

Compressed Multi-Access for MIMO-Based Vehicle Communications Network

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Abstract—An efficient and reliable multi-access scheme for large-scale Vehicle Communications Network (VCN) is necessary in future. In this paper, a compressed multi-access scheme is proposed for MIMO-based VCN via compressive sensing (CS) techniques. In particular, a Zero-Forcing (ZF) based random precoding scheme is proposed for vehicles to combine the advantages of MIMO and CS. Correspondingly, an iterative Orthogonal Matching Pursuit (OMP) algorithm is devised for half-blind reconstruction at central station's side. Based on these two sub-schemes, the active vehicles keep sending the precoded symbols until central station decodes successfully and sends back the feedback reports. Simulation results show that, while maintaining a certain level of mean square error (MSE) performance, the proposed multi-access scheme can save the time resources notably when comparing with traditional multi-access schemes.

Keywords—Vehicle communications network, Compressive sensing, MIMO, precoding, half-blind reconstruction

I. INTRODUCTION

In Vehicle Communications Network (VCN), developing an efficient and reliable multi-access scheme is a crucial issue because of the distributed and complicated communication demands in large-scale networks. It plays an important role in vehicle network monitoring and road traffic safety [1]. With the expansion of urban traffic systems, some typical features in VCN are always contained, which can be generalized as following: (1) Large-scale distributed sparse system. One central station always needs to monitor hundreds of vehicles. Though the amount is large, most of them do not transmit information only if significant changes are detected. (2) Delay Sensitive Network. VCN should shorten the access delay as much as possible to deal with emergencies. (3) Mobility. It will influence the link level performance as well as the design of upper-layer protocols. Moreover, Multiple Input Multiple Output (MIMO) technique has also been considered in VCN recently in order to increase system capacity [2].

These features impose great challenges for multi-access schemes in MIMO VCN. Recently, the VCN based on traditional multi-access schemes draws a lot of attention in research areas, such as self-organizing time division multiple access (TDMA), code division multiple access (CDMA), orthogonal frequency division multiple access (OFDMA) [3]. However, these schemes are all designed under the assumption that all vehicles are active and therefore should reserve enough resources for all users. In large-scaled sparse VCN, these schemes cannot utilize the sparsity mentioned above, and consequently has low efficiency and long access delay.

Compressed sensing is a well known approach to recover a compressible signal with much less observations [4]. Based on the joint sparsity of signal ensembles, Baron et al. extend the traditional CS algorithms to distributed system [5]. In data gathering applications, [6] [7] have discussed the usage of CS algorithms in different SISO systems and shown the promoting performance. However, these schemes cannot be used as multi-access schemes in MIMO-based VCN straightforwardly.

In this paper, we propose a new compressed multi-access scheme for the MIMO VCN based on compressive sensing (CS) techniques. Generally speaking, it contains a precoding scheme for all distributed vehicles and a half-blind reconstruction algorithm for the corresponding central station. At vehicles' side, all active vehicles precode their information with Zero-Forcing based Random Precoding (ZF-RP) matrix, which is proposed to combine the advantages of both CS and MIMO. They transmit one precoded symbol in one frame. At the central station side, a reconstruction algorithm based on iterative Orthogonal Matching Pursuit (OMP) is proposed to decode the superimposed symbols. Given to the half-blind feature, The above process above keep running until the stop criterion is achieved, and then a new turn for the multi-access of new active vehicles can be started. Simulation results demonstrate that, the proposed scheme can considerably compress the access delay while maintaining certain mean square error (MSE) performance when comparing with other multi-access schemes.

The remainder of the paper is organized as following: The system model of MIMO-based VCN is described in Section II. In Section III, the proposed compressed multi-access scheme for MIMO VCN is introduced in detail. The corresponding simulation results are presented in Section IV and Section V. Finally, the conclusions are drawn in section VI.

II. SYSTEM MODEL

We consider a distributed VCN which is comprised with L vehicles and a single central station, as shown in Fig. 1. There are M antennas in each vehicle and N antennas in central station. The work mode is Frequency Division Duplex (FDD). The uplink frequency band is utilized for uplink multi-access. All broadcast and feedback information from central station are all sent in downlink channel.

