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Spatial diversity for IEEE 802.11p Post-crash Message Dissemination in a Highway Environment

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Abstract—In this paper, we evaluate the performance of broadcast safety applications in a vehicular-to-vehicular (V2V) communication scenario using a BER-based reception model from a detailed IEEE 802.11p physical layer simulator for a more accurate interpretation of the vehicular communication system, instead of the prebuilt SNR threshold model available in a typical network simulators. Our main contribution is the spatial diversity analysis provided using MIMO-STBC, that is specific to modulation types, vehicular speeds and range of SNR values. To further improve the accuracy of the analysis, realistic vehicular traces from a bidirectional highway are used as the mobility model. Finally, we included post-crash warning message prioritization over periodic status updates by enabling a hybrid EDCA MAC. Our analysis shows that MIMO-STBC achieves up to 80% range extension of the 1-hop safety broadcast in a V2V when compared against single antenna system.

Index Terms—IEEE 802.11p, V2V, MIMO-STBC.

I. INTRODUCTION

IEEE 802.11p or Wireless Access Vehicular Environments (WAVE) is a new standard proposal to allow fast and reliable direct communication between vehicles in a rapidly changing node density, topology and Doppler shifts. The 9th Draft Standard of IEEE 802.11p [1] was recently released in September 2009. WAVE is intended to be one of the solutions to reduce road accident fatality and injury that claimed millions of lives around the world. In the year 2007, the European Union alone recorded about 43,000 deaths and more than 1.8 million injuries, representing an estimated costs of 160 billion Euros in addition to the human tragedies [2].

However, a high mobility vehicular environment suffers from extremely challenging channel characteristics. Spatial diversity is an attractive solution to handle high Doppler and delay spread in a vehicular environment and requires a low complexity design. Furthermore, it is suitable for deployment on vehicles with its abundance of space availability. In [4], the authors considered STBC in a rapidly changing vehicular environments, however their analysis is limited to the physical layer. We extend the spatial diversity analysis by integrating a detailed physical layer simulator and network simulator to include real vehicles mobility traces and higher layer IEEE 802.11p parameters. This higher layer analysis enables us to study the effect of periodic packet transmission and evaluate the performance in terms of the safety messages packet delivery ratio and communication distance compared to a SISO scheme.

In [5] the authors proposed a channel tracking mechanism such as the midamble data-aided method to cope with high Doppler

environments. Here, we provide further analysis of midamble channel estimation in MIMO-STBC Vehicular Ad hoc Network (VANET) scenarios. Although a number of vehicular-to-vehicular (V2V) channel measurements has been performed recently [6], [7], a complete model is not yet available. Therefore, we implemented a time-varying channel model of up to 1100 Hz Doppler shift adapted from the ETSI channel B [8], with mean rms delay spread as expected in a highway scenario. This has been used in our 802.11p physical layer simulator.

Typical network simulators are not able to model the complexity of the physical layer design and therefore use the SNR threshold reception model. The BER-reception model is more exhaustive but is known to give a more accurate and realistic evaluation of specific environments. It was used in previous work for MANETs (Mobile Ad Hoc Network) e.g. [9], but to the best of our knowledge, a specific model for VANET has not been investigated yet. Therefore, we present a MIMO-STBC analysis using a BER-based reception model, that is specific to vehicular speeds, modulation types and range of SINR values. Our work extends the analysis in [10] to include and quantify the impact of spatial diversity against single antenna configuration.

In this paper, we evaluate the performance of spatial diversity for broadcast safety applications in a V2V environment. The simulation environment considered is described in Section II. Section III presents the physical layer simulator results. Section IV evaluates the packet delivery ratio of post-crash warning messages in two scenarios, i.e. with and without interference from periodic status messages. In the latter part of Section IV, a hybrid EDCA (Enhanced Distributed Channel Access) MAC is also considered by prioritizing the post-crash warning messages over periodic status updates. Finally, Section V concludes the paper.

II. SIMULATION ENVIRONMENT

Two types of Constant Bit Rate (CBR) safety message broadcasts are considered, namely a periodic status update and an event-driven emergency message. The periodic status message is used to communicate node status such as coordinate, speed, direction and GPS information. Meanwhile, the event-driven message is used to send critical safety notifications.

We assume a highway scenario in Figure 1, where a stationary vehicle involved in an accident is repeatedly transmitting post-crash warning to high speed vehicles approaching the accident area. The dotted circle represents the intended communication range (CR)

with a two-ray ground (TRG) path loss model given by eq. (1), where P_R is the received threshold power, P_T is the transmit power, G_T and G_R is the transmit and receiver antenna gain, h_t and h_r is the transmit and receiver antenna height and L is other losses. The simulation parameters used are shown in Table I.

$$P_R = \frac{P_T G_T G_R}{L} \left(\frac{h_t h_r}{CR^2} \right)^2 \quad (1)$$

We performed the simulation following IEEE 802.11p Physical and MAC parameters as specified in [12]. Among the modifications of IEEE 802.11p from existing IEEE 802.11a parameters are the reduction of channel bandwidth to 10MHz, higher interframe duration, slot time and longer PLCP preamble and header duration. In addition, BER curves from our Physical layer IEEE 802.11p simulator were integrated in Qualnet [14].

