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Research Article

Selective Random CDD Enhanced Joint Cooperative Relay and HARQ for Delay-Tolerant Vehicular Communications

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We propose a selective random cyclic-delay diversity (CDD) enhanced joint cooperative relay and hybrid automatic repeat request (HARQ) scheme for two-hop vehicular communications. Our innovation mainly concentrates on design of the second-hop transmissions. On one hand, the CDD technique is applied across multiple relay nodes to artificially create frequency selectivity and then achieve diversity gain by applying channel coding. The employment of CDD does not necessarily require channel state information (CSI) at the transmitters and thus also decreases overhead caused by CSI feedback. On the other hand, retransmission for the second hop is performed based on relay selection. Particularly, the CDD is constructed only over selected relay nodes with qualified channel qualities to achieve a better frequency selective channel. As the selection results vary with random channel fading, our scheme is termed selective random CDD. Our scheme is presented based on a generic model and further applied into two scenarios, respectively: (1) car-to-car communications in high-way vehicular networks; (2) downlink transmission for the high velocity mobile station in cellular networks. Simulation results show that our proposed selective random CDD scheme can achieve higher throughput as well as lower transmission delay than the conventional cooperative beamforming based transmission scheme.

1. Introduction

With the explosively increasing demands on mobile communications services, supporting transmissions among/to mobile nodes with high velocity becomes a critically important task for the design of communications systems. Correspondingly, the vehicular communications have gained a wide spectrum of applications [1–5]. The vehicular communications and networks can be mainly divided into two categories. One category defines the information delivery for vehicles equipped with communications devices, where the network is ad hoc and typically does not rely on the infrastructure. The other describes the communications of cellular user equipment carried by vehicles to the infrastructure facilities such as cellular base station and/or road side unit. These two types of networks face a common challenge when the velocities of moving nodes get high. That is, the link quality directly connecting the transmit and receiver is unstable, leading to poorer reliability and very limited coverage.

To conquer the challenges, relay-aided transmissions [4–9] and hybrid automatic repeat request (HARQ) [9] are widely investigated to combat the drastically varying channel fading such that the reliability can be effectively enhanced. These two techniques typically improve reliability at the cost of longer delay, thus being suitable for delay-tolerant services in vehicular networks. In particular, HARQ can combine received signals through multiple retransmissions to increase the postprocessed signal-to-noise ratio (SNR), while relay-aided transmissions take advantage of shorter propagation distance by using the multihop connection to suppress SNR degradation in each hop. To further improve the reliability as well as other performance metrics such as outage probability, throughput, and energy efficiency, cooperative relay is often employed, where different relay nodes cooperate in forwarding information from a source to a destination [10–12]. Such a solution can exploit the diversity across spatially distributed wireless channels, while only single transmit/receive antenna for each node is needed. Following this principle, cooperative beamforming is the typical cooperative relay scheme [13–15] that received major research attention.

However, despite the efforts of research communities spent in improving the reliability for vehicular communications, some major problems have not been adequately studied. First, the cooperative beamforming needs accurate channel state information (CSI) to implement maximum ratio transmissions (MRT), thus frequently introducing extra overhead and degrading transmissions efficiency. Second, vehicular networks often generate fast varying channels, which may cause mismatch between the CSI fed back and the actual channel for followed data payload transmission. Third, conventional cooperative beamforming only exploits the diversity benefited from location-independent relays, while not addressing the frequency selectivity for further performance improvement.

To overcome the aforementioned problems, we in this paper propose selective random cyclic-delay diversity (CDD) enhanced joint cooperative relay and HARQ scheme for two-hop vehicular communications. We first apply the CDD technique across multiple relay nodes to create frequency selectivity of the equivalent channel. Then, we can achieve the inherent diversity gain when using channel coding. Moreover, HARQ for the second hop is employed with relay selection, where the CDD is constructed over selected relay nodes with better channel qualities, thus forming better frequency-selective channels. Discussions and simulations show that our proposed selective random CDD scheme outperforms the conventional beamforming in terms of transmission failure probability, throughput, and overhead for the typical car-to-car communications in highway environments and for cellular communications from the base station (BS) to moving mobile station (MS).

The rest of the paper is organized as follows. Section 2 describes the generic system model and applies it to two vehicular communications scenarios, including car-to-car communications in highway environments and BS-to-MS communications in cellular networks. Section 3 proposes the selective random CDD based relay and HARQ scheme. Section 4 evaluates the performance via simulations. The paper concludes with Section 5.

2. System Model

We first present a generic model of cooperative relay transmissions for delay-tolerant vehicular communications services, which share the common features among diverse vehicular communications scenarios. Following this generic model, we concentrate on two specific vehicular communications systems. One is for car-to-car communications in highways and the other is for relay communications from the base station of cellular networks to the mobile station with high velocity. We in this paper target at developing

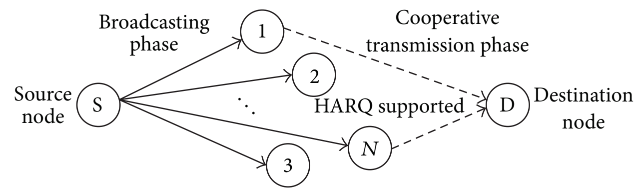

Figure 1: Generic model of relay transmissions for delay-tolerant vehicular communications.

the scheme that can bring performance gains for both scenarios as compared to the conventional approach using the cooperative beamforming. For presentation convenience, we collect the main notations and variables at the end of this paper and please see Notations and Variables section.

2.1. Generic System Descriptions. We consider a network consisting of one source node (node S), one destination node (node D), and a set of relay nodes (or called relay in short), which are denoted by n, $n = 1, 2, \ldots, N$, as shown in Figure 1. Each node (including source, destination, and relay nodes) is equipped with a single transmit antenna and a single receive antenna. The source attempts to deliver the data to the destination. We in this paper targets at the delay-tolerant services, where certain delay is tolerable but guarantee of reliability is the first priority.

Due to the limit of transmit power, the transmission range for the source is often limited. Thus, the relay nodes are used to help the source to forward the data based on the decode-and-forward (DF) relay techniques. The entire relay transmissions process includes two phases (corresponding to the two hops). The first phase (hop) is broadcasting phase, where the source broadcast data to all relays. The second phase (hop) is the cooperative transmission phase. Note that in the rest of this paper the terms *hop* and phase are interchangeable. All relay nodes which can correctly decode the data will transmit the recovered signal to the destinations. As we focus on delay-tolerant services, for the 2nd phase, hybrid automatic repeat request (HARQ) mechanisms are adopted for better reliability. But the maximum retransmission times are upper-bounded for HARQ. Note that we in this framework only use HARQ in the second phase. This is because the chance that the first-phase transmission fails for all recipients is usually small, while the second-phase transmissions only deal with a single receiver.

