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Review Article

Doppler Shift Compensation Schemes in VANETs

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Over the last decade vehicle-to-vehicle (V2V) communication has received a lot of attention as it is a crucial issue in intravehicle communication as well as in Intelligent Transportation System (ITS). In ITS the focus is placed on integration of communication between mobile and fixed infrastructure to execute road safety as well as nonsafety information dissemination. The safety application such as emergence alerts lays emphasis on low-latency packet delivery rate (PDR), whereas multimedia and infotainment call for high data rates at low bit error rate (BER). The nonsafety information includes multimedia streaming for traffic information and infotainment applications such as playing audio content, utilizing navigation for driving, and accessing Internet. A lot of vehicular ad hoc network (VANET) research has focused on specific areas including channel multiplexing, antenna diversity, and Doppler shift compensation schemes in an attempt to optimize BER performance. Despite this effort few surveys have been conducted to highlight the state-of-the-art collection on Doppler shift compensation schemes. Driven by this cause we survey some of the recent research activities in Doppler shift compensation schemes and highlight challenges and solutions as a stock-taking exercise. Moreover, we present open issues to be further investigated in order to address the challenges of Doppler shift in VANETs.

1. Introduction

Vehicular ad hoc networks (VANETs) have revolutionized road transport as the desire for improved safety through accident avoidance and nonsafety information dissemination gathers momentum. Over the recent years, wireless communication research community consisting of academia, industry, and government agencies has placed emphasis on the development of protocols addressing vehicular communications [1]. The allocation of 75 MHz frequency band dedicated to vehicular communication by US Federal Communication Commission (FCC) was a significant contribution in support of this initiative [2]. Furthermore, this campaign has seen major development of amendments to the IEEE 802.11 wireless standard to address specific needs such as bandwidth limitation problems (IEEE 802.11a) [3, 4], adaptation to high-mobility conditions (IEEE 802.11p) [5], and wireless access in vehicular environment (WAVE-IEEE 1609.x) [6]. IEEE 802.11p and IEEE 1609.x, often lamped together as IEEE 802.11p/WAVE, are the enabling technology geared towards the support of Intelligent Transportation System (ITS).

Recent researches have highlighted significant challenges to VANET deployment [7]. These challenges include inadequate bandwidth to meet the conditions imposed by the safety and nonsafety applications [8], low packet delivery rate (PDR) arising from congestion in dense traffic networks [9], and high BER due to Doppler shift degradation caused by high node mobility [10]. Whereas the first two challenges have adequately been addressed by introducing the cyclic prefix (CP) and enhanced distributed channel access (EDCA) mechanism, Doppler shift lacks such direct elimination methods in high-mobility networks [11].

The particular problem arises when the receiver is moving towards the source; the received frequency is increased, whereas if it is moving away from the source the received frequency is decreased [12, 13]. This effect, called Doppler Effect, causes a frequency offset with the local oscillator, the Doppler shift, and it is one of the major sources of increased BER experienced in a vehicular channel. This phenomenon is to be found in OFDM systems where Doppler shift breaks the orthogonality of the subcarriers by causing frequency dispersion across adjacent subcarriers leading to intercarrier interference (ICI) which significantly degrades the received signal [14]. In order to reduce this degradation, efforts have been made by the research community to design compensation schemes to reduce Doppler shift. Most of the compensation schemes address the time and frequency characteristics of Doppler shift.

Time variation in the Doppler frequency domain is characterized by the scattering function, $S(\tau, \nu)$, a function of delay dispersion τ, and node velocity ν [15]. $S(\tau, \nu)$ is obtained by Fourier transform (FT) of the channel impulse response (CIR) on the time (t) variable. The width of this function in the Doppler variable is the Doppler spread $f_{D\max}$ and measures the amount by which the channel spreads a transmitted tone in frequency. The Doppler spread is related to the node velocity as $f_{D\max} = (\nu/c) \cdot f_c$, where ν is the speed of the mobile, c is the speed of light, and f_c is the carrier frequency. The fact that $S(\tau, \nu)$ depends on τ implies that each path of the CIR has an associated scattering function which can vary in shape and Doppler spread. Furthermore, urban, suburban, and rural scenarios provide different propagation environments characterized by different scattering functions [16]. In [16], Doppler spectrum variation due to internal oscillator clock was analyzed in a measurement campaign with estimation and removal of the clock drift and the corresponding Doppler offset. This campaign demonstrated the variation of the Doppler spectrum dependence on typical VANET environmental scenarios presented in built-up, tunnel, and forest set-up.