To model a realistic vehicular environment in highways, mobility traces from [15] are processed into a format readable in Qualnet. The scenario used is a 3-lane bidirectional highway with 2 types of vehicular densities, 6 vehicles per-km-lane (low density) and 11 vehicles per-km-lane (high density). The trace is 15 km in length, which translates to more than 500 vehicles in the low density environment, and almost 1000 vehicles in a high density environment.

Five different highway mobility traces, each of duration 60 seconds, are split into six smaller 10 seconds traces and plots are based on the average values of these 30 simulation runs. All cars are assumed to be equipped with a 5.9 GHz DSRC OBU (On board Unit). The average packet delivery ratio (PDR) statistic at each receiving vehicle is plotted against its distance to the accident location. Since the receiving vehicles are moving, the distance value used is the average distance to accident location from when the simulation starts to when the simulation ends. The Rayleigh and Rician with 8dB K-factor channel model used is comparable to Nakagami-m probabilistic model with $m=1$ and $m=3$ accordingly. The capture effect in [11] is currently not used but will be considered in future work.

TABLE I
PHYSICAL LAYER PARAMETERS

Parameter	Value
Operating frequency	5.9 GHz
Transmit power	23 dBm
Receiver threshold	-82 dBm
Antenna gain	0 dBi
Antenna height	1.5 m
TRG Communication range (CR)	630 m (eq. 1)
Packet generation Rate (PGR)	10 packets/s
Broadcast CBR packet size	500 bytes
Channel Model	Rayleigh, Rician K=8dB

III. PHYSICAL LAYER PERFORMANCE

Typical network simulators do not include advanced and high complexity physical layer features. Considering this limitation, we have developed a detailed physical layer simulator to model a time-correlated and high Doppler channel as expected in a highway

Fig. 1. Vehicular accident scenario on highway

road topology for SISO and 2x2 STBC systems. The physical layer simulator block diagram for an STBC 2x2 antenna system is an extension from previous work in [16]. The transmitter is built from a scrambler block to eliminate long 0's or 1's sequences, convolutional encoder with a puncturing block to adjust the coding rate, an interleaver for protection against burst error, signal mapping to achieve the targeted data rate, and finally OFDM (Orthogonal Frequency Division Multiplexing) modulation that includes an IFFT (Inverse Fast Fourier Transform) and cyclic prefix to eliminate ISI (Inter-symbol interference) and ICI (Inter-carrier interference).

MIMO-STBC [3] is a well-known technique used to provide spatial diversity and combat multipath fading in wireless communications. With plenty of space availability on vehicles, antennas can be placed sufficiently apart so that the transmission paths experienced by each transmit or receive antennas are fairly decorrelated. However, due to the nature of the rapidly varying scatterers and Doppler shift caused by the moving vehicle, the conventional assumption of an independent and identically distributed channel can no longer be made [4]. Therefore, to simulate time evolution of the channel, we apply Clarke's model as presented in [17]. Each of the channel taps are derived from a standard time-varying Rayleigh process that can be adapted to specific maximum vehicular speeds as shown in eq. (2):

$$h(t) = \sum_{n=1}^L A_n \cdot \exp(j(\phi_n - 2\pi f_d t \cdot \cos(\alpha_n))) \quad (2)$$

where phase ϕ_n , and arrival azimuth α_n , is uniformly distributed over $(\pi, -\pi)$, A_n is unit value fading amplitude, f_d is the maximum Doppler frequency derived from $f_d = \frac{vf}{c}$, i.e. v is maximum vehicular speed in m/s, f is the IEEE 802.11p channel frequency set at 5.9GHz, $c = 3 \times 10^8$ m/s, and L is the number of multipath components. This Rayleigh channel is multiplied with an 8-tap exponentially decaying power delay profile from the ETSI Channel B model [8] with 100 ns mean rms delay spread. This delay spread is in agreement with highway measurements as reported in [6]. Maximum Doppler shifts of 550 Hz and 1100 Hz are derived from the relative motion of 2 cars travelling in opposite directions. Different relative speed of 100 km/h and 200 km/h are used to model a worst case scenario that cars are driving at a maximum speed of 50 km/h in a high density, and 100 km/h in a low density bidirectional highway.