The distance between the source node and the nth relay node is denoted by d_{Sn}; the distance from the relay node to the destination node is then denoted by d_{nD}. The transmit power for the source is denoted by P_S and that for the nth relay node is represented by P_n. The signal bandwidth is denoted by B. The topology as well as channel fading model for the car-to-car communications and those for cellular networks are different and will be addressed in Sections 2.2 and 2.3, respectively.

2.2. Car-to-Car Communications Model. The application of the generic model to the car-to-car communications can be substantialized as the scenario described in Figure 2. We

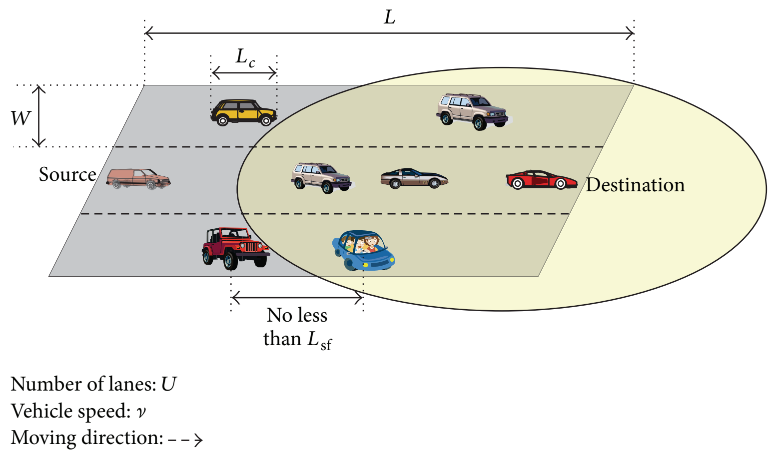

Figure 2: System model for car-to-car communications.

consider a segment of a highway with the length equal to L m. The highway includes U lanes each with the width equal to W m. There are total $N+2$ vehicles (cars) on the highway between the source and destinations vehicles. The source vehicle (node) and the destination vehicle are at the most left-hand side and the most right-hand side of the highway segment, as shown in Figure 2. The source and destination could be in either the same lane or different lanes. The other N vehicles function as the relay nodes, uniformly distributed over the U lanes each with length $L-2L_c$ (remove the vehicle lengths of the source and destination).

We assume that all vehicles move towards the same direction with the same velocity v (m/s). These assumptions are rational because of the following reasons. First, vehicles with the same driving direction can form more stable networks than those driving with different directions. Second, vehicles with the same driving direction on the highway usually keeps similar velocity. Although the velocities may vary often, the fluctuation rate is typically small as compared to the signal bandwidth. We further set all vehicles' lengths to L_c m and assume that the safe distance between two vehicles is denoted by L_{sf} m, which typically takes 2 seconds for a car to drive through. Thus, we have

$$L_{sf} = 2v + L_c. \quad (1)$$

Following the above settings, the maximum number of vehicles in a lane is given by

$$N_{\text{Lane}} = \left\lfloor \frac{L-2L_c}{L_{sf}} \right\rfloor. \quad (2)$$

We employ QPSK modulation, convolutional code, and orthogonal frequency division multiplex (OFDM) for the signal transmissions, where the total number of subcarriers is denoted by M. The OFDM symbols for each coded data block and a pilot (also called preamble) OFDM symbol (for channel estimation) form a data frame. The detailed parameters will be elaborated on Section 4.1.

Note that each transmitter uses different pilots, which can be thoroughly designed such that the pilots are orthogonal to each other, while still expanding the entire frequency band. Then, multiple relay nodes can concurrently transmit pilots without impacting on the channel estimation at the receiver. The transmit power for pilots is large enough so that the channel estimation can be sufficiently accurate. As we have total M subcarriers, the degree-of-freedom equals M in the signal space. Hence, the maximum number of orthogonal pilots is also M. In this sense, the total number N of relay nodes needs to be smaller than M. It is worth noting that, in practical systems, the M is often set large for a variety of typical networks and the bandwidth and M can also be regulated to adapt to the actual number of relay nodes.

The channel fading between any two vehicles is supposed to be flat and block fading and follow Rayleigh fading model. The channel gains vary across consecutive frames based on the following model:

$$g_{Sn}[t] = \left(\frac{d_{Sn}}{L_c}\right)^{-\theta/2} h_{Sn}[t], \quad g_{nD}[t] = \left(\frac{d_{nD}}{L_c}\right)^{-\theta/2} h_{nD}[t], \quad (3)$$

where θ is the exponent for path-loss of power, $[t]$ is the index for frames, and $h_{Sn}[t]$ and $h_{nD}[t]$ represent the small-scale time-varying fading processes. In particular, the time-varying fading process is characterized by the first-order autoregression (AR) model as follows:

$$h_{Si}[t+1] = \alpha h_{Si}[t] + (1-\alpha) z_{Si}; \quad h_{nD}[t+1] = \alpha h_{nD}[t] + (1-\alpha) z_{nD}, \quad (4)$$

where z_{Si} and z_{nD} are independent circularly symmetric complex Gaussian random variables with unit variance and α is the parameter such that the half of the fading process' 10 dB bandwidth is equal to the maximum Doppler frequency $f_{\max} = v f_c/c$. In the rest of this paper, we will drop the frame index $[t]$ for presentation convenience.

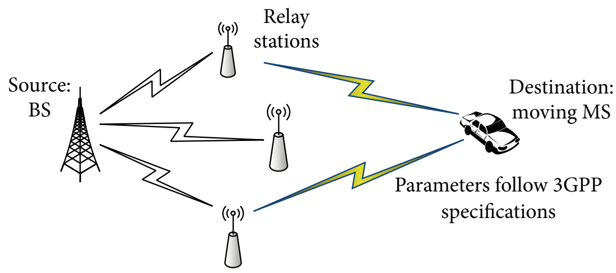

Figure 3: System model for cellular relay communications for mobile stations.

2.3. Cellular Relay Communications Model. The model of cellular relay communications for moving the mobile station is depicted in Figure 3, where the base station (BS) transmits data to the mobile station via relay stations. The modulation, coding, and channel model all follow the 3GPP specifications [16] and technical reports, which will be detailed in Section 2.3. Thus, the evaluations of our proposed scheme will be more meaningful for practical systems.

