{\hat{\mathbf{h}}}_{TFRI_t}), \quad (10)$$

where N_T is the number of OFDM-IM symbols used during the simulation.

In the simulation part, 802.11p standard and VTV urban canyon (VTV-UC) channel environment is applied. VTV-UC is a channel scenario measured in Edgewood avenue in downtown Atlanta, where urban canyon characteristics exist. The vehicles' speed in VTV-UC scenario is around 32-48km/h and the Doppler frequency is around 400-500HZ. The number of paths in VTV-UC environment is 12 [14].

Fig.2 illustrates an NMSE performance comparison between M-TFRI and the conventional LS channel estimation schemes in a QPSK modulated OFDM-IM system. Since the proposed M-TFRI scheme requires indices detection before channel

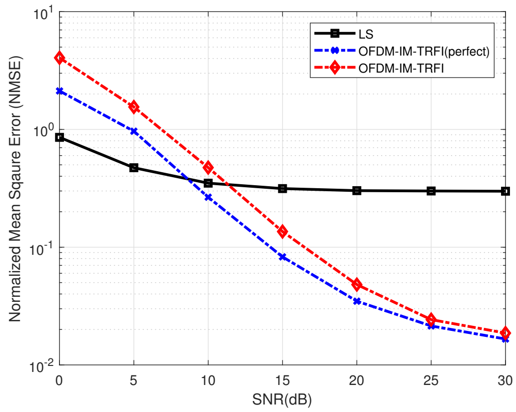

Fig. 2. NMSE performance for M-TFRI and LS scheme with OFDM-IM in VTV-UC environment

estimation, which may cause performance degradation due to detection errors, we added an M-TFRI result, which assumes perfect indices detection, as a benchmark. According to Fig.2, it is shown that compared with the conventional scheme, the proposed M-TFRI can effectively improve the channel estimation performance of OFDM-IM in vehicular channel environments. Moreover, as the SNR increases, the gap between the performance of practical M-TFRI and ideal M-TFRI becomes smaller. At SNR=30dB, both schemes perform almost the same.

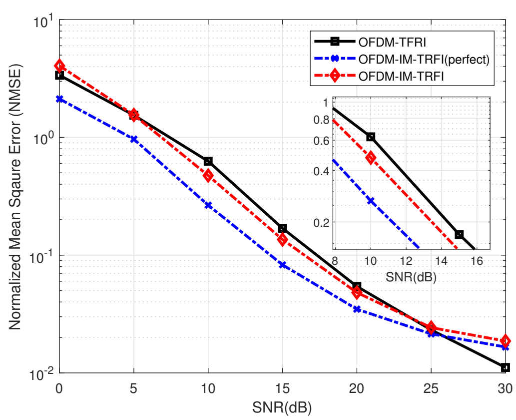

Fig. 3. NMSE performance for M-TFRI and TFRI scheme with OFDM-IM and OFDM in VTV-UC environment

Fig.3 illustrates an NMSE performance comparison between the proposed M-TFRI in an OFDM-IM system and the conventional TFRI in an OFDM system. It is shown that the ideal M-TFRI with all indices correctly detected significantly outperforms the OFDM TFRI in terms of NMSE. However, due to indices detection errors, the practical M-TFRI suffers performance degradation. Nevertheless, the M-TFRI still achieves a similar performance as that of the conventional OFDM TFRI. According to Fig.3, in the SNR range of 5dB to 25dB, the proposed M-TFRI outperforms the conventional TFRI. At low and high SNRs (0dB to 5dB and 25dB to 30dB), the conventional OFDM TFRI achieves better NMSE performance than that of our proposed OFDM-IM M-TFRI scheme.

