Robust Vehicular Communications Using the Fast-Frequency-Hopping-OFDM Technology and the MIMO Spatial Multiplexing

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Abstract

Vehicle to Vehicle communication is one of the more emerging technologies in the 21st century either from the comfortable transportation or safer transportation point of view. Vehicle to Vehicle communication has one crucial factor which is the huge information to be shared among vehicles, such as the position, the road data. In such situation, the accurate information sharing process is the most important factor in order to make the vehicles operating in the most feasible way. This work proposes a more robust vehicle communication system to make the existing vehicle transportation system more efficient. In this paper, we propose a fast frequency hopping orthogonal frequency division multiplexing to mitigate the Doppler spread effect on our previously published clustering benchmark. This benchmark contains both of a clustering weighting factor based stage and a multiparallel processing stage. This is in addition to modify the PHY layer of the existing IEEE 802.11p standard in order to impose Multiple Input Multiple Output) for higher throughput purposes.

The results show a noticeable stability compared to our previously published work. Furthermore, the results are almost exceeds the achieved results from the Lower-ID DCA from both of the speed and communication range.

1. Introduction

Vehicle-to-Vehicle (V2V) communications gain a high attention with the rapid developments of the recent wireless communications especially as an Intelligent Transportation Systems (ITS). It is considered as a strong proposition to achieve the targeted traffic safeness level by transmitting huge information among the vehicles in the Vehicular Ad-hoc Network (VANET). The IEEE 802.11p standard for VANETs has come with opportunities and challenges, which is a wireless network that were deployed in Vehicle to Vehicle (V2V)/ Vehicle to Road Side Unit (V2RSU) [1–5].

Although, the IEEE802.11p uses a 10MHz channel bandwidth and operates at a frequency range between 5.850 and 5.925 GHz to improve the system capacity, VANET still susceptible to multipath propagation effects. This is due to the mobility factor while passing through the network infrastructure. Accordingly, many different propositions have been found in the literature to compensate its lack of reliability under the real-time data distribution. Furthermore, two crucial requirements should be taken into consideration namely the high reliability and the low latency. This is in addition to the communication challenges in terms of either the accuracy or the throughput, which they are caused directly by the multipath fading or the vehicles mobility [6–10]. In order to enhance the Quality of Service (QoS) in wireless communication system, Orthogonal Frequency Division Multiplexing (OFDM) is one of the proposed techniques in the literature. This is true either for the high speed reliable communications or for the low delay time. Furthermore, the Multiband OFDM (MBOFDM) technique shows a very promising robustness in the high dense dispersive channels in addition to the consumed power reduction capability [11–13]. Moreover, the cooperative communication is considered as a solution to overcome the VANET drawbacks such as the transmission delay, the system reliability and the spectral efficiency [14–16]; therefore the Multiple Input

Multiple Output (MIMO) is considered as a solution. Alamouti as a Space Time Block Code (STBC) is considered as one of the diversity gain utilization techniques over MIMO, which is widely tested in the literature from the reliability pint of view under the high data rate communications circumstances [17–19].

In this work and in order to enhance the VANET reachability we will make use of the Long Term Evolution (LTE) mobile systems infrastructure. This kind of combination will cause an extra load burden on the system QoS such as increasing the delay, dealing with a large number of high speed moving vehicles [20]. Therefore, we will propose a PHY layer, which includes of both of multi-parallel processing reclustering technique for the multiband OFDM (MP-RC-MBOFDM) and of Spatial Multiplexing MIMO technology. Thus, the maximum throughput could be achieved and the system latency could be improved.

In the proposed PHY layer, the MP-RC-MBOFDM is consists of two parts; the facilitating part and the enhancing MBOFDM part. The OFDM technique is limited to the use of Fast Frequency Hopping (FFH) as a coding stage, which will result in investigating the BER since each hop can deal with both of different channels and different set of spread signals. Moreover, a clustering criterion is proposed in order to reclustering the huge number of moving vehicles and to enhance the connectivity between the VANET and the LTE [21, 22]. The benefit behind imposing more than one antenna either at the end side of the transmitter or of the receiver is to enhance the QoS from the data rate point of view. That’s why the scope of using the MIMO technology in this work is limited to use the Spatial Multiplexing form of MIMO. In this form, the data rate is increased proportional to the respect of transmit antenna ports [23].

The rest of this paper is organized as follows. Section II details the VANET communications including the V2V based LTE infrastructure and the communications through MIMO systems. The proposed V2V under LTE scenario is presented in section III. Section IV presents the experimental results, analysis and discussion. Finally, the conclusion is drawn in section V.

2. Vanet Communications

2.1 V2V communications based on LTE infrastructure

Figure 1 depicts the vehicles under the clustering topologies communicating to each other making use of the LTE wireless systems infrastructure. Each cluster contains on cluster head and the other vehicles under the control of this cluster head, which they communicate with each other using the IEEE802.11p protocol by a specific neighbor table. In this clustering topology N independent moving vehicles are considered, with different directions and speeds, which they will be grouped into cluster under the responsibility of the cluster Head.

As found in [20], dealing with huge number of moving nodes under the LTE infrastructure could cause of delay penalty that will affect the system latency. This opens a room of improvement and to propose an adaptive clustering method based on an adaptive weighting factor. Furthermore a multi-signal processing is considered as a combination between the MIMO and OFDM techniques to making use of the spatial multiplexing advantages, which will enhance both of the system reliability and the spectral efficiency.

Different clustering were found in the literature and used for enhancing the VANET QoS from different point of views including the link stability, the cost factor and the link quality. The authors in [24] proposed the lowest ID clustering algorithm, where they used the term ID (weighting term) that considered as a crucial term to identify the cluster head. The Mobility Based Metrics for Clustering (MOBIC) clustering method is used to regroup the moving vehicles based on the mobility different variables, which is attained under the cost of the resources efficiency [25]. The distributed and mobility adaptive (DMAC) clustering protocol is another work that regroup the vehicles. It combats the burden load in the communication link. However it is attained under the cost of the communication stability [26].

The literature work opens a new research scope. The proposed PHY layer should contains advantages over the work in the literature and enhances the V2V challenges, opportunities and the applicability that were summarized in some research works such as [2, 27, 28]. Therefore, this work will present a FFHOFDM pre-coder for the multi-signal processing stage as depicted in Fig. 2, as well as to a spatial multiplexing stage at the end of the transceivers ports by using the MIMO technology. Thus, the low complexity overhead and the stability factors could be investigated under this proposition. Figure 2 depicts the block diagram of the proposed PHY, where it shows the multi-signal processing among the clusters' Heads through the LTE infrastructure. Furthermore, the communications among the moving vehicles and their cluster's Head are done through the MIMO technique.