Note that the major differences between the cellular relay transmissions and the car-to-car relay communications include the followings. First, for cellular networks, the base station and the relay stations do not move, unlike the car-to-car communications. In this case, the channels of the broadcast phase in cellular networks are often statistically better than those in car-to-car communications. Second, the transmission environments for the 2nd-phase transmissions in cellular networks are usually more complex than car-to-car communications, leading to more sophisticated double-selective (time-selective and frequency-selective) channel models. Third, for cellular networks, we do not impose any constraints on the mobile station's size and positions. This is because the cellular network model usually deals with more general scenarios without specifying special requirements on the mobile stations.

As discussed in the above, in this paper we deal with two typical networks supporting delay-tolerant services. Our target is to develop the efficient relay and HARQ schemes which can fit well for diverse mobile networking environments by providing better reliability.

3. Selective Random CDD Enhanced Relay Transmissions

We in this paper proposed the selective random cyclic-delay diversity (CDD) enhanced relay beamforming scheme. Then, we will also discuss the conventional cooperative beamforming based relay transmissions in comparison with our proposed scheme.

3.1. The Selective Random CDD Transmission Schemes. The core idea of our scheme is to obtain the cyclic-delay diversity (CDD) in vehicular communications. The CDD technique is often used in multiple antenna techniques [17–20] for performance gain. As we have multiple relay nodes to cooperatively transmit data to the destination, we can virtually form a multi-input-multi-output (MIMO) transmission and thus be able to take advantage of CDD. The other merit for CDD is that the transmitter does not need the exact channel information. In this paper, we adopt the *selective random CDD* (to be explained later) for the 2nd-phase transmission and associated HARQ. Particularly, multiple relay nodes send data by using CDD. Correspondingly, the destination can choose the relay node based on the channel fading status if decoding is not successful. The selected relay nodes then again apply CDD for cooperative HARQ. The detailed processing procedures of the selective random CDD are given elaborated on as follows.

Step 1 (the first phase: broadcasting from source to relays). The source node broadcasts signal y_s (carrying a coded data block) to all potential relay nodes n, $n = 1, 2, \ldots, N$. Each relay node will attempt to decode the received signals. If a relay node successfully decodes the data, which will be verified by the Cyclic-Redundancy-Code (CRC) checking, this relay becomes a candidate node for next-phase transmissions. If all relays failed to decode, no relay will take action in next time frame. Then, the source node will hear nothing and thus can learn the failure of the first-phase transmission. Here we assume that the information control packets such as ACK/NACK/CSI feedback can use higher power and thus they are error-free once transmitted. In this case, although we do not transmit feedback packet, it takes one entire time frame for the source to know, which still causes one frame time overhead. Therefore, we can suppose a NACK packet is virtually transmitted when evaluating the throughput and overhead performances.

Step 2 (the second phase: random CDD based transmission from relays to destination). Assume that there are $\mathcal{N}$ candidate relay nodes and we denote the indices of candidate relay nodes by $q_1, q_2, \ldots, q_{\mathcal{N}}$, where $q_i \in [1, N]$. Then, the candidate relay nodes apply the CDD techniques to cooperatively transmit the successfully recovered signal y_s. In particular, y_s can be written as

$$y_s(k) = \frac{1}{\sqrt{M}} \sum_{m=1}^{M} Y_s(m) e^{j2\pi mk/M}, \quad k = 0, 1, \ldots, M-1, \tag{5}$$

where M is the total number of subcarriers, $Y_s(m)$ is the symbol on the mth subcarrier, and the notation (k) represents the kth time-domain sample of the corresponding OFDM symbol. Then, applying the CDD techniques across candidate relay nodes, we obtain the q_ith relay node's transmitted signal as

$$\begin{aligned} y_{q_i}(k) &= y_s\left(\left(k - \phi_{q_i}\right) \bmod M\right) \\ &= \frac{1}{\sqrt{M}} \sum_{m=1}^{M} \left[e^{(-j2\pi m/M)\phi_{q_i}} Y_s(m)\right] e^{j2\pi mk/M}, \end{aligned} \tag{6}$$

where ϕ_{q_i} is cyclic delay applied to the q_ith relay node. Correspondingly, the signals received at the destination node can be written as

$$y_{\mathrm{D}}(k) = \frac{1}{\sqrt{M}} \sum_{i=1}^{\mathcal{N}} g_{q_i \mathrm{D}} \sum_{m=1}^{M} \left[e^{(-j2\pi m/M)\phi_{q_i}} Y_{\mathrm{s}}(m) \right] e^{j2\pi mk/M} + n_{\mathrm{D}}(k), \quad (7)$$

where $n_{\mathrm{D}}(k)$ is the complex additive white Gaussian noise (AWGN) introduced at the destination's receiver. Thus, the equivalent fading channel coefficient for the mth subcarrier's symbol $Y_{\mathrm{s}}(m)$, denoted by $h_{\mathrm{eqv}}(m)$, can be written as

$$h_{\mathrm{eqv}}(m) \triangleq \sum_{i=1}^{\mathcal{N}} g_{q_i \mathrm{D}} e^{(-j2\pi m/M)\phi_{q_i}}. \quad (8)$$

We can see from (7) and (8) that, by applying cyclic shift at each relay node, we get the signals equivalent to CDD processing. That is to say, we can obtain an effective frequency-selective channel, which is constructed artificially. Correspondingly, if we apply channel coding in the system, which is a necessary function block in practical systems, we can achieve diversity gain in light of the constructed frequency-selective channels. Then, the problem remains which is how to set the cyclic delay for each candidate relay node. For this step, the cyclic delay for the q_ith relay node can be predetermined by

$$\phi_{q_i} = \frac{M}{N}(q_i - 1), \quad (9)$$

where N is the total number of relay nodes in the system. Clearly, ϕ_{q_i} does not depend on $\mathcal{N}$ and can be easily implemented by practical protocols. However, we need to note that the frequency selectivity by using CDD depends on the candidate relay nodes, which is determined by the independent fading across these nodes. Therefore, we call this approach the *Random CDD* scheme.

Step 3 (the second phase: ACK/NACK by the destination). If CRC checking returns correct results at the destination node, ACK packet is transmitted back to relays and further forwarded to the source by relays. New packet transmission will then be scheduled. In contrast, if CRC checking does not pass, NACK packet will be sent back. But the NACK packet is only forwarded towards selected candidate relay nodes. The selection is performed by the destination based on certain criterion, such as the signal-to-noise ratio (SNR) threshold based criterion. Then, the selected relay nodes will perform retransmission, that is, HARQ, in next step.