Although significant grounds have been covered by the research community in the design of Doppler shift compensation schemes, few surveys have appeared in the literature highlighting the state-of-the-art collection.

In this paper, a survey of Doppler shift compensation schemes recently proposed in literature is undertaken and open research issues are discussed on the future of Doppler shift compensation schemes in VANETs.

The main contribution in this paper is twofold. Firstly, the paper creates a single platform for state-of-the-art schemes in large numbers focused on Doppler shift compensations. Secondly, a new paradigm in conducting surveys is presented where challenges, solutions, and research issues are packaged for individual schemes for the benefit of researchers and technology auditors. To the best of our knowledge, no other survey on Doppler shift compensation schemes has been conducted and presented in such a compact way.

The rest of the paper is arranged as follows. Section 2 is the main compensation schemes and Section 3 is the open research issues and conclusion.

2. Doppler Shift Compensation Schemes

This section presents taxonomy of the compensation schemes designed based on core space, time, and frequency domains (Figure 1). Frequency domain compensation schemes are based on pilot carriers strategically positioned in either block-type or comb-type configurations. They include modulation and coding-based and interference cancellation-based schemes. This is in contrast with time domain compensation schemes which rely on autocorrelation function of the channel impulse response (CIR) to extract the signal compression/expansion characteristics for Doppler estimation. They include time-partitioning-based and autocorrelation-based schemes. The space domain compensation schemes on the other hand take on either approach with dependence on high diversity orders to cancel ICI in high-mobility scenarios. They include diversity combining-based and beamforming-based schemes. This modular approach makes it easy for independent yet collaborative research groups to mutually exist and maximize the outputs.

Based on Figure 1, challenges, solutions, and open research issues are then discussed in the following subsections.

2.1. Frequency Domain Compensation Techniques

2.1.1. Modulation and Coding-Based Schemes. VANETs are prone to Doppler shift which breaks the orthogonality of the subcarriers causing frequency dispersion across adjacent subcarriers. This frequency dispersion causes intercarrier interference (ICI) leading to received signal degradation. Modulation and coding schemes have been proposed to compensate for Doppler shift in VANETs.

A method described by Albarazi et al. [10] investigated the impact of Doppler shift on the quality of the transmitted/received signal by building a channel model that combined AWGN and Rayleigh channel fading to emulate a realistic wireless channel experiencing Doppler shift. The authors observed that Doppler shift causes signal degradation in a sense that an increase in Doppler shift increases BER performance in a system. They further proposed a Doppler frequency compensation scheme based on an adaptive algorithm that adjusts the modulation scheme according to the Doppler shift value present. The numerical results revealed that QAM schemes are more sensitive to Doppler shift than PSK schemes with 64-QAM attracting 9 dB higher BER than BPSK at Doppler shift of 300 Hz. This result is explained by the fact that QAM schemes constitute higher bit constellation corresponding to a proportionately higher BER. Similarly, lower coding rate was demonstrated to present a better BER performance [17]. By combining the two features BPSK with 1/2 coding provides the highest robustness to Doppler shift. These findings were in agreement with the results by Sur and Bera [12] and Feukeu et al. [18].

Sur and Bera [12] proposed a Doppler shift compensation scheme based on VBLAST MIMO-OFDM in high-mobility conditions. The idea was to analyze BER performance of the system in high-mobility conditions under different modulation schemes. Simulation results revealed that at 300 Hz Doppler frequency BPSK outperformed 16-QAM by 13 dB and QPSK by 6 dB.