To combat multipath delay and Doppler shifts in vehicular environments, we utilized the midamble data-aided method as proposed in [5]. Using this method, the preamble long training sequence is reused as midamble for channel tracking. We implemented a 30 symbols midamble spacing unlike [5] where the use of 10 OFDM symbol is proposed. This is based on our analysis as shown in Figure 2 that with the chosen payload size, 30 symbols spacing achieves almost similar error performance but with half the overhead requirement. This is in agreement with the space-time correlation $\rho(\Delta t)$ as a function of zero-th order Bessel function of the first kind, $J_0(\cdot)$, velocity, v , Doppler spread, f_d and distance traversed, Δt as shown in eq. (3). Based on our analysis, the coherence time, T_c for 500 bytes payload is 55 and 28 OFDM symbols for vehicular speed of 100 km/h and 200 km/h accordingly.

$$\rho(\Delta t) = J_0(2\pi f_d v \Delta t) \quad (3)$$

Using the midambles, the channel state information (CSI) is constructed at the receiver using a zero-forcing algorithm and spline interpolation across each subcarrier. After FFT and cyclic prefix removal, the frequency domain $N_R \times D$ received signal, $R[k]$ is given by eq. (4):

$$R[k] = H[k] \cdot S[k] + N[k] \quad (4)$$

where $S[k]$ is the $N_T \times D$ transmitted signal, $H(t)$ is a $N_R \times N_T$ channel matrix, $N[k]$ is complex AWGN (Additive White Gaussian Noise) with zero mean and $N_0/2$ variance, D is the number of transmitted OFDM symbols, N_T and N_R is the number of transmitting and receiving antennas.

TABLE II
DATA RATES IN IEEE 802.11P

Mode	Modulation & Coding Rate	Data rate (Mbps)	coded bits/OFDM symbol	Data bits/OFDM symbol
1	BPSK 1/2	3	48	24
2	BPSK 3/4	4.5	48	36
3	QPSK 1/2	6	96	48
4	QPSK 3/4	9	96	72
5	16QAM 1/2	12	192	96
6	16QAM 3/4	18	192	144
7	64QAM 3/4	27	288	216
8	64QAM 2/3	24	288	192

Figure 2 shows that at BER of 10^{-3} , STBC 2x2 gives a coding gain of 4 dB at speed 100 km/h and 6 dB at 200 km/h against SISO system. It is also shown that by only using a preamble for channel estimation, an error floor will occur even at a low relative speed of 50 km/h. Figure 3 depicts the BER comparison of all the data rates supported in IEEE 802.11p as illustrated in Table II. It can be seen that at the highest modulation and coding mode, an error floor started to occur from insufficient channel tracking. We have chosen QPSK 1/2 (6 Mbps data rate) in Qualnet higher layer simulations as one of the most robust communication modes for safety message broadcast transmission. This data rate is also defined as the default data rate in IEEE 802.11p [13]. Our analysis in Figure 4 also shown that error rate performance is impacted by the packet size, and that STBC performs better in all cases as compared to SISO system.

Fig. 2. Error performance in a vehicular channel: SISO vs. STBC 2x2 for various speed at 6Mbps

Fig. 3. Error performance in a vehicular channel: SISO for various data rates at 100 km/h using midamble

IV. SIMULATION RESULTS

A. Emergency Broadcast Without Interference

For safety messages broadcast, we consider ad hoc broadcast messaging, with no requirement on RTS/CTS reservation, no acknowledgment of packet reception and no authentication or association procedures. The MAC parameters that have been modified in Qualnet following guidelines from [12] are captured in Table III. In this scenario, the speed used in BER curve corresponds to the maximum speed of approaching vehicles.

TABLE III
MAC PARAMETERS

Parameter	Value
Slot Time, T_{slot}	13 μs
SIFS (Short Inter frame Spacing)	32 μs
PLCP Preamble Length	32 μs
PLCP Header Length	8 μs
OFDM symbol duration, T_s	8 μs
Minimum contention window, CW_{min}	31 $\cdot T_{slot}$

We first analyze an ideal scenario where there is no interference from moving vehicles approaching the accident area. In this scenario, only the vehicle that had the accident will be transmitting

Fig. 4. Error performance in a vehicular channel: SISO vs. STBC 2x2 for various packet size at 6 Mps using midamble

emergency event-driven message broadcasts and there are no periodic beacons. This represents a channel free from collisions. The PDR curve for a SISO system in low traffic density in Figure 5 shows that both the Rayleigh and Rician channels increase the communication distance compared to the Two Ray Ground 630 m intended communication range. It is also shown that although a Rayleigh channel has worst performance than a Rician channel above 25% PDR, the Rayleigh channel performance is slightly higher than Rician at low PDR and it extends the 1-hop broadcast range as also shown in [10]. We have extended the numerical studies to include STBC results obtained using our Matlab physical layer simulator that achieves further communication range extension from its spatial diversity capability.