According to IEEE802.11p, the first phase of the PHY layer is the interleaver and the coder where the fed data from the MAC layer into the PHY layer is interleaved and encoded by one of different coding rates. In our case it is limited to the coding rate of 2/3 convolutional encoding. After that, the encoded data will fed into the modulation phase which is limited to the use of two modulation techniques namely; QPSK, and 16-APSK. Then into the OFDM forming phase with a guard interval by making use of N point inverse fast Fourier transform (IFFT). After producing the OFDM signal, it will be transmitted through different antennas at the transmitter side. Furthermore, the whole procedure is reversed at the receiver side to get the bits data. Due to that the communications link performance is affected severely by the radio channel properties; the next subsection will discussed the communications through MIMO channel.

2.2. Communications through MIMO Channel

The communications framework among the moving vehicles and the cluster's head in each cluster is based MIMO communications, which is licensed by the Federal Communications Commission (FCC) in the 5.9 GHz band with a spectrum of 75 MHz under the protocol of Dedicated Short Range Communication (DSRC) [29]. As mentioned earlier, each vehicle adopts OFDM transceiver, which is compatible with the DSRC protocol. Under the V2V communication scenario, multipath propagation is characterizing the link among the moving vehicles which affect the link performance as a result of observing huge number of object in the city area. Therefore, the transmitted signals will be distorted due to different multipath phenomena such as the reflection, diffraction, scattering and shadowing. Thus and in order to make use of the multipath scenario, the spatial multiplexing MIMO technique is proposed. The advantage behind this proposition is to enhance the QoS from the data rate point of view, which is proportional to the number of the transmit antenna and the utilized bandwidth [17, 23]. Let m is the number of antennas at the transmitter end and n represents the number of the antennas at the receiver end, and then the communication link is represented as:

$$[y]_{n\times 1} = \left[\begin{bmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nm} \end{bmatrix} \times [x]_{m\times 1}\right] + [n]_{n\times 1} \text{———(1)}$$

Where in (1), $[h]_{n\times m}$ represent the channel response in a matrix dimension of $n \times m$; m transmit paths which are received from n received paths as described in Fig. 3. $[y]_{n\times 1}$ Represents the received data vector, while the $[x]_{m\times 1}$is the transmitted data vector and the $[n]_{n\times 1}$ is the added noise vector because of the channel phenomena. Therefore and extra phase will be added at the beginning of the receiver that contain a method of regeneration to remove the effect of the channel before processing the received signals [30]. In this work the scope is limited to use either 2×2 or 4×4 MIMO configuration, in addition to use the Zero Forcing (ZF) and the Minimum Mean Squared Error (MMSE) methods at the receiver side.

3. Proposed V2v Under Lte Scenario

This section is divided into three parts. The first part will depict the stages of our proposed the FFH-OFDM work inside the cluster as a processing stage in the V2V PHY layer. The second part will describe the multi-signal processing of the transmitted signal through the $n \times m$MIMO channel. The third part will deal with the proposed reclustering procedure, which is based on the adaptive weighting reclustering factor.

3.1 The MIMO-FFH-OFDM Stage

As a processed data in the PHY layer, the FFH precoder is used reduce the channel effect in order to enhance the system QoS from the BER point of view. The OFDM processing stage is easily done by imposing the N points inverse FFT (IFFT) stage which is represented in the matrix format as $e^{j\left(\frac{2\pi ik}{N}\right)}$ during the transmission stage [31]. Then the transmitted matrix format of the OFDM symbol could be formatted for the transmitted data d, as:

$$\mathbf{S}\left(n\right) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} d\left(i\right) e^{j\left(\frac{2\pi in}{N}\right)}, 0 \leq i, n \leq \left(N-1\right) \text{———(2)}$$

The OFDM symbol matrix format is modified by imposing the hopping criterion as found in [31]:

$$\mathbf{S}_{\mathrm{FFH}}\left(n\right) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} d\left(k\right) e^{j\left(\frac{2\pi n C_{n,i}}{N}\right)}, 0 \leq i, n \leq \left(N-1\right) \text{———(3)}$$

In (3), the hopping criterion is limited to the fixed cyclic criterion to control the design complexity issues and then the $N \times NC_{n,i}$ matrix is defined as in (4). Accordingly, a shuffled representation of the IFFT is attained.

$$C_{n,i} = \begin{bmatrix} 1 & 0 & \dots & 0 \\ & e^{j\frac{2\pi}{N}} & & \vdots \\ & & \ddots & 0 \\ 0 & \dots & 0 & e^{j\frac{2\pi(N-1)}{N}} \end{bmatrix}, 0 \leq i, n \leq (N-1) \text{——} (4)$$

As well the OFDM transmitter is modified accordingly to have the hopping criterion $C_{n,i}$ as shown in Fig. 4.

Moreover and after the FFH-OFDM stage, a MIMO transmitter is added to fit the MIMO channel that is used and described earlier as in Fig. 3 as an $n \times m$ channel response matrix scenario, $[h]_{n\times m}$. At the receiver side a reception block is added before the OFDM receiver to choose the best received signals after the MIMO channel; either ZF stage or an MMSE stage. Furthermore and to check the performance of the proposed MIMO work, a benchmark were proposed and simulated by MATLAB to contain a normal 1×1 communication configuration with a ZF equalization stage at the receiver. In this part, the throughput is the main performance measure that is used to check our proposition. The used transfer time is 0.5 ms for the throughput calculations for each frame.

3.2 The Multi-Signal Processing Stage

The novelty behind using this stage is to deal with the communications' links among the clusters' heads at the same time in parallel as depicted in Fig. 1. In this stage, we are dealing with enhancing the QoS from reducing the transmitted power point of view. Thus, at the end of this stage, a new version of the transmitted OFDM signal will be generated efficiently. This step will enhance the data rate and the speed of communications. This stage will be processed by making use of different Daubechies wavelets types and at different levels. The steps of this algorithm are described as follows:

1. The data acquisition step: it is considered as the pre-processing stage. It deals with formatting the OFDM signals from different cluster head for a maximum of 512 OFDM signals, which they are fed into Daubechies wavelet block with different types and different processing levels. In this stage we used 14 different Daubechies wavelet functions ('db1';'db2';'db3';'db4';'db5';'db7';'db10';'db13';'db20';'db25';'db30';'db35';'db40';'db45') and 8 different decomposition levels.