On their part, Feukeu et al. [18] investigated Doppler shift compensation by proposing a scheme called Automatic Doppler Shift Adaptation (ADSA) based on a novel Modulation Code Scheme (MCS) adaptation technique that compared BER performance of PSK and QAM modulation schemes. In further investigation, the authors proposed Direct Development Method (DDM) strategy [19] and

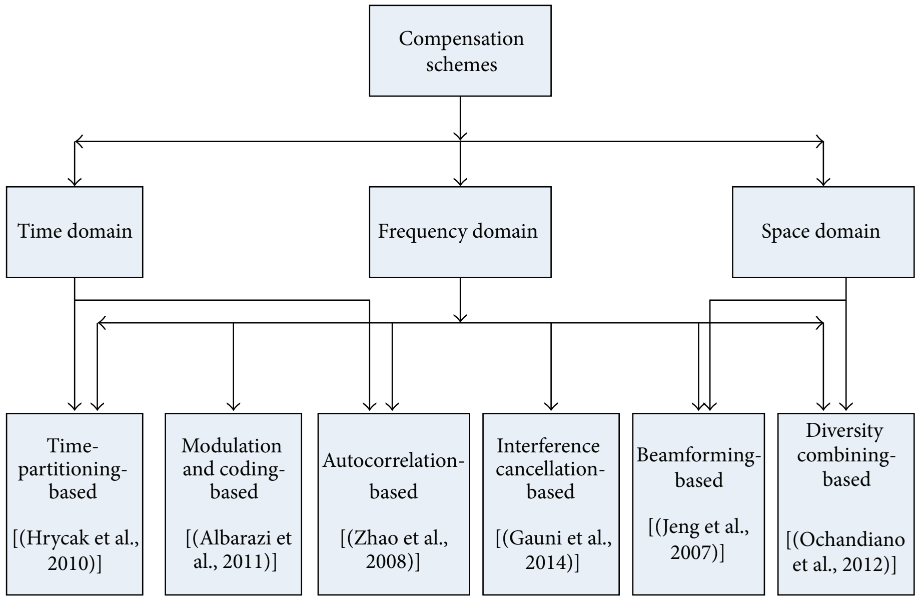

Figure 1: Taxonomy diagram for Doppler shift compensation schemes.

decryption of the effect of Doppler shift impact [20] scheme. The idea was to combat Doppler Effect in vehicular networks using an adaptive modulation scheme. Simulation results revealed that the adaptive scheme based on BPSK, QPSK, 16-QAM, and 64-QAM outperforms the fixed BPSK rate 1/2 in BER which has been previously regarded as the most robust modulation scheme to Doppler shift [17].

However, despite exemplary performance of the scheme by Albarazi et al., modulation and coding-based schemes require a full duplex channel to synchronize the receiver to the transmitter for the algorithm to run, a condition that imposes extra spectral constraints on the already spectrally constrained vehicular channel. Secondly, numerical results indicated that Albarazi's scheme achieves the error-free velocity threshold at 72 km/h which is much lower than the typical vehicular velocities particularly in highway and rural scenarios [21].

Consequently, modulation and coding-based schemes require further research to address the problems of efficient closed form operation and error-free velocity enhancement before full scale deployment can be realized in VANETs.

2.1.2. Interference Cancellation-Based Schemes. In OFDM systems, low levels of intercarrier interference (ICI) can be eliminated by prefixing each OFDM symbol by a cyclic prefix (CP) [22]. However, higher values, as occurs in high node mobility due to Doppler shift, make signal restoration difficult hence the need for interference cancellation schemes to reduce Doppler shift effects.

Tsai and Wu [23] proposed a compensation scheme for carrier frequency offset (CFO) based on pilot tone-aided scheme with ICI elimination (PTA-IE). The idea was to reduce Doppler shift which caused such CFOs using a low complexity iterative scheme without the need of FFT or IFFT. The numerical findings revealed that at 25 dB SNR the first iteration was 27 dB, the second iteration was 10 dB, and the third iteration was 0 dB in Mean Square Error (MSE) away from the ideal (pilot tone-aided with weighting) thus achieving both improved Doppler shift compensation and low system complexity by avoiding channel matrix inversion in just three iterations.

Applying the same iteration techniques Hong and Thibault [24] proposed a Doppler shift compensation scheme based on a novel iterative channel estimation and ICI cancellation scheme that used decision feedback to estimate both channel gain and the ICI gain without requiring knowledge of the channel statistics. The idea was to iteratively estimate the channel gain with decision feedback from the previous iteration as an alternative to the IDFT-filtering method. Simulation results indicated that five iterations effectively provide a good tradeoff between complexity and performance, while 5-tap equalization and ICI cancellation can provide the best tradeoff between performance and complexity. In terms of BER performance at 30 dB SNR the 5th iteration achieves BER of 5×10^{-3}, way above the 10^{-3} threshold for error-free threshold, therefore providing robust Doppler shift compensation performance under a wide range of fading conditions similar to the approach implemented by Qian et al. [25] and Ma et al. [26]. Hua et al. [27] achieved the result using the level crossing rate estimation error analysis.