Step 4 (the second phase: retransmission by selective random CDD). In this step, the indices of selected candidate relay nodes are denoted by $r_1, r_2, \ldots, r_{\mathcal{N}_\ell}$, where ℓ represents the ℓth retransmission. The signal transmitted by the r_ith node is then given by

$$y_{r_i,\ell}(k) = \frac{1}{\sqrt{M}} \sum_{m=1}^{M} \left[e^{(-j2\pi m/M)\phi_{r_i,\ell}} Y_{\mathrm{s}}(m) \right] e^{j2\pi mk/M}, \quad (10)$$

where $\phi_{r_i,\ell}$ is the cyclic delay for the r_ith relay node in the ℓth retransmission. Specifically, $\phi_{r_i,\ell}$ can be set to

$$\phi_{r_i,\ell} = \frac{M}{\mathcal{N}_\ell}(i - 1). \quad (11)$$

Different from ϕ_{q_i} in (6), $\phi_{r_i,\ell}$ varies with $\mathcal{N}_\ell$, such that the cyclic delays between different selected relay nodes are separated as much as possible, where we can get better frequency selectivity. This can be implemented in that selected relay nodes can identify $\mathcal{N}_\ell$ by using the feedback signals from the destination.

Correspondingly, the received signal at the destination is given by

$$y_{\mathrm{D},\ell}(k) = \frac{1}{\sqrt{M}} \sum_{i=1}^{\mathcal{N}_\ell} g_{r_i \mathrm{D},\ell} \sum_{m=1}^{M} \left[e^{(-j2\pi m/M)\phi_{r_i,\ell}} Y_{\mathrm{s}}(m) \right] e^{j2\pi mk/M} + n_{\mathrm{D},\ell}(k), \quad (12)$$

where $n_{\mathrm{D},\ell}$ denotes the AWGN noise for the ℓth retransmission. Note that here we use $g_{r_i \mathrm{D},\ell}$ to denote the channel gain in the ℓth retransmission, which might be different from the CSI in the initial CDD based transmission due to channel variations caused by high velocities of moving vehicles. The destination node applies maximal ratio combing (MRC) to combine all received signals from initial transmission and retransmissions. Then, the destination node will redecode the combined signals and check CRC again.

Next, using the processing for $Y_{\mathrm{s}}(m)$ as typical example, we will explain how MRC is applied for HARQ in our selective CDD approach. In particular, after demodulation for the OFDM signal $y_{\mathrm{D}}(k)$ given in (7), we can get the signal useful for $Y_{\mathrm{s}}(m)$, denoted by $\widetilde{Y}_{\mathrm{s}}(m)$, as

$$\widetilde{Y}_{\mathrm{s}}(m) = h_{\mathrm{eqv}}(m) Y_{\mathrm{s}}(m) + \widetilde{n}_{\mathrm{D}}(m), \quad (13)$$

where $\widetilde{n}_{\mathrm{D}}(m)$ is the noise after FFT processing. We assume that the noise power and $Y_{\mathrm{s}}(m)$'s power are σ^2 and 1, respectively. Then, the SNR for $Y_{\mathrm{s}}(m)$ equals $|h_{\mathrm{eqv}}(m)|^2/\sigma^2$. Similarly, if the 1st retransmission is conducted, we can extract the useful signal for $Y_{\mathrm{s}}(m)$ from $y_{\mathrm{D},\ell}(k)$ (see (12)), denoted by $\widetilde{Y}_{\mathrm{s},1}(m)$, and then get

$$\widetilde{Y}_{\mathrm{s},1}(m) = h_{\mathrm{eqv},1}(m) Y_{\mathrm{s}}(m) + \widetilde{n}_{\mathrm{D},\ell}(k), \quad (14)$$

where

$$h_{\mathrm{eqv},1}(m) \triangleq \left(\sum_{i=1}^{\mathcal{N}_\ell} g_{r_i \mathrm{D},\ell} e^{(-j2\pi m/M)\phi_{r_i,\ell}} \right) \quad (15)$$

is the equivalent channel coefficient of $Y_{\mathrm{s}}(m)$ in the 1st retransmission. The variable $\widetilde{n}_{\mathrm{D},\ell}(k)$ is the noise after FFT processing in the 1st retransmission, whose power is clearly also σ^2. Then, the SNR here is $|h_{\mathrm{eqv},1}(m)|^2/\sigma^2$. By applying MRC over $\widetilde{Y}_{\mathrm{s}}(m)$ and $\widetilde{Y}_{\mathrm{s},1}(m)$, the combined signal is expressed by

$$h^*_{\mathrm{eqv}}(m) \widetilde{Y}_{\mathrm{s}}(m) + h^*_{\mathrm{eqv},1}(m) \widetilde{Y}_{\mathrm{s},1}(m), \quad (16)$$

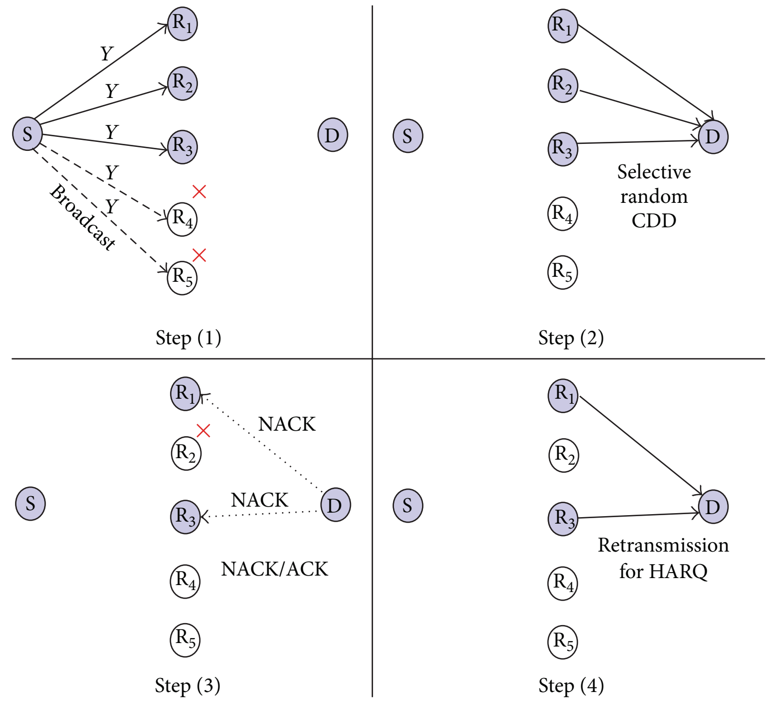

Figure 4: The procedures for our proposed selective random CDD based joint cooperative relay and HARQ scheme.

which is known to yield a combined SNR equal to

$$\frac{\left|\sum_{i=1}^{\mathcal{N}} g_{q_i\mathrm{D}} \cdot e^{(-j2\pi m/M)\phi_{q_i}}\right|^2}{\sigma^2} + \frac{\left|\sum_{i=1}^{\mathcal{N}_\ell} g_{r_i\mathrm{D},\ell} e^{(-j2\pi m/M)\phi_{r_i,\ell}}\right|^2}{\sigma^2}. \tag{17}$$

Clearly, the combined SNR is larger than either SNRs before MRC, implying the benefit obtained by HARQ over the selective CDD approach.