Using the BER reception model, we are able to differentiate the probability of reception according to traffic density (100 km/h maximum vehicular speed for the high traffic density and 200 km/h for the low traffic density model). As expected, the packet reception curve for SISO is increased in a high traffic density due to the improved BER curve at lower speeds. At 500m, a 15% PDR improvement for SISO in Rayleigh channel, and 20% improvement between low and high density traffic for SISO in Rician channels are seen. Meanwhile, the PDR curves for the STBC 2x2 in high and low density scenarios are overlapping in a no interference scenario due to the almost similar BER curves as shown in Figure 2. With no interference, at 30% PDR, STBC 2x2 provides 60% and 55% range improvement in Rayleigh and Rician channels against SISO system.

B. Emergency Broadcast With Interference

In the IEEE 802.11p standard, the status update and emergency messages will interfere with one another as they are transmitted in the same control channel (CCH). Due to the bidirectional highway scenario, the speed used in the BER curves corresponds to maximum relative motion between cars from different lanes. Since all safety messages shall be transmitted using the same channel frequency, all vehicles must contend with their neighbours before transmitting. Here, we analyze the performance of single antenna against multiple antennas with and without traffic prioritization.

Fig. 5. Emergency message broadcast with no interference

Vehicles are considered as QSTA (QoS-supported stations) and the EDCA feature in IEEE 802.11e hybrid MAC is enabled. We assigned two different priorities as shown in Table IV with different AIFSN (Arbitration Inter-Frame Space Number) and ECWmin (EDCA minimum contention window). In the original 802.11 MAC, a station (STA) that wishes to transmit shall sense the wireless medium so the medium must be continuously idle for DIFS (DCF Inter-Frame Space) period of $58 \mu s$ and an average backoff time of $208 \mu s$ is required. But with QSTA in the case of EDCA, AIFS (Arbitration Inter-Frame Space) as in eq. (5) according to traffic priority is used instead of DIFS, thus the inter-frame spacing for low priority traffic is increased. For high priority traffic, the AIFS value is the same as DIFS but the average backoff is reduced.

TABLE IV
EDCA PARAMETERS FOR TWO DIFFERENT SAFETY MESSAGES

Message type	ECW_{min}	AIFSN	AIFS	Average backoff
Status update	$CW_{min} = 31$	7	$123 \mu s$	$208 \mu s$
Post-crash warning	$\frac{CW_{min}+1}{4} - 1 = 7$	2	$58 \mu s$	$52 \mu s$

$$AIFS = SIFS + AIFSN \cdot T_{slot} \quad (5)$$

$$T_{ave. backoff} = \frac{(ECW_{min} + 1) \cdot T_{slot}}{2} \quad (6)$$

$$Total\ duration = DIFS[@AIFS] + T_{ave. backoff} + \frac{MPDU\ size}{R} + SIFS \quad (7)$$

Figure 6 and Figure 7 show that the maximum PDR of post-crash message in interference can never reach 100% even at close distances unlike previous analysis in Figure 5, with more adverse effect seen in a Rayleigh channel. Contradictory to Figure 5, it is also shown that high traffic density always has worst PDR performance than low traffic density. This is proportional to the level of interference from higher number of surrounding vehicles, that has more impact than better BER performance due to the lower speed assumption in high density traffic as illustrated in Figure 2.

At 30% PDR, EDCA provides less than 10% range extension in low density traffic as compared to no prioritization. For a high

density scenario, around 15% to 30% range extension is provided by EDCA. The comparison of a SISO and STBC 2x2 system shows that in low density, spatial diversity provides 60% to 80% range extension. Meanwhile, in high density scenario, around 43% to 70% range extension is provided. These ranges however are almost half the reception range possible without any interference.

Fig. 6. Emergency message broadcast with interference from periodic status message in Rayleigh channel

Fig. 7. Emergency message broadcast with interference from periodic status message in Rician channel

V. CONCLUSION

In this work, the performance of two types of safety broadcast messages, i.e. an event-driven post-crash message and a periodic status update message have been presented. The integration of a network simulator and a detailed physical layer simulator for SISO systems and MIMO-STBC in a time-correlated vehicular environment allows a more accurate analysis of wireless communication in a vehicular scenario. It can be concluded that MIMO-STBC offers between 43% to 80% range extension as compared to a SISO system, and that the performance improvement of MIMO-STBC is more pronounced in scenarios when there is high interference from surrounding vehicles. It is also shown that traffic prioritization using the hybrid MAC EDCA feature can increase up to 30% packet

delivery ratio of the IEEE 802.11p emergency message. Standard deviation of all PDR figures are around 5%. This analysis shows that spatial diversity not only reduces the SNR requirement, but also extends the driver awareness horizon.

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