A different Doppler compensation scheme based on ICI cancellation technique called general phase rotated conjugate cancellation (PRCC) scheme was proposed by Wang and Huang [28] which relied on prerotated transmission signal. The idea was to compensate for high Doppler shift via ICI self-cancellation mechanism using an artificial phase prerotation on the signal to be transmitted.

Numerical results revealed that at 30 dB SNR PRCC scheme outperformed the conjugate cancellation (CC) scheme for two-ray model by 5 dB in BER, thus confirming that the scheme can compensate for Doppler shift more efficiently.

These conjugate schemes were also investigated by Yeh et al. [29], where the authors deployed a two-path OFDM algorithm employing regular and conjugate transmission to form a conjugate ICI cancellation scheme that outperformed the conventional OFDM cancellation schemes resulting in enhanced Doppler shift compensation.

Similarly, adjacent conjugate symbol repetition (ACSR) and symmetric conjugate symbol repetition (SCSR) investigated by Sathananthan et al. [30] achieved ICI self-cancellation through removal of phase error due to frequency offset to reverse the effects of Doppler shift.

Equally related approach is progressive parallel interference canceller (PPIC) and parallel interference canceller (PIC) proposed by Gauni et al. [31] which eliminated the problem of interantenna interference (IAI) in the space domain and interchannel interference (ICI) in the frequency domain simultaneously and proved effective in Doppler shift compensation performance.

Other related schemes in this domain include those which cancel ICI while reducing hardware consumption [32] and those which rely on reduction of the number of subcarriers to cancel ICI [33]. Wang et al. [34] applied the columnwise complementary codes to the original OFDM-based physical layer design to mitigate the Doppler shift.

While posting superior Doppler shift compensation performance compared to other schemes, iterative equalization schemes usually suffer from high computation complexity, albeit at varying degrees, thus raising practical application challenges such as need for large silicon area for implementation and high battery power for operation. In view of this dilemma, Namboondiri et al. [35] proposed a suboptimal successive interference cancellation- (SIC-) based algorithm which leveraged on the soft feedback symbol estimate to remove the intercarrier interference from the received data and achieved Doppler shift compensation with lower computation complexity.

Borrowing heavily from this approach are Raafat et al. [36] and Seo et al. [37] who realized higher Doppler shift compensation performance through successive interference cancellation and Zheng et al. [38] who extended the technique to dynamic canonical communication networks to arrive at a dynamic channel adaptation in time-varying radio environment.

From the introduced schemes in this domain, the proposed models cited in the literature conform to the standard VANET channel models such as in [15] and hence they are compatible with high likelihood of successful deployment in VANETs. However, the problem with the iterative schemes, though noncomplex in implementation, is the fact that they score poorly in BER performance and fail to achieve the VANET error-free velocity under high Doppler shifts. Further schemes, therefore, need to be designed to increase error-free velocity thresholds in the noncomplex ICI cancellation schemes to leverage the benefits of simple detection in VANETs.

2.2. Time Domain Compensation Schemes

2.2.1. Autocorrelation-Based Schemes. Channel estimates obtained from frequency response are significantly affected by noise and ICI leading to preference of channel estimates in time domain to improve the performance of Doppler spread estimation [39–41].

Mirza et al. [42] proposed a method for estimating the maximum Doppler shift for MIMO-OFDM systems based on autocorrelation function (ACF) in a Rayleigh fading channel. The aim was to estimate frequency shift that induces intercarrier interference (ICI) between adjacent OFDM subcarriers in time domain.

Numerical results revealed that the scheme yields 9 dB improvement in BER performance at 10 dB SNR compared to no Doppler estimation in a 2×2 MIMO system at the vehicular velocity of 60 MPH (96 km/h) under Minimum Mean Square Error (MMSE) detection scheme. These results are outperformed by Alamouti/MRC scheme which posts a performance gain of 20 dB more than the system without Doppler estimation at 3 dB SNR under similar mobility conditions.