If CRC check does not pass, the destination will feed the NACK back and require retransmission again. This process is repeated until the maximum number of retransmissions is reached. Once successful, an ACK packet will be sent back to relays and relays will also transmit ACK to the source, indicating the successful transmission. Note that the selection is performed only once, and retransmission is always done from the selected nodes. This setup is motivated by the fact the channel often varies slowly as compared to the signal bandwidth. Figure 4 illustrates the procedures described in the above by a typical example with 5 relay nodes. As shown in Figure 4, there are three relays which become candidate nodes after broadcast phase. Among all candidate relay nodes, relay node 2 with poor channel quality will not involve retransmissions.

3.2. Discussions on the Proposed Scheme and the Conventional Approach. A conventional yet straightforward approach for cooperative relay and HARQ is cooperative beamforming. The cooperative beamforming has been proposed to achieve high throughput or minimum energy consumption in [13–15]. In the cooperative beamforming, the source broadcasts the data to the relay nodes, and some or all of which cooperatively perform beamforming to forward the data to the destination. For completeness of this paper, we summarize the basic procedure of the straightforward cooperative beamforming for HARQ transmission in the following.

Step 1 (broadcasting). The source broadcasts data to the multiple relay nodes. If the relay node decodes the data correctly, it involves the 2nd-phase transmission.

Step 2 (training). The selected relay nodes transmit the pilot signals to destination node.

Step 3 (feedback of CSI). The destination node chooses relay nodes based on the received pilots and feeds CSI back to the chosen relay nodesl.

Step 4 (cooperative beamforming). The selected relay nodes use maximal ratio transmission (MRT) beamforming to cooperatively send data to the destination based on CSI feedback.

Step 5 (NACK and CSI update). If CRC is correct in the destination, send back ACK and continue; if CRC is not correct, send back NACK and the update CSI to the selected relay nodes.

Step 6 (retransmission). The selected relay nodes transmit data Y cooperatively based on the feedback update CSI.

Step 7 (signal combination). Destination will combine the 2nd transmission selected results with the 1st transmission and check CRC again. If CRC is not correct, ask for retransmission again if the maximum transmission number is not achieved.

Compared to cooperative beamforming, the features of the proposed selective random CDD are as follows.

(i) If the direct forwarding through random CDD can get the correct results, that is, one time of packet transmission is enough to decode the data correctly in the 2nd hop, the new packet transmission can be scheduled in the following time. While in cooperative beamforming, the pilot signal must be transmitted at first, and the first packet transmission must wait for the CSI feedback from the destination based on the estimation of the pilot signal. Therefore, the feedback signaling overhead and round trip time of our proposal can be reduced compared to cooperative beamforming.

(ii) If the direct forwarding through random CDD fails, the selective random CDD only send back NACK to the relay nodes after the selection, which is performed by the destination based on some criteria, such as SINR threshold. The selection can get rid of relative bad relay nodes and then form a better frequency-selective channel, which can achieve diversity gain when concatenating with channel coding (channel coding is used generally in the wireless communication system), just like the description and evaluation in [21–24]. Moreover, the power consumption of the bad relay nodes can be saved because the unnecessary transmission is avoided.

(iii) Selective random CDD can work in fast fading channel, while the cooperative beamforming needs accurate CSI from the destination and is generally only used in slow fading channel.

(iv) Selective random CDD has no strict requirement on synchronization because of its inherent characteristics. However, in the cooperative beamforming, the multiple relay nodes need to keep the precise synchronization when transmitting the packets. Otherwise the performance will be reduced greatly.

4. Performance Evaluations

We in this section evaluate the performances of our proposed scheme via simulations. Specifically, we will summarize the simulation results in Sections 4.1 and 4.2, respectively, because the network environments and system parameters are very different for the two networks. For comparative purposes, we also simulate the performances of the conventional cooperative beamforming approach described in Section 3.2 as the baseline scheme.

4.1. Simulations Setup and Results for the Scenario of Car-to-Car Communications. For the vehicular network described in Section 2.2, the parameters for the car-to-car communications are as follows. We set the vehicular velocity by $v = 60$ km/h. The carrier frequency locates at 2 GHz, leading to the maximum Doppler frequency 111.11 Hz. The OFDM symbol length is equal to 80 μs and thus the subcarrier interval is equal to 12.5 kHz. The length of cyclic prefix (CP) equals 20 μs, and then an OFDM symbol eventually spans 100 μs. We use total 32 OFDM subcarriers, resulting in the total signal bandwidth $B = 400$ kHz. Further, the convolution code with rate 1/2 and constraint length 9 is applied across 9 OFDM symbols. A 32×9 interleaver is also adopted. One OFDM symbol (preamble/pilot) is inserted before the coded OFDM symbols for channel estimation at the receiver. Correspondingly, these 10 OFDM symbols together form a frame with time length equal to 1 ms, thus carrying 272 information bits. We suppose that the frame length for feedback packet (ACK/NACK with/without CSI) is also 1 ms, which is the same as data frame. The rational of the frame length setup lies in the following facts.

First of all, 1 ms frame is widely used for the practical communications system such as LTE-A [16]. Making the frame length further short does not provide useful guidance for practical systems. Moreover, given the vehicular velocity v at 60 km/h and the carrier frequency of 2 GHz (typical frequency band for cellular networks), the maximum Doppler frequency is thus equal to 111.11 Hz, which suggests that the wireless channels usually change significantly over around 10 ms (roughly obtained by taking the reciprocal of the maximum Doppler frequency). In this sense, if using a long frame, the channel may vary drastically within a frame, causing considerable difficulties for channel estimation and signal detection in practical systems. It is worth noting that this issue in fact just reflects the unique features for car-to-car communications. Due to the high moving speed, the wireless channels vary very fast and therefore the employment of short time frames is desired, although the amount of overhead increases a bit accordingly. Following the above discussions, we can see that setting frame length to 1 ms is reasonable by taking both the channel variation and the practical implementations into consideration.

The path-loss exponent $\theta = 2.5$ and the small-scale fading follows the AR model described in Section 2.2. The transmit power is equivalently characterized by a parameter termed coverage radius, denoted by CR (m). Specifically, the transmit power is selected such that the uncoded QPSK's BER (consider large-scale fading only) is 0.1 for transmission distance CR.