In most applications, such as network monitoring or active road safety, there is no need to send information frequently. Only when significant change has been detected by drivers or vehicular sensors, the updated information should be sent to

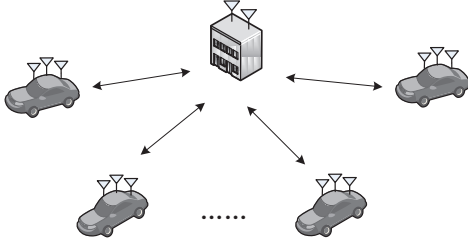


Fig. 1. An illustration of the distributed vehicle communications network.

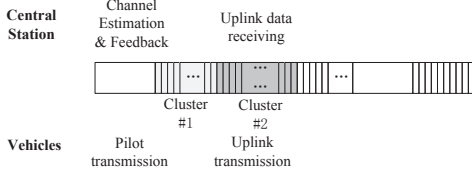


Fig. 2. Frame structure and multi-access procedure.

central station. Therefore, though the total number of vehicles may be quite large, only a small fraction of them send information simultaneously in most cases. We assume perfect timing synchronization in the network is obtained, which can be realized by GPS terminals in vehicles or downlink synchronizing information broadcasted by central station.

Assume that there are $K \ll L$ active vehicles requiring for updated data transmission. Regardless of the activity states, the modulation symbols vectors of all L vehicles equipped with M transmitting antennas can be expressed as $\{\mathbf{x}_l \in \mathbb{C}^{M \times 1}\}_{l=1}^L$. We define the indices set of the active vehicles as $L_a = \{l : \mathbf{x}_l \neq \mathbf{0}_{M \times 1}\}$. The $N \times 1$ received vector at the central station in the t th time slot is given by,

$$\mathbf{r}(t) = \sum_{l=1}^L \mathbf{H}_l \mathbf{W}_l(t) \mathbf{x}_l + \mathbf{n}(t), \quad (1)$$

where $\mathbf{H}_l \in \mathbb{C}^{N \times M}$ is the channel matrix from the l th vehicle to central station. $\mathbf{W}_l(t) \in \mathbb{C}^{M \times M}$ is the precoding matrix which will be discussed latter. $\mathbf{n}(t) \in \mathbb{C}^{N \times 1}$ is complex additive white Gaussian noise $\mathcal{CN}(\mathbf{0}_N, \sigma^2 \mathbf{I}_N)$.

III. COMPRESSED MULTI-ACCESS SCHEME FOR MIMO VCN

In this section, we introduce a compressed multi-access scheme for MIMO VCN. The so called compressed multi-access means that it can utilize the sparsity in MIMO VCN via compressive sensing algorithms and spend much less communication resources for uplink multi-access procedure comparing with other schemes.

The frame structure of the multi-access procedure is shown in Fig. 2. The time resource can be divided into frames. In the initial part of frames, all vehicles send pilots for channel estimation. The CSI obtained at central station can be feedback to vehicles in the downlink channel. Then, the rest part of the

frame comprised with numbers of uplink time slots are utilized for uplink multi-access transmission.

The proposed multi-access scheme contains two main parts: the MIMO precoding and transmitting process at vehicles' side and the CS-based reconstruction process at central station' side. We will introduce them separately in the remainder parts of this section.

A. Zero-Forcing Based Random Precoding (ZF-RP)

By utilizing channel estimation results, we construct a ZF based random precoding method for in vehicles in order to combine the advantages of MIMO and CS. With different purposes, two typical precoding matrix can be designed: diversity and multiplexing. In this paper, we consider the diversity case only.

In spatial diversity scheme, all M antennas of one vehicle transmit the same symbol in one time slot. The $M \times 1$ symbol vector of the l th vehicle is therefore $\mathbf{x}_l = [x_l \ \cdots \ x_l]^T$.