V. Conclusion

In this article, the channel estimation problem in vehicular communications for 802.11p standard is investigated. Different from the existing works, this paper have studied the estimation scheme for channels with double dispersive nature in OFDM-IM systems. Based on the structure of OFDM-IM and indices detection method, the proposed modified TFRI, M-TFRI scheme utilizes LS estimates and preambles to make up for the lack of channel information caused by the inactive subcarriers. Simulation results show that the proposed M-TFRI scheme achieves similar estimation results as that of the OFDM TFRI scheme, and significant better performance than that of the conventional estimation scheme in OFDM-IM systems.

References

[1] D. Jiang and L. Delgrossi, "Ieee 802.11 p: Towards an international standard for wireless access in vehicular environments," in *VTC Spring 2008-IEEE vehicular technology conference*. IEEE, 2008, pp. 2036–2040.

[2] E. Başar, Ü. Aygölü, E. Panayırcı, and H. V. Poor, "Orthogonal frequency division multiplexing with index modulation," *IEEE Transactions on signal processing*, vol. 61, no. 22, pp. 5536–5549, 2013.

[3] S.-Y. Zhang and H. Zheng, "Papr reduction in ofdm-im using dither signal sets," in *2022 International Conference on Computer Engineering and Artificial Intelligence (ICCEAI)*. IEEE, 2022, pp. 275–278.

[4] Y. Acar, S. A. Çolak, and E. BAŞAR, "Channel estimation for ofdm-im systems," *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 27, no. 3, pp. 1908–1921, 2019.

[5] S. S. Mi, A. Siriwanitpong, P. Boonsrimuang, and P. Boonsrimuang, "Channel estimation for enhanced subcarrier index modulation ofdm using zadoff-chu sequence pilot in nonlinear channel," in *2022 19th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*. IEEE, 2022, pp. 1–4.

[6] A. Kaplan, G. K. Kurt, İ. Altunbaş, U. Altun, F. A. Onaty, and D. Küçükyavuzy, "Impact of channel estimation on the performance of ofdm-im with barrage jamming," in *2020 28th Signal Processing and Communications Applications Conference (SIU)*. IEEE, 2020, pp. 1–4.

[7] J. A. Fernandez, K. Borries, L. Cheng, B. V. Kumar, D. D. Stancil, and F. Bai, "Performance of the 802.11 p physical layer in vehicle-to-vehicle environments," *IEEE transactions on vehicular technology*, vol. 61, no. 1, pp. 3–14, 2011.

[8] Z. Zhao, X. Cheng, M. Wen, B. Jiao, and C.-X. Wang, "Channel estimation schemes for ieee 802.11 p standard," *IEEE intelligent transportation systems magazine*, vol. 5, no. 4, pp. 38–49, 2013.

[9] T. Wang, A. Hussain, Y. Cao, and S. Gulomjon, "An improved channel estimation technique for ieee 802.11 p standard in vehicular communications," *Sensors*, vol. 19, no. 1, p. 98, 2018.

[10] G. Naik, B. Choudhury, and J.-M. Park, "Ieee 802.11 bd & 5g nr v2x: Evolution of radio access technologies for v2x communications," *IEEE access*, vol. 7, pp. 70 169–70 184, 2019.

[11] P. Yang, Y. Xiao, Y. L. Guan, M. Di Renzo, S. Li, and L. Hanzo, "Multi-domain index modulation for vehicular communications: A survey," *IEEE Vehicular Technology Magazine*, 2018.

[12] A. K. Gizzini, M. Chafii, A. Nimr, and G. Fettweis, "Joint trfi and deep learning for vehicular channel estimation," in *2020 IEEE Globecom Workshops (GC Wkshps*. IEEE, 2020, pp. 1–6.

[13] ——, "Deep learning based channel estimation schemes for ieee 802.11 p standard," *IEEE Access*, vol. 8, pp. 113 751–113 765, 2020.

[14] C.-X. Wang, X. Cheng, and D. I. Laurenson, "Vehicle-to-vehicle channel modeling and measurements: recent advances and future challenges," *IEEE communications magazine*, vol. 47, no. 11, pp. 96–103, 2009.