We concentrate on three metrics for performance evaluations, namely, *transmission failure probability*, *average overhead* (frame), and *average throughput*. Specifically, the transmission failure probability is defined as the probability that the transmission of a coded data block is failed. The average overhead is defined by the average number of feedback packets (ACK/NACK with/without CSI) consumed for the transmission of each data block (either success of failure). The average throughput counts for the information bits transmitted per second.

Figure 5 plots the transmission failure probability as a function of the number N of relay nodes in the vehicular network. According to Figure 5, the transmission failure probabilities of both our proposed selective random CDD scheme and the conventional cooperative beamforming scheme decrease when getting more relay nodes. This is expected in that more relay nodes offer better selection, increasing the possibility of success transmission. From Figure 5, we can

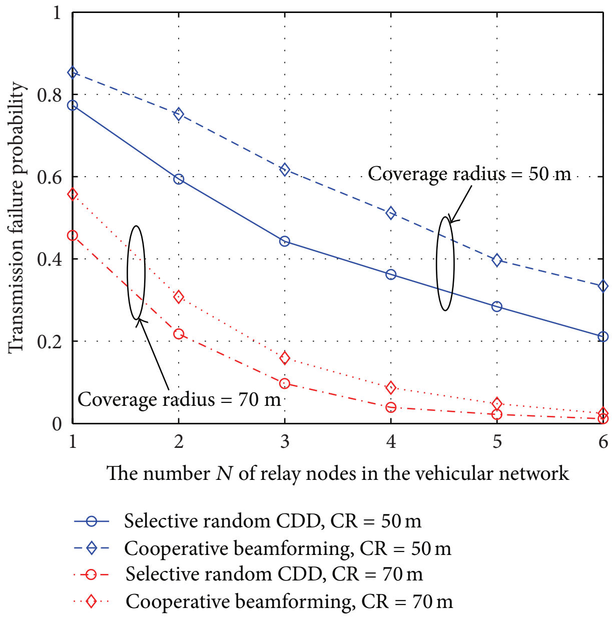

FIGURE 5: The transmission failure probability versus the number N of relay nodes in the vehicular network.

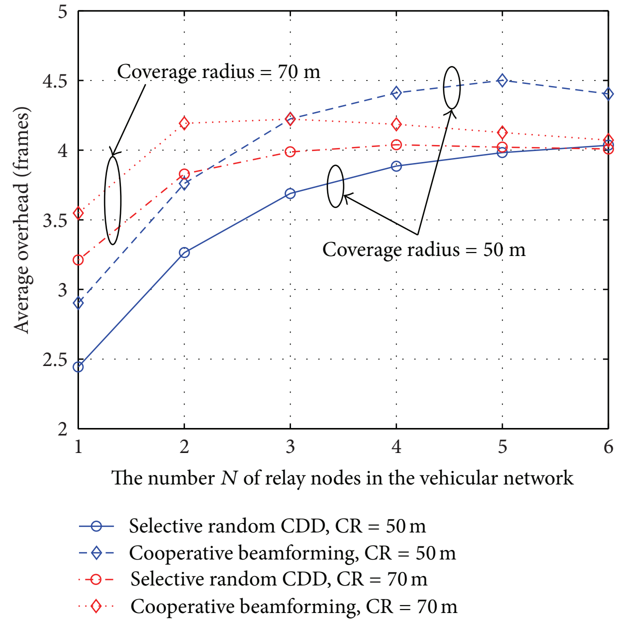

FIGURE 6: The average overhead per data block transmission versus the number N of relay nodes in the vehicular network.

also see that larger coverage radius (or, equivalently, higher transmission power) causes lower transmission probability.

The more important observation from Figure 5 is that our proposed scheme achieves a significant reduction of failure probability compared with the cooperative beamforming approach. This advantage comes from two facts. As discussed previously, the selective random CDD scheme can create artificial frequency selectivity, thus attaining extra diversity gains when channel coding is employed. On the other hand, the selective CDD scheme does not need CSI, not like the cooperative beamforming. In car-to-car communications, the channels vary fast and CSI obtained one frame before is often not very accurate already. Moreover, the cooperative beamforming requires dedicated pilot frame (without data payload, see Section 3.2), causing extra delay and thus further degrading the accuracy of CSI. In the meantime, the extra delay also lowers the throughput, which will be demonstrated in Figure 7.

Figure 6 depicts the average overhead against the number N of relay nodes. Figure 6 demonstrates that our proposed selective random CDD scheme dominates the cooperative beamforming scheme under all values of N. An interesting observation from Figure 6 is that the average overhead might not be a monotonic function of N, which is also expected based on the following reasons. For small N, the broadcasting phase is very likely unsuccessful. So, the second-phase transmission will not proceed, which in fact avoid more overhead transmissions. For large N, better choice of relays can be made to decrease the number of retransmissions and thus the overhead. Similar arguments can be used to justify the observation that higher coverage radius (i.e., higher transmit power) does not necessarily lower the overhead.

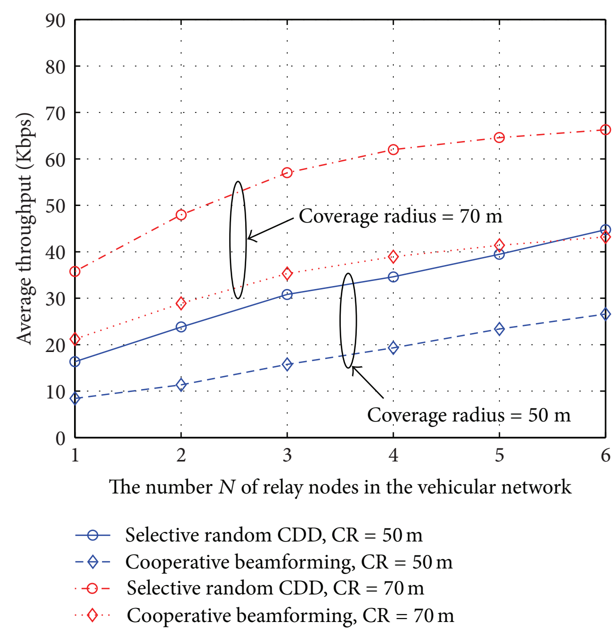

FIGURE 7: Average throughput versus the number N of relay nodes in the vehicular network.