We construct the ZF based random precoding matrix for the l th vehicle as following,

$$\mathbf{W}_l(t) = \hat{\mathbf{H}}_l^H (\hat{\mathbf{H}}_l \hat{\mathbf{H}}_l^H)^{-1} \mathbf{A}_l(t), \quad l \in L_a, \quad (2)$$

where $\hat{\mathbf{H}}_l \in \mathbb{C}^{N \times M}$ is the estimation of $\mathbf{H}_l$. $\mathbf{A}_l(t) \in \mathbb{C}^{N \times M}$ is the random spreading matrix of vehicle l in time slot t . In order to taking full advantage of spatial diversity, we design the random spreading matrix as the following form,

$$\mathbf{A}_l(t) = [\mathbf{a}_l(t) \ \cdots \ \mathbf{a}_l(t)]. \quad (3)$$

It can be seen that this matrix is constructed with a random spreading vector $\mathbf{a}_l(t)$ which is repeated by M times. The vector $\mathbf{a}_l(t)$ is generated according to Gaussian distribution. Combining (1) with (3) we can obtain that,

$$\begin{aligned} \mathbf{r}(t) &= \sum_{l=1}^L \mathbf{H}_l \mathbf{W}_l(t) \mathbf{x}_l + \mathbf{n}(t) \\ &= \sum_{l=1}^L \mathbf{H}_l \hat{\mathbf{H}}_l^H (\hat{\mathbf{H}}_l \hat{\mathbf{H}}_l^H)^{-1} \mathbf{A}_l(t) \mathbf{x}_l + \mathbf{n}(t) \\ &= M \sum_{l=1}^L \mathbf{a}_l(t) x_l + \mathbf{n}(t) \end{aligned} \quad (4)$$

From (4) it can be seen that, the M rows precoding vectors for M antennas are the same one. Because all symbols in M antennas are also same, the desired part in the received symbols are amplified by M times.

In urban environment, vehicles usually move at moderate speed. Therefore a certain level of channel estimation error will be caused inevitably, which are always modeled as $\mathbf{E}_l = \hat{\mathbf{H}}_l - \mathbf{H}_l$. For simple but without loss of generality, its entries can be seen i.i.d. complex Gaussian random variables $\mathcal{N}(0, \sigma^2)$.

With the existence of $\mathbf{E}_l$, (4) should be rewritten as

$$\begin{aligned} \mathbf{r}(t) &= M \sum_{l=1}^L \mathbf{a}_l(t) x_l \\ &\quad - M \sum_{l=1}^L \mathbf{E}_L \hat{\mathbf{H}}_l^H \left(\hat{\mathbf{H}}_l \hat{\mathbf{H}}_l^H \right)^{-1} \mathbf{a}_l(t) x_l + \mathbf{n}(t) \\ &\triangleq M \mathbf{A}_{de}(t) \mathbf{x}_{de} + \mathbf{n}_e(t) + \mathbf{n}(t) \end{aligned} \quad (5)$$

where $\mathbf{A}_{de}(t) = [\mathbf{a}_1(t) \cdots \mathbf{a}_L(t)]$ is the $N \times L$ total random spreading matrices in the same time slot. $\mathbf{x}_{de} = [x_1 \cdots x_L]^T$ is the $L \times 1$ symbol vector contained all transmitted symbols by all vehicles (With many 0 in it). $\mathbf{n}_e(t) \in \mathbb{C}^{N \times 1}$ is the precoding noise caused by mobility.

When active vehicles begin a uplink multi-access process, they should keep transmitting the same modulation symbols vectors $\{\mathbf{x}_l\}_{l=1}^L$ in numbers of time slots until they receive the relative feedback reports broadcasted by central station in downlink channel. Therefore, if the total number of time slots is T , the $NT \times 1$ combined received vector is

$$\mathbf{r} = M \bar{\mathbf{A}}_{de} \mathbf{x}_{de} + \mathbf{n}_{de} \quad (6)$$

where $\bar{\mathbf{A}}_{de} = [\mathbf{A}_{de}(1)^T \cdots \mathbf{A}_{de}(T)^T]^T$ is the $NT \times L$ combined random spreading matrix. Since the precoding vector $\mathbf{a}_l(t)$ for an antenna of one vehicle is generated from the Gaussian distribution, the matrix $\bar{\mathbf{A}}_{de}$ is a Gaussian random matrix. In fact, it also can be designed like other forms as long as it satisfies the RIP [8]. $\mathbf{n}_{de} \in \mathbb{C}^{NT \times 1}$ is the total noise vector comprised with precoding noise and receiver noise. The symbols vector $\mathbf{x}_{de}$ keeps the same values in all time slots. In this scheme, the received useful signal M is times amplified comparing with single antenna scheme. If the precoding noise can be limited in a certain range, the diversity gain is significant, especially in low signal-to-noise ratio condition.