Using a slightly modified approach from the scheme in [42], Tian et al. [43] proposed a method for adaptive Doppler frequency shift estimation based on autocorrelation function of the time domain channel estimation. The purpose was to achieve a wide estimation range.

Numerical results indicate that performance of the proposed method at 5 dB SNR maps 1 : 1 with analytical values over a wide velocity range of more than 500 km/h, while fixed-length estimates over the same range fluctuated with a maximum deviation of 200 Hz.

Several other schemes fall within this time convolution framework. They include analysis of the impact of moving scatterers on Doppler spread using autocorrelation function (ACF) and power spectral density (PSD), BER evaluation over transmit-correlated MIMO Rayleigh flat-fading channels based on MMSE criterion, and Doppler spread estimation for low mobility OFDM systems in frequency selective Rayleigh fading channels [44–47].

Accordingly, the time correlation schemes are simplistic in implementation as they avoid estimation pilot sequences but their performance based on equally simple linear detection algorithms (ZF and MMSE) is low. The scheme by Mirza et al., for example, fails to achieve the acceptable BER of 10^{-3} for error-free decoding recommended in wireless networks even at 20 dB SNR. To address this shortcoming Alamouti/MRC scheme becomes a natural choice but because of its high receiver complexity implementation can be challenging.

Further research to extend performance range of ZF and MMSE algorithms to capture the VANET velocity range is necessary to provide a more practical implementation solution.

2.2.2. Time-Partitioning-Based Schemes. Rapidly time-varying channels with large Doppler spread will introduce ICI in frequency domain. Many of the popular algorithms assume a linear model with block diagonal structure for the channel matrix, neglecting off-diagonal elements. This model fails to capture the effect of ICI sufficiently for larger Doppler and delay spreads. Estimation of time variant channel impulse and pilot-based method on the other hand require high amount of computational cost. In response to these challenges time-partition-based schemes have been proposed.

These schemes factor Doppler shift degradation into time-dispersive and frequency-dispersive components and provide block-structured algorithms to deliver solutions block-by-block. Belonging to this group is a novel time domain method which relies on the use of multiple directional receive antennas proposed by Klenner and Kammeyer [48] to deliver high diversity gain that alleviates channel estimation. The method achieves reduction in Doppler shift degradation by decomposing large Doppler spread into sectors and applying directional antennas to each sector space. With the sectorized spatial components a coherent receiver will exploit this structure to deliver high diversity gain in time domain which will alleviate channel estimation with eventual reduction in Doppler shift degradation. Zero Padding technique as a time domain technique on the other hand was implemented by Li et al. [49] to achieve nonuniform Doppler compensation and high-resolution uniform Doppler compensation by exploiting block-by-block processing in underwater acoustic channel. The method was further applied by the same authors [50] to confirm that OFDM is a viable option for high-rate communications over wideband underwater acoustic (UWA) channels with nonuniform Doppler shifts.

Contrary to the preceding techniques, frequency-dispersive component in a time-partition scheme can also be exploited to yield a solution to Doppler shift. Zhang and Liu [51] proposed a scheme to solve the problem of Doppler shift in the presence of time-selective fading over Rayleigh fading channels for MIMO-OFDM system and obtained improved performance by phase noise suppression based on MMSE criterion. In a related scheme, a time-varying channel modeling and estimation method based on the Discrete Evolutionary Transform to obtain a complete characterization of MIMO-OFDM channels in high-mobility conditions was proposed by Akan et al. [52], where the time-varying channel was modeled as a time frequency function. The idea was to estimate the channel parameters from the time frequency spreading function. Numerical results revealed that at 30 dB SNR the time frequency based scheme with 32 pilot carriers outperformed the conventional system by 24 dB in BER for a 2×2 MIMO-OFDM system to demonstrate that the authors' time-frequency-based method is robust to large Doppler frequency variations. Similar doubly selective methods were proposed by Hrycak et al. [53], Cano et al. [54], and Fang et al. [55] who achieved better BER performance by use of soft MMSE block equalizer (BE) which exploits banded structure of the frequency domain channel matrix to achieve compensation in high Doppler spreads. Using the same approach are Schniter [56] and Hrycak and Matz [57] who obtained excellent performance including significant Doppler diversity in conjunction with channel coding by basing operation on time domain, while Parrish et al. [58] obtained similar results with time-synchronization protocols.