Figure 7 illustrates the average throughput versus the number N of relay nodes. The throughput of both schemes increases with N getting larger, which is consistent with the results obtained in Figure 5. Moreover, it is expected that the selective random CDD scheme performs better, because it dominates the cooperative beamforming in terms of lower failure probability as well as lower overhead. We can also see that, for $N = 6$, the performance of our scheme with coverage radius 50 m can even match that of

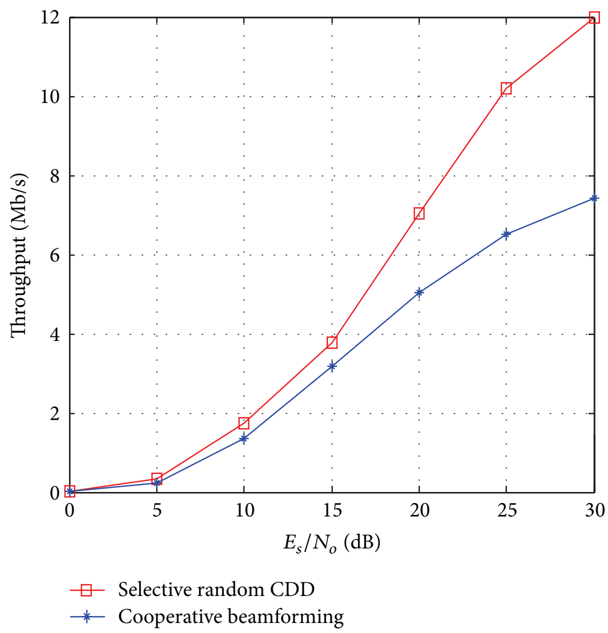

FIGURE 8: Throughput comparison between selective random CDD scheme and cooperative beamforming scheme (Case IV, 3 km/h).

the cooperative beamforming with coverage radius 70 m, which also demonstrates the advantages of our selective random CDD scheme. Figure 7 further shows that when higher transmit power is used (i.e., yield larger coverage radius), we can achieve higher throughput gain by the selective random CDD scheme compared with the cooperative beamforming approach.

4.2. Simulations Setup and Results for the Scenario of the Cellular Network. The main simulation parameters for the cellular network with mobile stations are summarized in Table 1. The detailed simulation settings such as OFDM parameters and frame structures follow the 3GPP specifications. In Table 1, we employ the single antenna setup for transmitting and receiving data. Note that our scheme can be also readily extended to the scenario with multiantenna transceivers. But in simulations, in order to concentrate on the gain brought by the HARQ and CDD techniques, we assume to use the single antenna systems.

Figure 8 plots the throughput performance of the selective random CDD and cooperative beamforming schemes as the function of SNR per symbol denoted by E_s/N_o, where the velocity of the mobile station is 3 km/h. It is worth mentioning that the time of the feedback is also taken into consideration in simulations. We can see from Figure 8 that the selective random CDD achieves much higher throughput than the conventional cooperative beamforming, especially in the high SNR region. The reason of the performance improvement is mainly because that the selective random CDD has lower transmission delay as well as overhead compared with the cooperative beamforming. This observation is consistent with the results obtained for car-to-car communications (see Figure 7). Therefore, our proposed

TABLE 1: Simulation parameters for the cellular network.

3GPP LTE system enhanced with relay	20 MHz bandwidth
The number of transmit antennas for BS, RS, and UE (MS)	1
The number of receive antennas for BS, RS, and UE (MS)	1
The maximum number of retransmissions	1
The number of RS	3
Channel model	3GPP SCM channel: (a) Case II 120 km/h; (b) Case IV: 3 km/h
Channel code	Turbo code
Code rate	1/2
Modulation constellation	QPSK

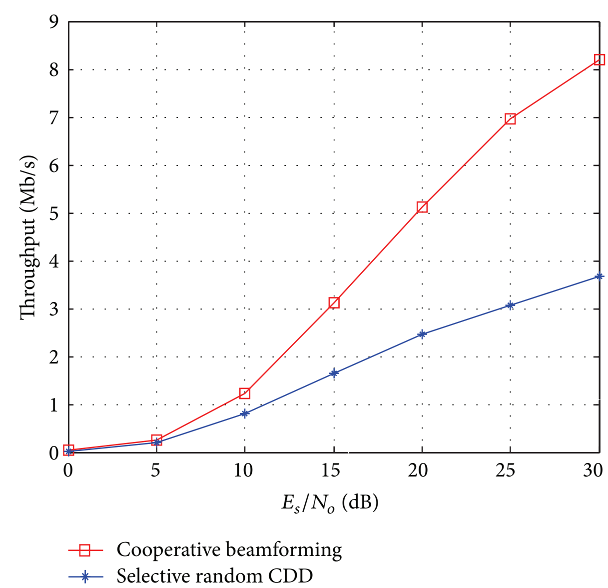

FIGURE 9: Throughput comparison between selective random CDD and cooperative beamforming (Case II, 120 km/h).

selective random CDD scheme can work well in diverse networks with mobile nodes.

Figure 9 illustrates the throughput performance against SNR, where the velocity of the mobile station is 120 km/h. We can see that when the moving speed gets higher, the throughput improvement of the selective random CDD over the cooperative beamforming further becomes more significant correspondingly. This is also expected because larger velocity of mobile stations leads to higher variation rate of wireless channels. As a result, the CSI to the relay will be more inaccurate when they are used for cooperative beamforming.

The transmission time delay is also evaluated by counting the average uplink and downlink transmission time, that

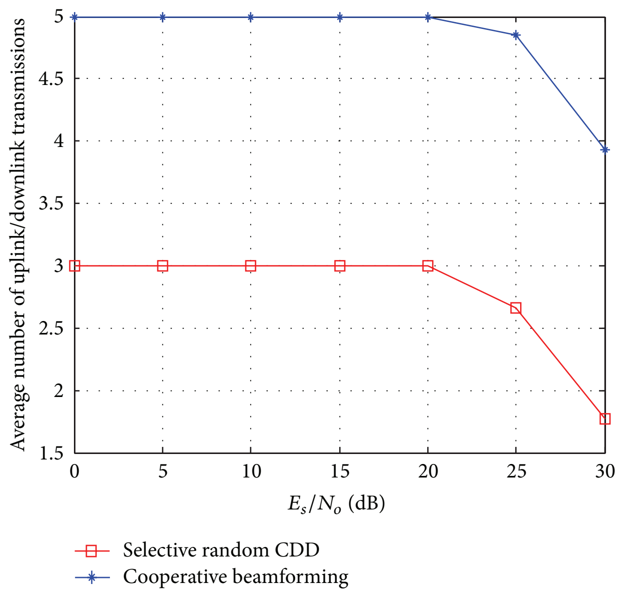

Figure 10: Transmission time delay comparison between selective random CDD and cooperative beamforming.

is, round trip time, in Figure 10. The two schemes are compared in the simulation. It can be seen from the statistical results given in Figure 10 that the round trip time (RTT) of the selective random CDD is lower than our proposed scheme. This is because the selective random CDD does not need CSI feedback in the first transmission attempt, which already gets considerable probability of success. In contrast, the cooperative beamforming needs to wait for CSI feedback, causing major delay for data delivery in the dual-hop transmissions.