2. The 1-D Wavelet Decomposition step: In this step wavelet coefficients were computed for all OFDM signals that come from the cluster head for different wavelet types and processing levels.
3. New OFDM signal generation step: This step deals with computing the OFDM signal energy percentage and distribution for both of the approximation and details wavelet components. Storing the most important wavelet components (coefficients) that reserve a high and acceptable percent of signal energy for each OFDM signal separately and adaptively using Zero Embedded Criterion for non-effective coefficients. Then a new OFDM signals are reconstructed using all combinations based on the new wavelet decomposition structure.

The performance of this processing stage is checked based on different performance evaluation methods. This is in order to check the performance of the new generated version of the OFDM signals. These methods are as follows:

1. Ratio Value, Ratio%, is the percent of number of zeros coefficients (Zeros) form to the total number of coefficients (Coeff).
2. Sum of the absolute differences (SoDif).
3. Maximum absolute value of the samples' differences, reconstructed signals are taken direct from the reconstructed structure (MxAbs1).
4. Maximum absolute value of the samples' differences, reconstructed signals are taken direct from the reconstructed each signal separately (MxAbs2).
5. Correlation matrix and highlight the correlation value between signals (Corr_P).
6. Mean-Squared Error (MSE).
7. Signal-to-Noise Ratio (SNR db).
8. Peak Signal-to-Noise Ratio (PSNR db).
9. Relative Error (Norm).

According to performance evaluation methods, Table 1 depicts the result of the best replacement of the original OFDM signals for the first 10 signals based on the PSNR criterion.

Table 1
New OFDM signals generation based on the PSNR criterion.

Signals number	The PSNR value	The Decomposition Level	The Wavelet function Type
1	18.841	7	db45
2	21.475	6	db40
3	18.406	5	db35
4	20.402	7	db13
5	18.792	7	db35
6	20.957	7	db30
7	20.608	2	db25
8	18.685	8	db10
9	18.780	5	db06
10	23.046	7	db35

From the depicted results in Table 1, as an example the new generated OFDM signal for the original signal number 1 is generated by db45 at the 7th decomposition level since it PSNR value is 18.841 and was the lowest value among the used wavelet functions from the decomposition levels 1 to 7.

Furthermore, another performance criterion is based on the Complementary Cumulative Distribution Function (CCDF) that checks the Peak-to-Average Power Ratio (PAPR). In this performance criterion we will check the enhancement based on reducing the PAPR of the new generated signal. In this step, the original and the new generated OFDM signals were normalized before PAPR calculating and then adaptively thresholded as in (5) to get new OFDM signals, the thresholding formula used in this case is the following:

$$T_N = M_N + A_P * S_N \text{ ——(5)}$$

Where T_N is threshold value calculated adaptively, M_N is the mean value of the normalized OFDM signal, A_P is the adaptive parameter ($1 < A_P \leq 3$) and S_N is the standard deviation of the normalized OFDM signal. The CCDF measurements of the multi OFDM signals is used to measure the probability of an OFDM signal's instantaneous power being greater than a given level over its average power. Figure 5 depicts a sample of using the CCDF factor to check the performance of our proposed work.

It is clearly depicted in the drawn results that the reconstructed OFDM signal has better PAPR than the conventional one. At a PAPR threshold of 10^{-1}, the SNR has been reduced from 8.5 dB ab to almost 6 dB.

The used three methods that were used in the reconstruction process have almost the same results between 6dB and 6.3dB SNR range.

3.3 Adaptive Weighting Reclustering Stage

This stage is previously published in [31]. It will be used as a benchmark of checking the enhancement rate of our proposed work based on MIMO-FFT-OFDM. In [31], some optimization factors were checked such as the clustering stability, the cost of re-clustering, and the ripple effect. This work was based on proposing a clustering weighting factor (CWF) that was used to assign the clusters' Heads as shown in (6).

$$CWF_i = \begin{cases} 0, & \cos(\theta) \leq 0 \\ \frac{\sum_{j=1}^{J}\left(\delta_1\left(\frac{R_{max}-\sqrt{(x_i-x_j)^2+(y_i-y_j)^2}}{R_{max}}\right)+\delta_1\left(\frac{\min(v_i-v_j)}{\max(v_i-v_j)}\right)\right)}{J} & O.W. \end{cases} \quad (6)$$

In (2), J is the total number of moving vehicles around the vehicle$i$, R is the maximum acceptable communications range between the moving vehicles in order to re-clustering them. x stands for the actual position, where v is the vehicle velocity and δ stands for an adaptive factor that differs from scenario to another based on different number of lanes, the type of the city and the condense of moving vehicle. θ is the angle between the moving vehicles to limit the work to reclustering the moving vehicles just on the same direction. The whole process is summarized in Fig. 6.

4. Experimental Results, Analysis And Discussion

The environment is simulated according the following specifications:

- The OFDM signal is characterised as:
  - 52 subcarriers (48 data subcarriers, 4 Pilot subcarriers)
  - 8 μsec symbol interval with (1/8 Guard Interval)
  - 10 MHz channel bandwidth with 156.25 kHz subcarriers frequency spacing.
  - 80 OFDM symbol per frame
  - 2/3 convolutional encoder
  - QPSK, 16-APSK modulation techniques
- The MIMO channels is characterised as:
  - $2 \times 2, 4 \times 4$ Antennas
  - ZF and MMSE equalizers at 30Hz and 300Hz Doppler shifts.
  - Rayleigh fading channel

- The VANET characterisation
  - Node speed 70-100km/h,
  - Two lanes cross road,
  - Vehicle's transmission range is up to 300m,
  - Number of trials are 100,
  - Time of changing the head equals 2s,

The systems performance has been checked from both of the BER and the throughput point of view as found in Fig. 7 and Fig. 8 respectively.

As a result from the achieved results from Fig. 7, a conclusion is drawn an inverse relationship between the BER and the number of the Antennas. Furthermore, at low SNR values the effect of the Doppler at 30Hz is almost similar to the one of the 300Hz. However, the performance is enhanced somehow at the 30Hz when increasing the SNR.

From the depicted throughput results from Fig. 8, our proposition outperforms the conventional work that has been published in [31]. Moreover, it is clearly that increasing the number of Antennas enhances the system QoS from the throughput point of view especially with increasing the SNR. This is in addition to the effect of the Doppler shift, which is worse at 300Hz than at 30Hz shifts.