In a network layer-based scheme Kotzsch and Fettweis [59] proposed a method for Doppler shift compensation based on asynchronous spatially multiplexed transmission. The idea was to factorize the model and identify the most effective factor for Doppler shift compensation in relay networks. The authors found that, among intercarrier interference (ICI), intersymbol interference (ISI), and interblock interference (IBI), the last two constituting timing errors were identified as the main course of performance degradation. In related work Kotzsch et al. [60] and Lin [61] obtained improved Doppler shift compensation by suppressing multipath interference caused by frequency-selective fading and intercarrier interference resulting from data subcarriers.

In [62], the authors proposed an efficient Doppler shift compensation scheme based on ICI suppression technique with less noise enhancement for multicarrier equalization by applying a parallel canceling scheme via frequency domain equalization techniques and obtained enhanced Doppler shift compensation results.

Resolving Doppler shift degradation into time-dispersive and frequency-dispersive components promises a simpler solution to Doppler shift compensation. Considering that a number of algorithms have already been developed in time domain with high performance such as use of cyclic prefix (CP), OFDM symbol size, signal correlation, and diversity schemes which do not require complex equalization mechanisms, Doppler shift compensation via time-partition-based option can be easier and cheaper. Moreover, detection algorithms implemented in the time domain schemes promise even better results since their characterization is abundant in the literature. Future research, therefore, could target this approach as compared to the conventional frequency domain approach to achieve enhanced detection performance in VANETs.

2.3. Space Domain Compensation Schemes

2.3.1. Diversity Combining-Based Schemes. Scenarios employing large OFDM symbol period face challenges of dealing with ICI under high-mobility conditions although it makes the system more robust to intersymbol interference (ISI). The more reduced subcarrier spacing makes the system more sensitive to frequency offsets and hence becomes more vulnerable even under low Doppler shift. Under this condition, many of the existing ICI reduction techniques cannot be applied.

In view of the above problem, Ochandiano et al. [63] proposed a Doppler shift compensation scheme based on a novel factor graph (FG) approach. Essentially, FGs represent graphically the factorization of a function based on Forney observation model [64] upon which various schemes such as progressive parallel ICI cancellation have been proposed [65]. The FG scheme has been shown to be a good alternative to solve complex interference problems by exploiting the output of a whitened matched filter for computing the branch metrics of the Viterbi Algorithm. The idea was to provide high diversity orders to cancel ICI in high-mobility scenarios by exploiting frequency diversity introduced in the received signal by the ICI in the OFDM symbol. Simulation results revealed that the diversity gain allowed high speed joint detection and decoding to outperform existing schemes.

In maintaining diversity approach, the effect of Doppler spread in a time variant mobile radio channel on the performance of QAM and BPSK OFDM systems was evaluated by Wang et al. [66] using truncated Gram-Charlier expansion of the ICI bivariate probability density function and obtained BER characterization with reduced computational complexity.

Simulation results indicated that the ICI joint moments not only depend on Doppler frequency and the number of subcarriers but also depend on the correlation structure among the subcarriers.

Relying further on diversity, Qiao et al. [67] proposed a method for Doppler shift compensation in underwater acoustic (UWA) communication called fast frequency domain resampling (FFDR) based on frequency diversity. The idea was to maintain orthogonality among the OFDM subcarriers under water in the presence of Doppler shift. Simulation results indicated that the Doppler shifted signal can be timely tracked and efficiently compensated in agreement with the schemes proposed by Zorita and Stojanovic [68] and Roman et al. [69].

In their work, Zhang et al. [70] proposed a Doppler shift compensation scheme in relay networks which considered both the existence of oscillator instability frequency offsets and Doppler shifts based on diversity schemes. The idea was to eliminate Doppler shift using diversity schemes and solve oscillator instability CFOs by other means. Simulation results revealed that diversity schemes sufficiently compensated Doppler shifts, while the oscillator instability CFOs were eliminated at the destination to enhance the overall performance.

In furtherance of Doppler shift compensation in relay networks, Song et al. [71] investigated Doppler shift compensation using the analytical performance of the average BER in MMSE-based spatial multiplexing MIMO relaying systems. Applying closed form expressions for BER performance and through Monte Carlo simulations, the authors confirmed that analytical work accurately predicted the numerical performance of the compensation algorithm. The authors extended their work with a new design strategy for optimizing the relay amplifying matrix [72] to obtain better results.