5. Conclusions

We proposed a selective random CDD based joint cooperative relay and HARQ scheme for delay-tolerant services in vehicular communications. Our design can take advantage of frequency selectivity created by applying CDD techniques. In the meantime, the selective random CDD can reduce the overhead as well as the dependency on CSI compared with conventional cooperative beamforming scheme. Our design was proposed under a generic model and can be applied to two typical vehicular networking scenarios, including car-to-car communications in highway environments and BS-to-MS communications in cellular networks. Through simulations, our proposed scheme exhibited performance superiority over the conventional cooperative beamforming scheme in terms of throughput and transmission failure probability.

Notations and Variables

N: The number of relay nodes in the network

d_{Sn}: The distance between the source node and the nth relay node

d_{nD}: The distance from the nth relay node to the destination node

P_S: The transmit power for the source node

P_n: The transmit power for the nth relay node

B: Total signal bandwidth

v: The velocity of moving vehicles

L_c: Each vehicle's length

L_{sf}: The safe distance between two moving vehicles

N_{Lane}: The number of lanes in highway

M: The number of subcarriers in the OFDM system

$g_{Sn}[t]$: The complex channel gain between the source node and the nth relay node in the tth frame

$g_{nD}[t]$: The complex channel gain between the nth relay node and the destination node in the tth frame

f_{max}: Maximum Doppler frequency

$y_s(k)$: Signal broadcast by the source node, where (k) indices the kth sample in an OFDM symbol

$Y_s(m)$: The symbol on the mth subcarrier

$\mathcal{N}$: The number of candidate relay nodes after broadcast-phase transmission (first-hop transmission)

q_i: The q_ith candidate node's original index over all N relay nodes

$y_{q_i}(k)$: The CDD signal sent by the q_ith relay node

$y_D(k)$: The signal received at the destination node during the initial CDD based transmission in the second phase (i.e., the transmission for second hop)

$h_{eqv}(m)$: The equivalent fading channel coefficient during the initial CDD based transmission in the second phase

ϕ_{q_i}: The cyclic delay for the q_ith relay node

$h_{eqv,\ell}(m)$: The equivalent fading channel coefficient within the ℓth retransmission in the second phase

$\phi_{r_i,\ell}$: The cyclic delay for the r_ith relay node in the ℓth retransmission

$g_{r_iD,\ell}$: The channel coefficient between the r_ith relay node and the destination node within the ℓth retransmission.

Conflict of Interests

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

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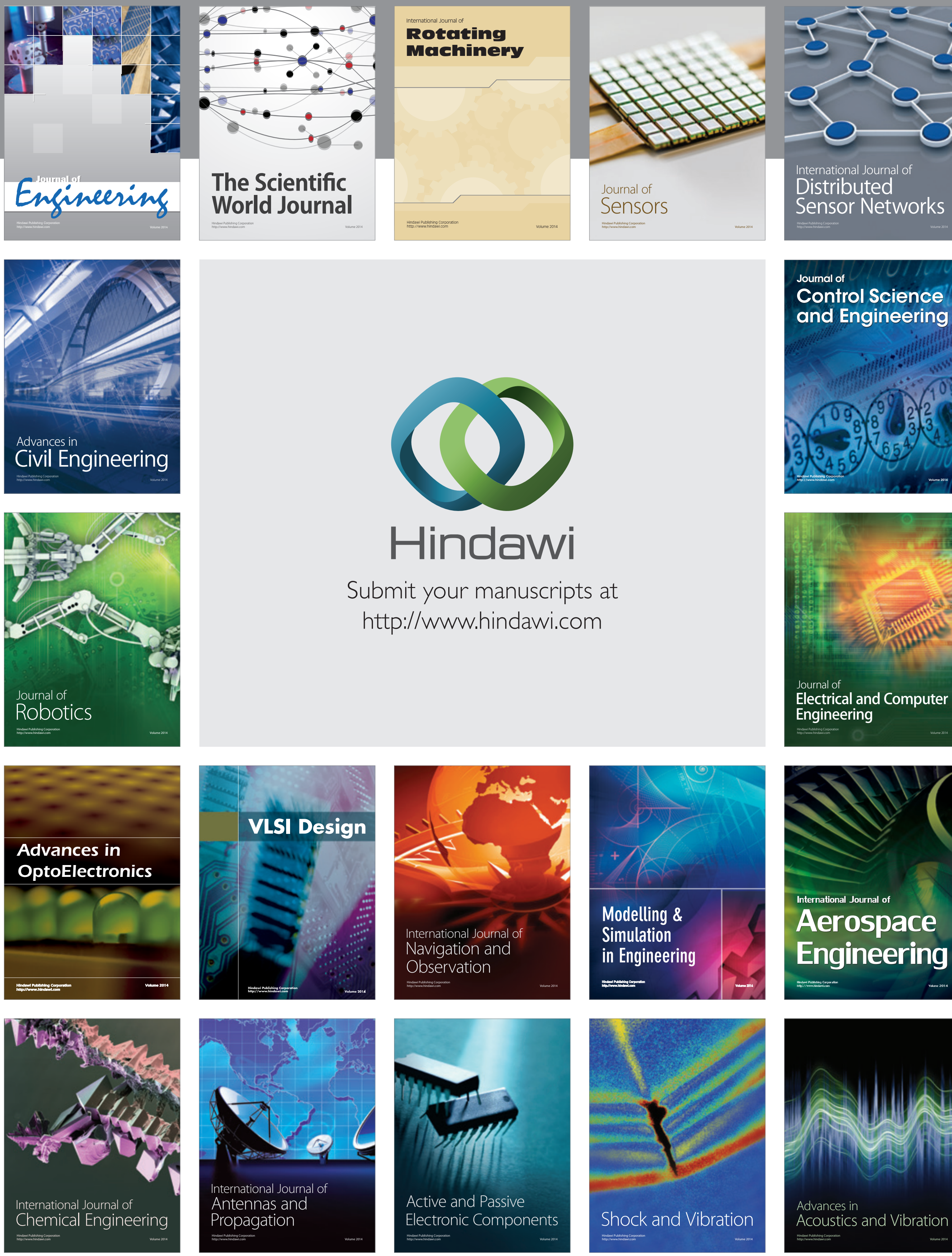

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