In order to check the VANET reclustering performance, the clusters' Heads life time results have been depicted in Fig. 9 based on two terms; the maximum speed and the maximum transmission range. From the depicted results, it is clearly that the use of MIMO system based on FFH enhances the previously achieved results in [31] that have been achieved using 1X1antenna system. Using MIMO system increases the CH life time from almost 10s into around 80s with respect to the maximum vehicle speed between 80km/hr to 100km/hr. Also a conclusion is drawn based on the relation between the number of antennas and the stability; a direct proportional relationship between them is found. Furthermore, when the Doppler shift increases from 30Hz to 300Hz, the life time has been reduced within a range of 4s. This is in addition to the use of MMSE gives almost better results than the use of ZF. A similar conclusion has been found between the relationship between the life time and the maximum communications range. The CH life time has been improved from 22s to around 45s when using MIMO antennas based systems. Furthermore, conclusion from our work in [31] can be drawn as a downward trend for the cluster head life time with increasing either the moving nodes speed or the moving nodes transmission range. The results in Fig. 9 shows that the use of the MIMO systems combined to FFH-OFDM enhances the previously published work based on MP-MBOFDM benchmark performance in [32]. This is true, either from the maximum speed point of view or from the vehicle transmission range.

Figure 10 represents the number of cars in the highway and its effect on the quality of transmission and reception process. The peak signal to noise ratio (PSNR) metric is used to determine the link quality among the CH communications through the LTE infrastructure. This metric and the quality of transmission are derived in [33]. The archived results in this figure prove the BER results in Fig. 7, where the BER for 4X4 antennas is worse than the one for the 2X2 antennas. Here, the quality of the received streams using 2X2 antennas through the LTE infrastructure also is better. However, the number of vehicles has an inverse relationship with the quality as draw from the results, where the results of 5 cars are better than the one of 40 cars. Also the as we achieved from the previous results in Figs. 7, 8 and 9, the use of the MMSE gives better results than the ZF. This is true as well for the relation between the Doppler shift and the results; the one of the 30Hz is better than the ones for the 300Hz.

5. Conclusion

The existing VANET technologies can transfer information between vehicles with good reliability, however they lack in having a high data rate communications. Therefore, this work proposes a combinations between the benefits of Spatial multiplexing MIMO and an enhancement over our previously OFDM work. In this paper the performance of V2V communications based LTE system has been investigated based on imposing the two different approaches; FFHOFDM and MIMO technology. The proposition has been investigated based on our previously published clustering architecture combined to the multi-signal processing.

From the depicted results, four different parameters were investigated in order to check our proposition, namely BER, throughput, the CH life time and stability, and the link quality. We have proposes two sizes of MIMO systems; 2X2 and 4X4, in addition to two types of equalizations; MMSE and ZF. Also, two Doppler shifts values have been taken into consideration 30Hz and 300Hz.

Powerful results of using spatial multiplexing based on MMSE and 4X4 antennas were achieved. The performance the multi-signal transmission is checked and enhanced. The stability, the power reduction, the link quality and the high data rate are the parameters that have been proven the QoS enhancement of the proposition.

Declarations

• Availability of data and material.

All data generated or analysed during this study are included in this published article (and its supplementary information files).

• Competing interests.

The author(s) declare(s) that they have no competing interests.

• Funding.

Not applicable

• **Authors' contributions.**

Not applicable

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Figures

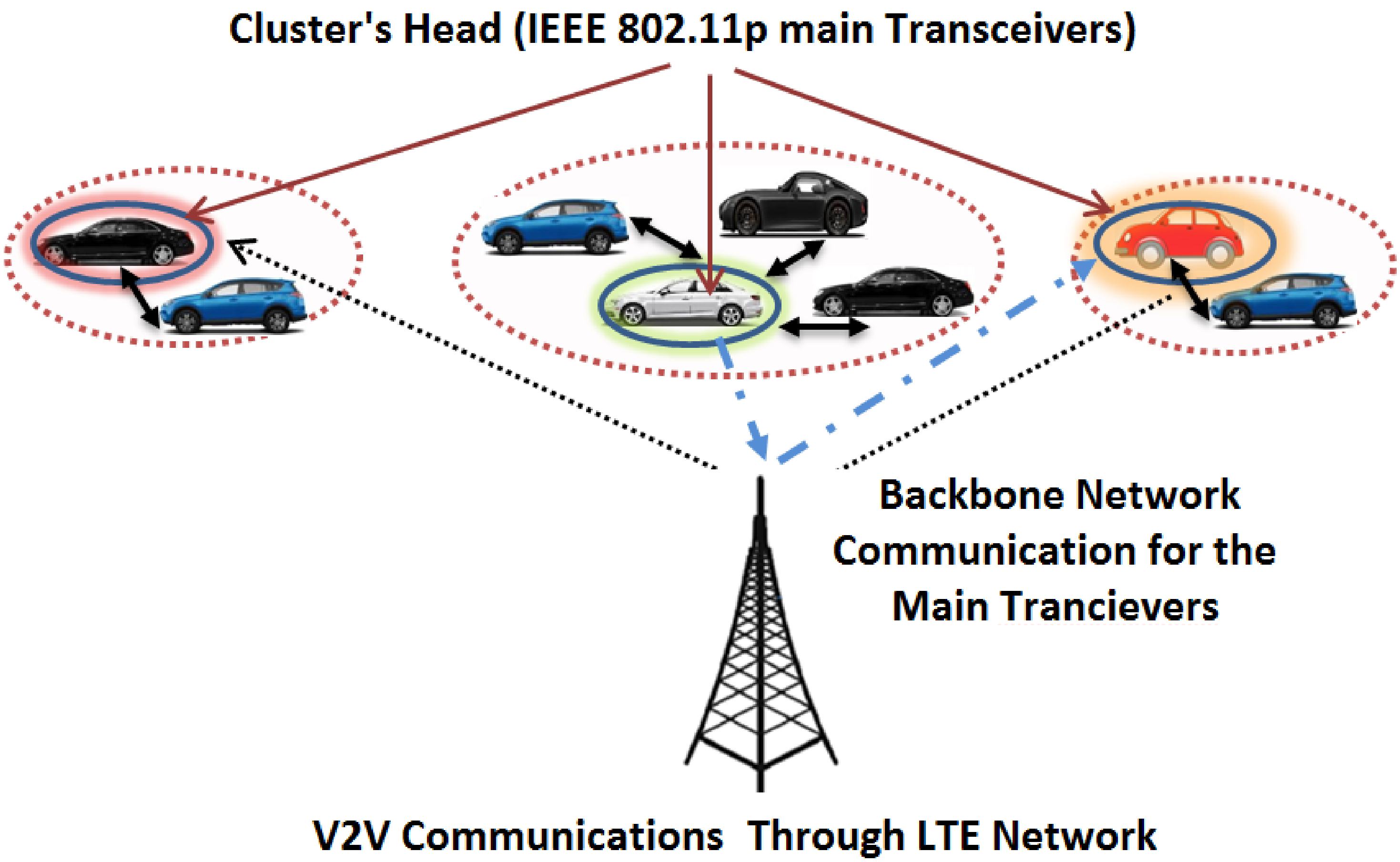

Figure 1

VANET communications under the LTE infrastructure.

