Design of a Software Defined Radio Channel Simulator for Mobile Communications: Performance Demonstration with DSRC for Different Vehicle Speeds

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Abstract – The reconfiguration scheme and channel algorithms of the software defined radio (SDR) channel simulator is designed for testing the baseband transceiver of various mobile radio systems. The flexibility in selecting a combination of waveform and fading channel software modules and setting the system parameters is the main feature of the SDR channel simulator. An example of the SDR channel simulator implemented with the air interface standard of the dedicated short range communications (DSRC) system is set to be less than the guard interval (GI) of OFDM symbol, i.e., the upper limit of the maximum delay spread time \( T_{\text{max}} \) is set to be less than the guard interval (GI) \( T_{\text{GI}} \) of OFDM symbol, i.e., the upper limit of the maximum delay spread time \( T_{\text{lim}} = T_{\text{GI}} = 1.6 \mu \text{sec} \) [6] in order to avoid inter symbol interference (ISI). Substituting above system parameters into the channel fading conditions of the four types of multipath fading channels [7] yields Table 1, which indicates the relations between the multipath channel parameters \( f_d \) (Doppler frequency), \( \tau_{\text{rms}} \), and the types of fading experienced by the DSRC signal. Besides, the maximum relative vehicle speed is set as \( 300 \) km/hr and the number of fading paths in the SDR channel simulator is \( L \).

All the reconfigurable parameters of the SDR channel simulator includes \( L, B_r, T_{\text{min}}, \tau_{\text{lim}} \). Based on those parameters, other important channel parameters can be determined as follows.

The average power at the \( i \)th path which is assumed to be an exponential function [8]:

\[
P_{i+1} = [1 - e^{-1/(B_r \tau_{\text{rms}})}] e^{-i/(B_r \tau_{\text{rms}})}, i = 0, 1, ..., L - 1
\]

The delay time \( \tau_i \) at the \( i \)th path is

\[
\tau_i = \tau_{i-1} + \frac{1}{B_r}, i = 2, 3, ..., L; \tau_0 = 0
\]

The path delay \( D_i \) at the \( i \)th path in the circuit is determined by its corresponding excess delay \( \tau_i \) and the sample rate of the transmitted signal \( f_{\text{sig}} \).

\[
D_i = \left| \tau_i f_{\text{sig}} \right|, i = 1, 2, ..., L
\]

where the largest integer function \( \lfloor \cdot \rfloor \) is defined as

\[
\lfloor a \rfloor = \arg \max_a \{ A \leq a \cap A \in \mathbb{Z} \}
\]
The envelope of the $i$th path can be set as a Rician distribution function, which is described in terms of K-factor $k_i$. If $k_i = 0$ then the probability density function (pdf) of envelope tends to a Rayleigh distribution whilst if $k_i$ is greater than one then the pdf of the envelope becomes Gaussian with a mean value which is the dominant line of sight (LOS) signal amplitude. The log-normal characteristics of the K-factor $k_i$ were measured in [9], where the mean is 10 dB and standard deviation is 5.7 dB. The lognormal pdf of $K_i$ at the $i$th path is represented as

$$p_{k_i}(k_i) = \frac{1}{5.7\sqrt{2\pi k_i}} e^{-\frac{(\ln{10} k_i - 10)^2}{2(5.7)^2}}$$  \hspace{1cm} (5)

Therefore, $k_i$ is randomly generated in the reconfigurable controller and sent to configuration processing unit through configuration command. $f_{d_i}$ and $f_o_i$ are the Doppler offset and Doppler shift, respectively, at the $i$th path. Their values will change with the type of channels. $\theta_i$ is the incident direction of angle at the $i$th path. The path spectra used in the SDR channel simulator consist of flat spectrum, rounded spectrum and Jakes spectrum [6]. The flat spectral shape is defined as

$$S_f(f_i) = \begin{cases} g \left| f - f_{o_i} \right| < 0.999 f_{d_i} \\ 0 \text{ otherwise} \end{cases}$$  \hspace{1cm} (6)

The factor $g$ is chosen so that the integral of the spectrum is equal to a specified path power. The rounded spectrum is defined as

$$S_r(f_i) = g \sqrt{1 - \left( \frac{f - f_{o_i}}{f_{d_i}} \right)^2} \left| f - f_{o_i} \right| < 0.999 f_{d_i}$$  \hspace{1cm} (7)

The log-normal distribution of $K_i$ was truncated to 0.999 at $f_{d_i}$ in order to avoid singularities. The Jakes spectrum is defined as

$$S_J(f_i) = \begin{cases} g \left( f - f_{o_i} \right) \left| f - f_{o_i} \right| < 0.999 f_{d_i} \\ 0 \text{ otherwise} \end{cases}$$  \hspace{1cm} (8)

### III. RECONFIGURATION PROCEDURE

Figure 1 shows that the SDR channel simulator consists of three units: application interface processing unit, configuration processing unit and reconfiguration processing module unit. Besides, a reconfigurable controller is utilized for controlling the whole reconfiguration process of the channel simulator by sending mode selection command and reconfiguration command into application interface unit and configuration processing unit, respectively.