On the same note, Wang et al. [73] proposed space-frequency codes (SFCs) constructions for cooperative relay networks with multiple CFOs for frequency asynchronous cooperative communications and achieved full cooperative diversity with only linear receivers which significantly enhanced Doppler shift compensation.

Schemes based on diversity techniques suggest ISI/ICI tradeoff in the implementation of Doppler shift compensation schemes. The large OFDM symbol duration serves to eliminate ISI but simultaneously increases sensitivity to ICI over rapid time-varying channels. The optimum ratio has not been evaluated by the schemes which have investigated compensation algorithms in this domain. Research opportunities, therefore, do exist to determine the optimum ratios for efficient modeling of Doppler shift compensation schemes exploiting diversity.

2.3.2. Beamforming-Based Schemes. Due to users' mobility, the Doppler shift can cause the estimation error of the direction of arrivals (DOA) in antenna systems and increase BER by degrading beamforming and consequently reducing the overall system performance.

Jeng et al. [74] proposed a Doppler shift compensation scheme in smart antenna systems based on spatial signature to estimate Doppler shift. The idea was to estimate and compensate for Doppler shift and have the DOAs of received signals restored to support correct radiation pattern in beamforming.

Simulation results revealed that the proposed method can utilize the spatial signature to estimate the closest frequency shift caused by Doppler Effect and compensate the same in line with the scheme proposed by Islam and Adam [75].

Oumar et al. [76] on their part proposed angle of arrival (AOA) estimation using the Multiple Signal Classification (MUSIC) and estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) algorithms. The idea was to compare MUSIC with ESPRIT in Doppler shift compensation performance. Simulation results indicated that MUSIC algorithm is more accurate and stable compared to ESPRIT algorithm.

Similarly, Khmou et al. [77] investigated Doppler shift compensation scheme based on DOA estimation of noise-corrupted narrowband signals. The motivation was to compare various algorithms utilizing different AOA at given SNR.

Simulation results showed that, in high-level noise, the minimum norm algorithm performs better, while MUSIC, propagator, and partial covariance matrix method performed better in low-noise conditions.

In an effort to enhance smart antenna performance in reducing Doppler shift degradation, Shrestha et al. [78] proposed a scheme based on a complex mobile network such as railroad wireless communication system. The idea was to analyze the selection of a DOA estimation algorithm which provides the maximum efficiency when deployed in the system.

Simulation results revealed that MUSIC is the more effective option to use for high velocity sources and poor channel conditions, same results as reported by Vesa [79], Sawada et al. [80], and Singla and Saxena [81].

In multiuser OFDM, Space Division Multiple Access (SDMA) utilizes information of users' location to derive the user's signal and suppress the undesired interference using the smart antenna system, a process called beamforming. Beamforming is built on the assumption that the time variation over the OFDM symbol is constant and the angle of arrival (AOA) is also constant. In realistic situations, rapid movement of the receiver causes rapid variation of AOA, thus inhibiting correct pattern generation. The current algorithms deliver optimum compensation values but increased AOA variation as is expected in high speed space ships; more versatile algorithms will have to be investigated to enhance detection.

Table 1: Summary of Doppler shift compensation schemes performance.