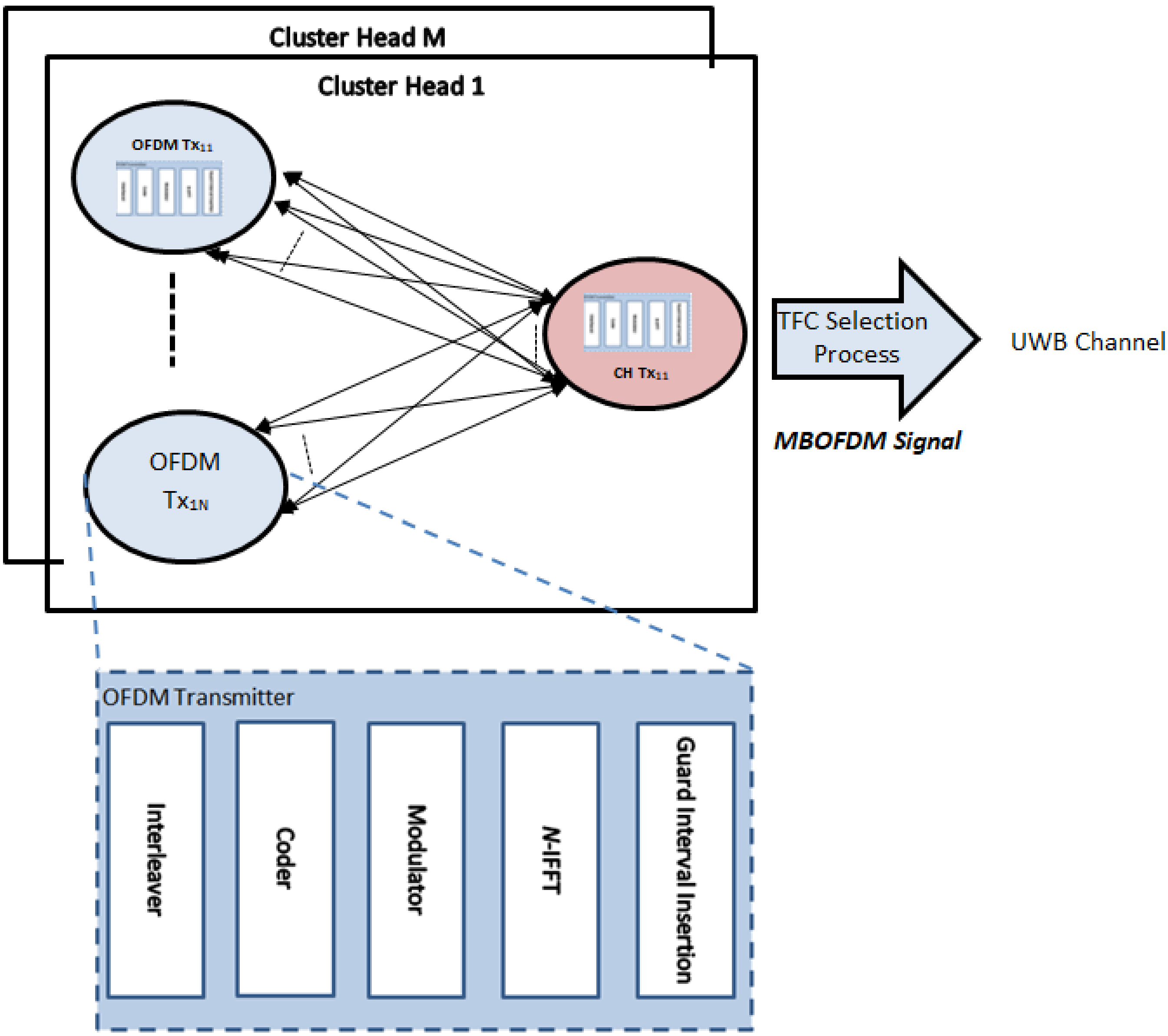

Figure 2

The block diagram of the clusters' heads communications under the multi-signal communications.