B. Half-Blind Reconstruction Based on Compressive Sensing

Since the symbols vector $\mathbf{x}_{de}$, which is to be decoded, is always sparse, we can employ compressive sensing algorithms at central station for signals reconstruction. We assume that some predeterminate parameters are known at both sides, such as the scheme adopted by vehicles and random spreading matrix $\bar{\mathbf{A}}_{de}$. However, due to indices set of active vehicles L_a is unknown at central station side, it is a half-blind reconstruction problem, which also can be seen as a joint random access and sparse multi-user detection problem.

In existing literatures, there are different classes of compressive sensing algorithms. For simplicity, we utilize Orthogonal Matching Pursuit (OMP) based algorithm for demonstration. Though its performance is worse than optimization algorithms, but it is enough for advantage verification of the proposed multi-access schemes.

However, the standard OMP algorithm [9] is not suitable for VCN. First, the number of active vehicles is unknown in half-blind situation. Moreover, the number of measurements

TABLE I. ITERATIVE OMP ALGORITHM FOR HALF-BLIND RECONSTRUCTION AT CENTRAL STATION

For each time slot
Receive the new superimposed signals $\mathbf{r}(t)$.
Repeat
Standard OMP algorithm
Until
The maximum number of iterations $K_{\max}$ is reached or Residuals $\mathbf{r}_e$ is small enough
Until
Deviation of the reconstruction results $\ \hat{\mathbf{x}}(t_n) - \hat{\mathbf{x}}(t_{n-1})\ _2$ in several successive time slots are small enough
Then
$\hat{L}_a$ and $\hat{\mathbf{x}}$ can be obtained
Send feedback reports in downlink channel

in OMP algorithm changes with time slots. Therefore, we introduce an iterative OMP algorithm in this multi-access scheme. The reconstruction procedure at central station is shown in Table 1.

During the multi-access procedure, the central station keeps receiving the superimposed symbols from all vehicles until the outer stop criterion has been satisfied. When the reconstruction procedure has finished, central station sends the feedback reports in downlink channel to notice the success of reconstruction.

IV. SIMULATION RESULTS

In this section, we demonstrate the performance of the proposed multi-access schemes in MIMO-based VCN by Monte Carlo simulation. We assume there are totally 500 vehicles in the network and only 20 vehicles are requiring for multi-access at the same time. The data is modulated with Binary Phase Shift Keying (BPSK) and the payload length of each vehicle is 4. The channels are all Rayleigh distributed as $\mathcal{CN}(0, 1)$. We also assume that perfect timing synchronization has been obtained and there is no feedback error.

Fig. 3 shows the change of the MSE performance in SISO case when and the payload length is 1. From Figure 3(a) we can observe the change of the normalized MSE between estimated results in consecutive time slots. It can converge to a level lower than 0.01 after nearly 89 time slots. During this period, the system MSE performance also converges to a low level gradually, as shown in Figure 3(b). Limited by the space constraints, the results in other SNR are not given. In fact, the trends are similar. Therefore, we set outer stop criterion to 0.01 in the following.

Fig. 4 shows the delay vs. SNR performance in MISO diversity case ($N = 1, M = 1, 2, 4$) when the payload length is 4. We can see that with the increasing of M , the time cost to achieve the same MSE performance reduces greatly, especially in low SNR regions. Since the signal observed at the receiver are M times amplified compared with single antenna case or multiplexing scheme, and thus resulting M times power-gain.

Fig. 5 shows the delay vs. SNR performance in MIMO diversity case ($M = 4, N = 1, 2, 4$). If we fix the condition $M = 4$, the increase of the number of receiving antennas

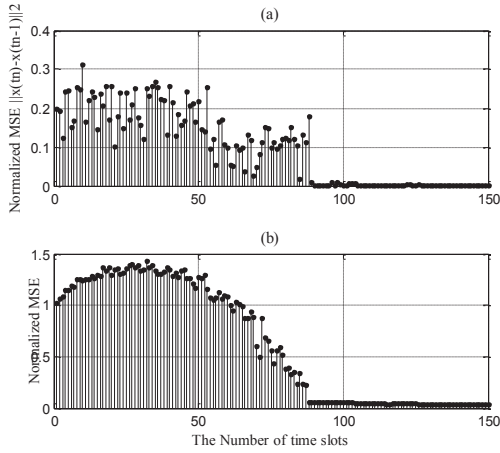


Fig. 3. MSE performance in SISO case.