Method	Main characteristics	Advantages	Drawbacks	Validity
		Frequency domain compensation schemes		
Modulation and coding-based schemes	Based on pilot carriers and training sequences. Evaluated by matrix inversion and compensated by variable modulation and coding schemes [10–21]	Applicable adaptive schemes with large performance range. Low complexity system through IFFT/FFT implementation	Low BER performance at high bit constellation and large computational data from matrix inversion	Adaptive MCS guarantee VANET performance
Interference cancellation-based schemes	Based on pilot-aided iterative equalization schemes that exclude IFFT/FFT operation [22–38]	Improved Doppler shift (DS) compensation and low computational complexity by avoiding matrix inversion	Requiring large processing area and power to address iterative operation	Low BER limits application in high mobility VANETs
		Time domain compensation schemes		
Autocorrelation-based schemes	Based on channel autocorrelation function (ACF) to extract received signal compression/expansion as a measure of Doppler spread [39–47]	Simplistic in implementation by avoiding pilot sequences	Low BER performance under linear detection algorithms	Unattractive in VANET application in linear detection schemes
Time-partitioning-based schemes	Factor DS degradation into time- and frequency-dispersive components and providing block structured algorithms to deliver solutions block-by-block [48–62]	Achieving high diversity gain resulting in DS reduction with high BER performance	Decision on the type of algorithm imposes extra complexity	A window for choice between the blocks supports VANET application
		Space domain compensation schemes		
Diversity combining-based schemes	Providing high diversity orders to cancel ICI in high mobility scenarios. The large OFDM symbol duration eliminates ISI but simultaneously increases sensitivity to ICI [63–73].	High BER performance even under oscillator instability frequency offsets and DS	Challenges of ICI/ISI tradeoff constrain model design	Optimum ICI/ISI tradeoff will guarantee efficient application in VANETs
Beamforming-based schemes	BER performance based on spatial dimension. Accuracy in angle of arrival (AOA) is key to optimum beamforming [74–81].	Beamforming increases directional gain with increased BER performance	Rapid variation in AOA undermines BER performance	Efficient application in VANETs will depend on successful tracking of AOA

3. Conclusion and Open Research Issues

In summary, a survey of Doppler shift compensation schemes in high-mobility wireless networks has been undertaken based on a new classification comprising six different schemes as illustrated in the taxonomy. Most of the presented schemes yielded good performance results but may not be directly implementable in their current form because of pending issues. For example, it is proved that techniques based on modulation and coding schemes deliver good results in terms of BER performance but their practical implementation causes new challenges such as provision of extra spectral requirements for closed form operation. In order to be implemented, such schemes call for further research to address the new challenges. Secondly, some suggestions have been made on the direction of future research in some individual schemes but it largely remains with the research community to consider adopting the research philosophy based on the presented classification of the schemes. This approach can provide a rapid comparative performance among the research groups to fast-track outputs by identifying and focusing on specific schemes for maximum returns on research investments.

In perspective, the emerging open research issues to optimize Doppler shift compensation in VANETs as discerned in the survey are finally presented:

(i) Modulation and coding-based schemes require further research to address the problems of efficient closed form operation and error-free velocity enhancement before full scale deployment can be realized in VANETs.
This problem will be addressed by investigating algorithms which optimize spectral resources to facilitate efficient closed form operation and enhancement of error-free velocity threshold through improvement of BER at high velocities.

(ii) Time correlation-based schemes implement noncomplex linear decoding algorithms but the problems with this scheme include the low performance in terms of BER and the resultant low error-free velocity threshold.

The solution lies in investigation of decoding algorithms capable of extending detection velocity range based on the BER limits set in the literature using the linear decoding algorithms to retain system simplicity.

(iii) Similar to the issues observed in time-partitioning-based schemes above, interference cancellation-based schemes suffer from low BER performance with similar implication of low error-free velocity threshold despite their simplistic advantage.

To address this problem, there is need to design less computationally complex algorithms to optimize the velocity range in the noncomplex ICI cancellation schemes to leverage the benefits of simple detection in VANETs.

(iv) In time-partitioning-based schemes, detection algorithms implemented in the time domain avoid the equalization process, thus simplifying the process to promise better results given that their characterization is also abundant in the literature.

Future research, therefore, could target the same time domain approach as compared to the conventional complex frequency domain approach to enhance Doppler shift compensation in VANETs.

(v) In diversity combining-based schemes, the large OFDM symbol duration serves to eliminate ISI but simultaneously increases sensitivity to ICI over rapid time-varying channels, thus suggesting some kind of ISI/ICI optimization in operation.

The future research in this scheme, therefore, should aim to optimize the ISI/ICI tradeoff in the modeling of Doppler shift compensation schemes.

(vi) In beamforming-based schemes, beamforming is built on the assumption that the time variation over the OFDM symbol is constant and the angle of arrival (AOA) is also constant. In realistic situations, rapid movement of the receiver causes rapid variation of AOA, thus inhibiting correct pattern generation.

Future research should aim to address the rapid variation in spatial signature to strengthen the beamforming algorithms to improve Doppler shift compensation in VANETs.

In conclusion, a summary of the compensation schemes based on BER is presented in Table 1 for performance comparison of the different schemes.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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