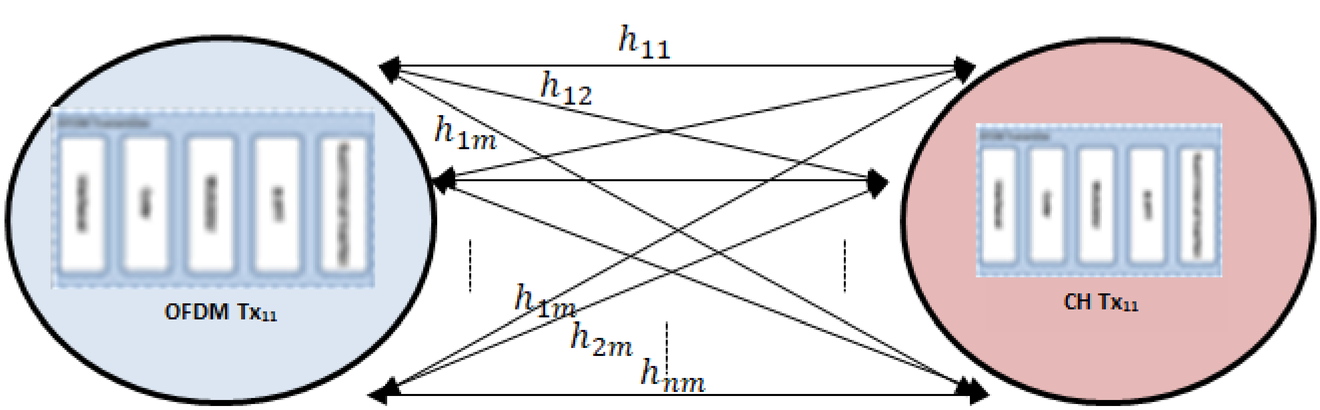

Figure 3

n× *m* MIMO channel response matrix scenario$[h]_{n\times m}$

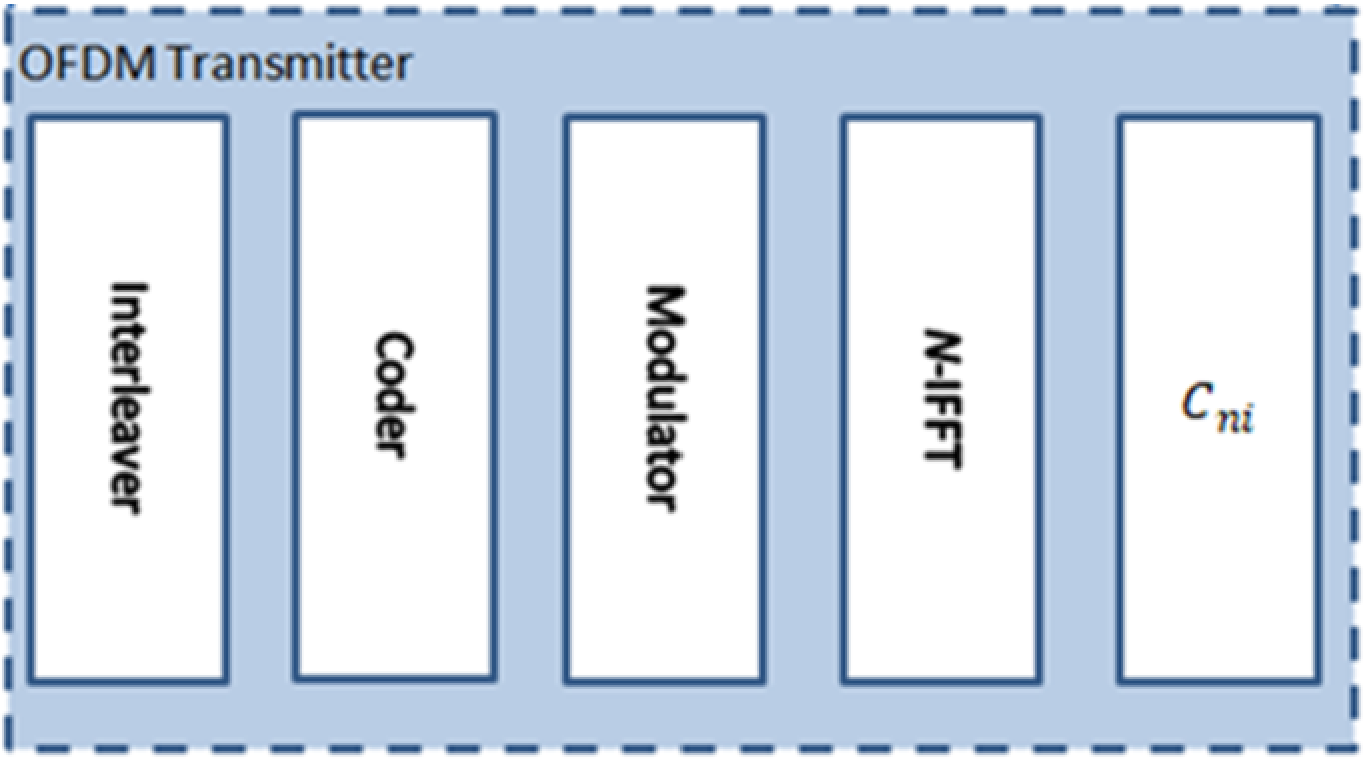

Figure 4

The modified PHY layer of the FFH-OFDM.

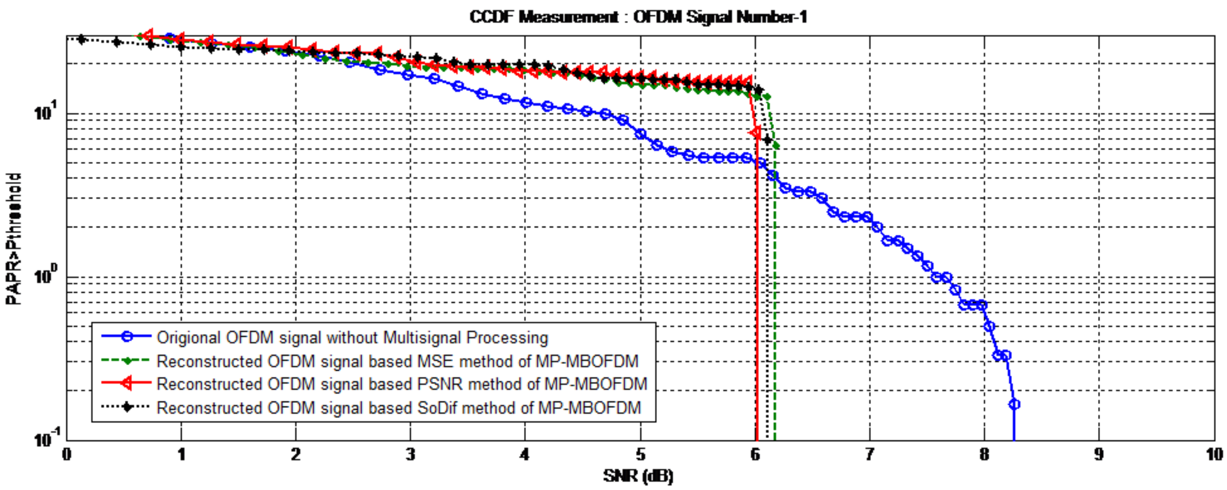

Figure 5

The CCDF measurements as a distinguishing criterion.