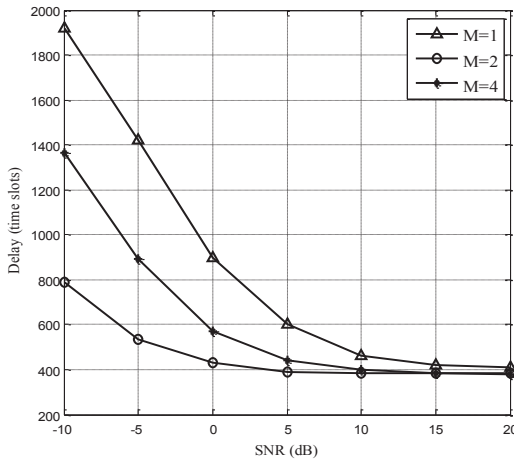


Fig. 4. Delay performance in MISO diversity case.

N can also reduce the time slots required for reconstruction. In high SNR regions, the enhancement compared with MISO case is nearly proportional to N . The reason is that with larger N , RIP can be satisfied faster. Therefore, under the same condition, MIMO diversity scheme can provide the same performance with shortest delay.

Fig. 6 shows the influence of mobility on delay performance in VCN. We take MIMO diversity case as the reference. When vehicle speed is not very high, the diversity scheme can deal with the influence well. However if the speed is quite high, we need much more time slots for successful transmission. Even in this case, the delay is still much lower than other multi-access schemes such as CDMA and CSMA. Therefore, it is more suitable for sparse VCN situation.

V. CONCLUSION

In this paper, we propose a compressed multi-access scheme for VCN, which is a combination of MIMO and CS techniques. In vehicles, we introduce a zero-forcing based random pre-coding method for compressed transmission. Accordingly, an

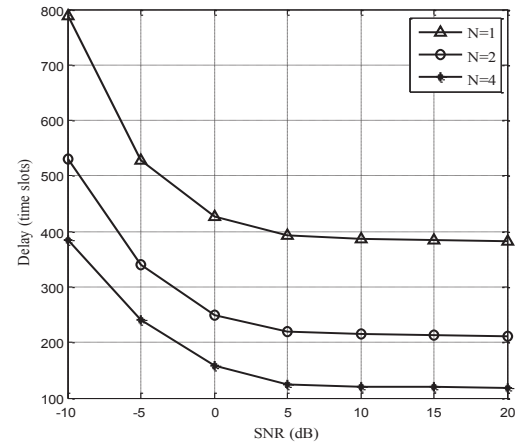


Fig. 5. Delay performance in MIMO diversity case.

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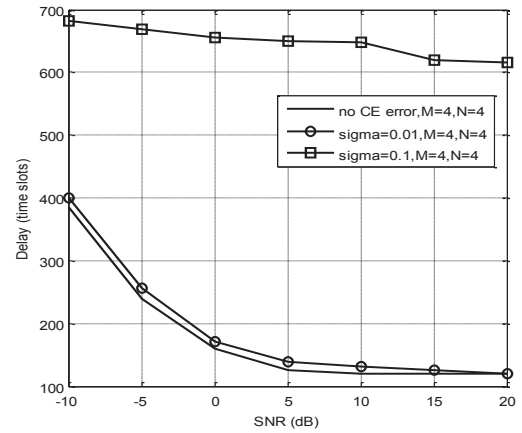


Fig. 6. The influence of mobility on delay performance.

iterative OMP algorithm at central station is also given. With the advantages of combining CS with MIMO-based VCN, the communication delay can be compressed to a low level, which makes it more suitable for VCN. Comparing the two transmission schemes in vehicles, the multiplexing scheme has the advantage in feedback overhead and the diversity scheme can obtain better delay performance.

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