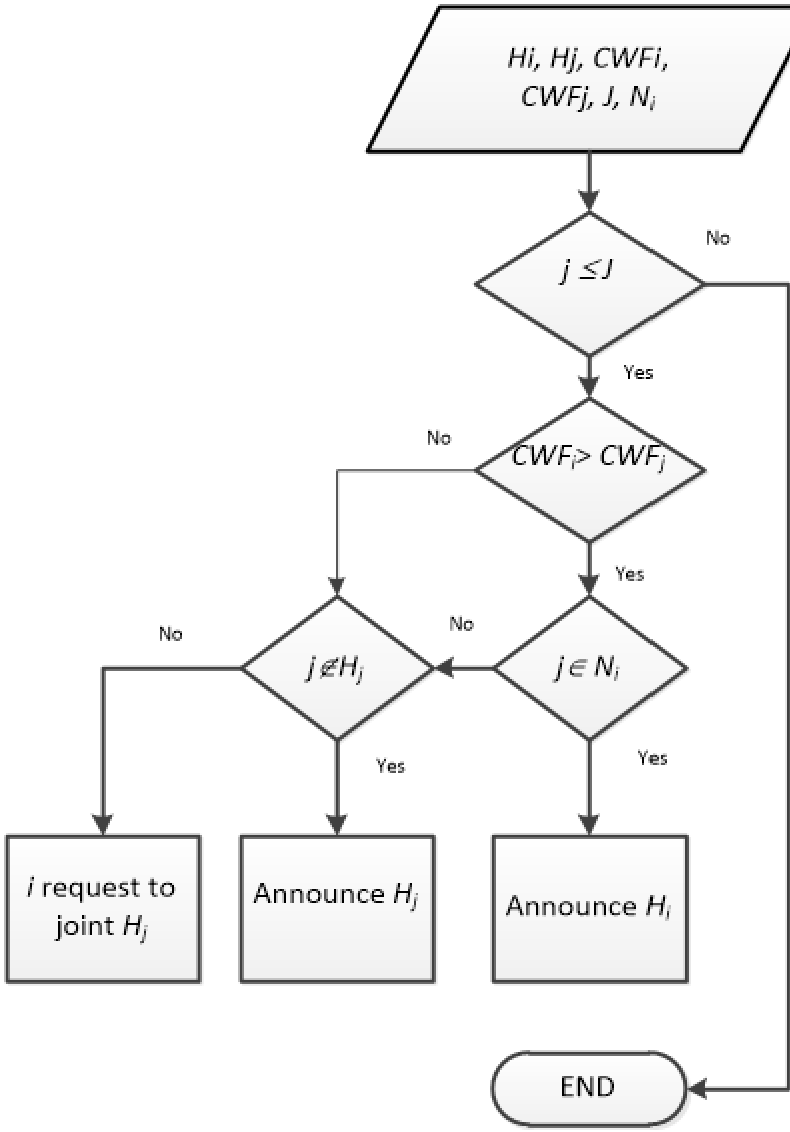

Figure 6

The flowchart of the adaptive reclustering algorithm and choosing the cluster Head.

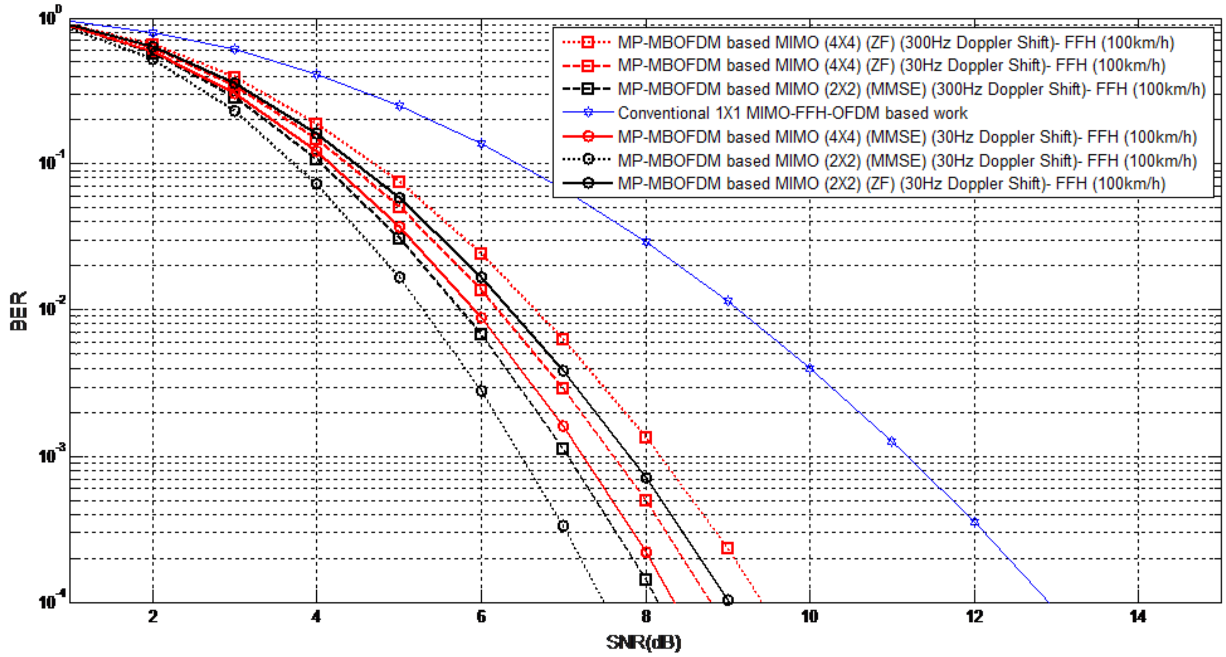

Figure 7

Systems Performance based on the BER.

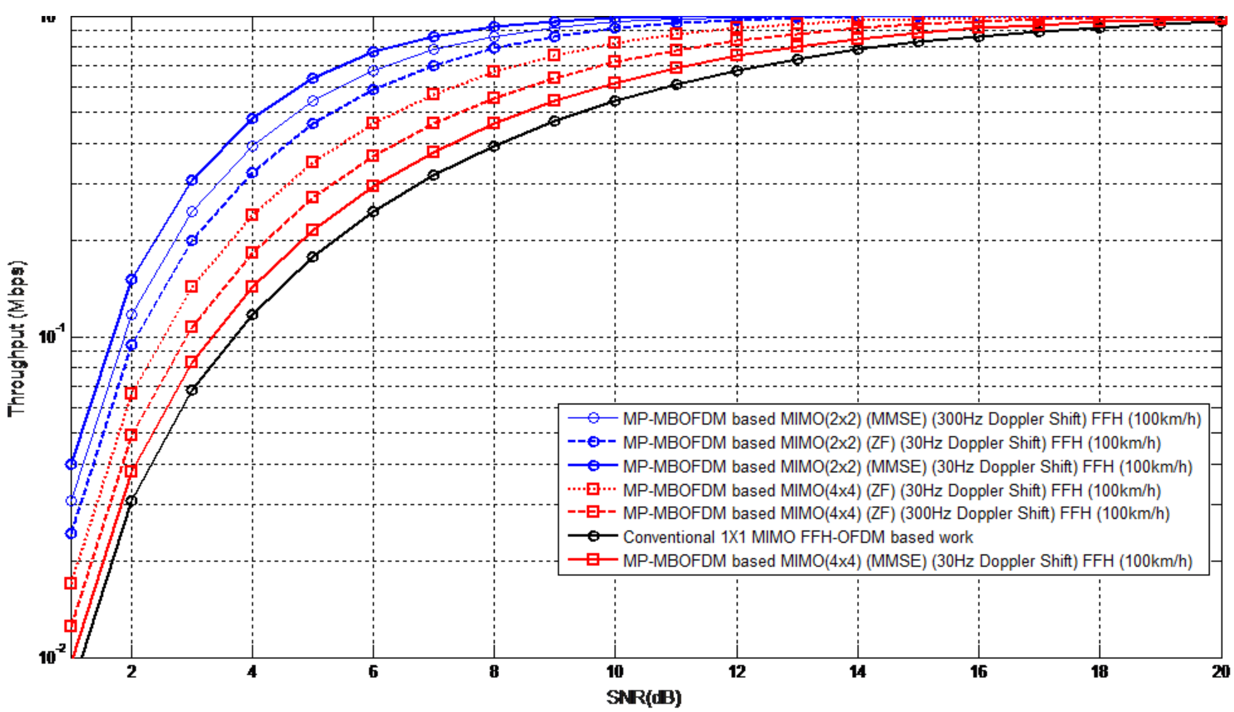

Figure 8

Systems Performance based on the Throughput

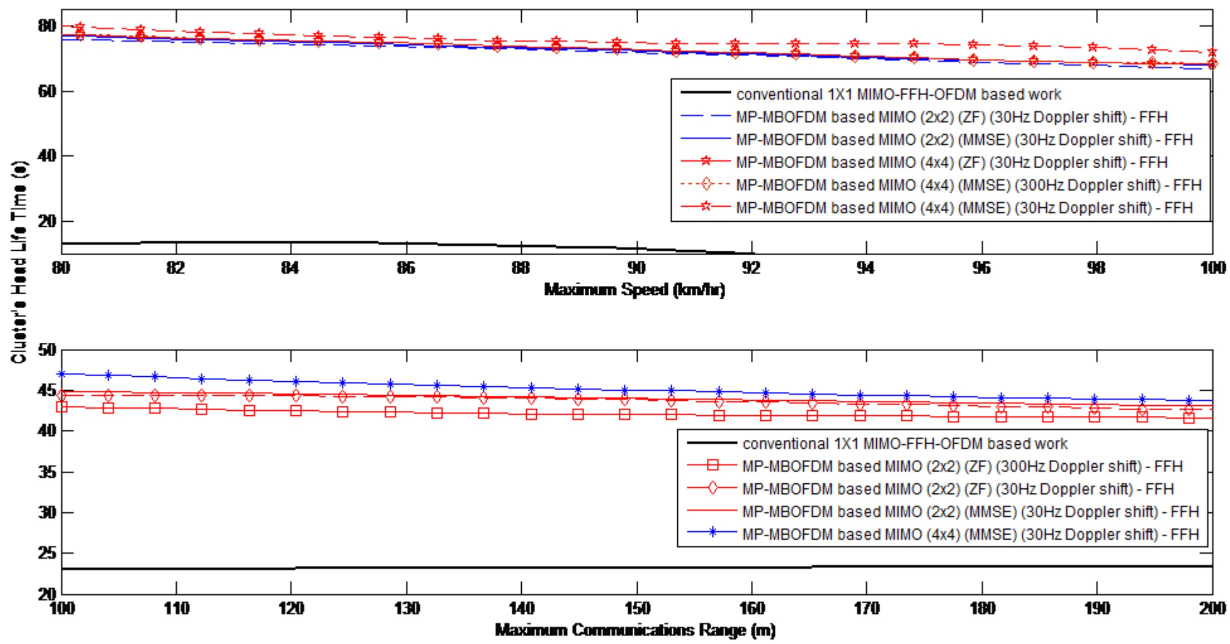

Figure 9

Cluster's Head Average Lifetime Performance.

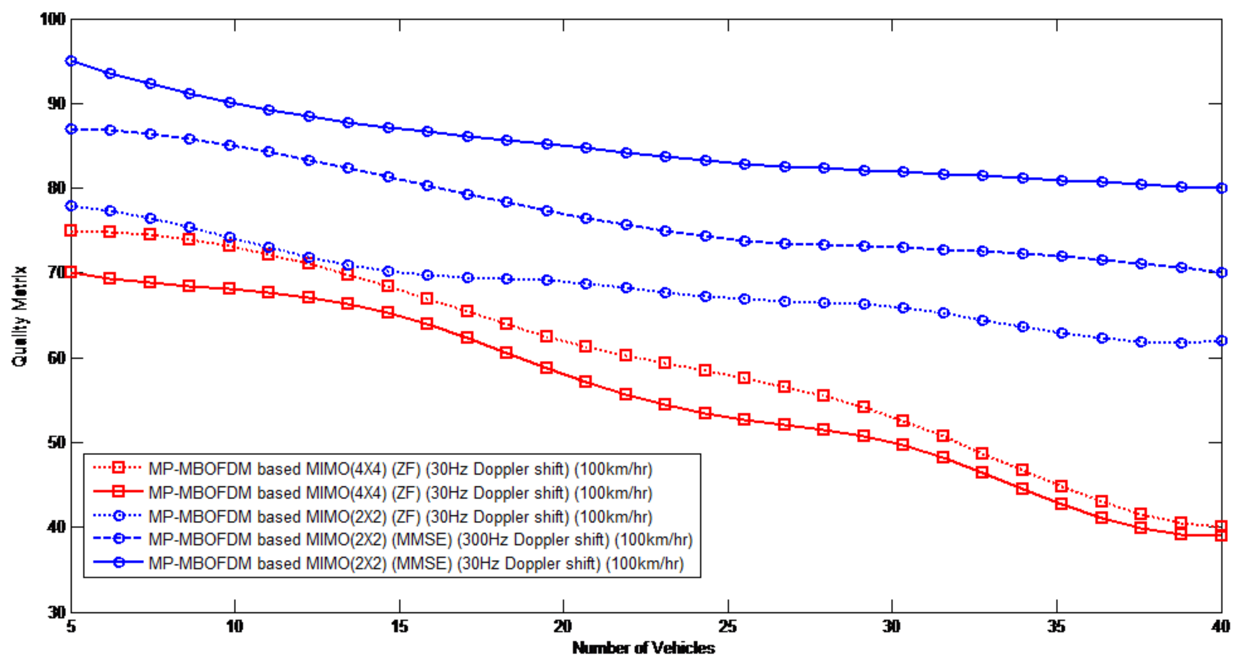

Figure 10

The Quality metric with respect to the number of Vehicles