The SDR reconfiguration procedure can be described as follows, first the reconfigurable controller sends the mode selection command to decide the channel fading in the SDR channel simulator. Here we provide five kinds of channel fadings could be chosen, which are flat/slow, flat/fast, frequency selective/slow, frequency selective/fast and DSRC channel. While the reconfigurable controller sends mode selection command “5” to the application interface processing unit, ‘DSRC channel’ code module is selected. In addition, the corresponding channel parameters $P_i$, $r_i$, $k_i$, $\theta_i$, $f_{d_i}$, $f_{o_i}$, and spectrum shape are also determined in advance and downloaded into the configuration processing unit along with the DSRC channel code module.

<table>
<thead>
<tr>
<th>Fast fading</th>
<th>Slow fading</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \text{sec} &lt; r_{ms} &lt; 20 \text{sec}$</td>
<td>$20 \text{sec} &lt; r_{ms} &lt; 320 \text{sec}$</td>
</tr>
<tr>
<td>$0 \text{Hz} &lt; f'_{d_i} &lt; 595.2 \text{Hz}$</td>
<td>$0 \text{Hz} &lt; f'_{d_i} &lt; 595.2 \text{Hz}$</td>
</tr>
<tr>
<td>$(0 &lt; v &lt; 109 \text{km/hr})$</td>
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<tr>
<td>$595.2 \text{Hz} &lt; f'_{d_i} &lt; 1638.9 \text{Hz}$</td>
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</tr>
<tr>
<td>$(300 \text{km/hr} &gt; v &gt; 109 \text{km/hr})$</td>
<td>$(300 \text{km/hr} &gt; v &gt; 109 \text{km/hr})$</td>
</tr>
</tbody>
</table>
The DSRC channel parameters of twelve paths are given by [6], which are determined with the measured Doppler shift \( f_d \) and offset frequency \( f_o \). However, we can still obtain the channel parameters with considering vehicle speed that is different from the specification. With considering different vehicle speed, the reconfiguration command from reconfigurable controller sends other system parameters \( v \) and \( f_{sig} \) to determine the values of \( f_d \), \( f_o \), and \( D_i \). It is noted that the relative vehicle speed defined in the specification is 280 km/hr. From the measured Doppler shift \( f_d \) and offset frequencies \( f_o \) listed in [6], the measured Doppler shift and offset frequencies for each of twelve paths were both scaled by the input relative vehicle speed \( v \).

\[
f_d = f_d \frac{v}{280 \text{km/hr}}, i = 1, 2, \ldots, 12
\]  
\[f_o = f_o \frac{v}{280 \text{km/hr}}, i = 1, 2, \ldots, 12\]  
where \( v \) is the relative vehicle speed between transmitter and receiver. The path delay \( D_i \) at the \( i \)th path is generated from (3). While the configuration processing unit set all channel parameters, the channel parameters is sent to reconfiguration module unit for calculating the channel weighting \( r_i[k] \) of each path. Finally, the multipath fading signal generator would generate the desired fading signal \( m_i[k] \) by multiplying the channel weighting to the input signal \( s_i[k] \).

### IV. PROCESSING MODULE UNIT

Base on the requirement of sharing the same hardware for multimode operations, modular design of the processing module unit will lead to software reconfigurability and flexibility of the SDR channel simulator when the parameters for an update arrive. The processing module unit is divided into four parts: fading channel weighting generator, interpolator, register bank and multipath fading signal generator. Following are the detail design algorithms of each part.

#### Fading Channel Weighting Generator

The fading channel weighting generator at the \( i \)th path consists of two non-line-of-sight (NLOS) branches and a LOS branch. In NLOS branch, two independent and identically-distributed (iid) Gaussian signal sources are connected to identical Doppler filters. The channel weighting \( w_i[k'] \) is determined by

\[
w_i[k] = P_i (s_{i-NLOS}[k] + s_{i-LOS}[k]), k = 1, 2, \ldots, N
\]  

where the output of NLOS branch at the \( i \)th path in the fading channel weighting generator is

\[
s_{i-NLOS}[k] = y_i[k] \times \left( \frac{1}{\sqrt{1+k_i}} \right), k = 1, 2, \ldots, N
\]  
\[
y_i[k] = \left( \sum_{l=-\infty}^{\infty} x_1[l] \hat{h}_l[k-l] \right) + j \left( \sum_{l=-\infty}^{\infty} x_2[l] \hat{h}_l[k-l] \right)
\]  

\[
\hat{h}_l = \exp(2\pi(f_d \cos \theta_l + f_o) \frac{k}{f_{sig}})
\]  

where \( y_i[k] \), and \( x_1 \) and \( x_2 \) are independent Gaussian functions, and \( \hat{h}_l \) is the impulse response of the Doppler filter. The output of LOS branch at the \( i \)th path in the fading channel weighting generator is

\[
s_{i-LOS}[k] = \sqrt{k_i} \times \exp(j2\pi(f_d \cos \theta_l + f_o) \frac{k}{f_{sig}})
\]  

\[
k = 1, 2, \ldots, N
\]  

#### Interpolator

\( w_i[k'] \) is interpolated by factor \( I \) to get the sequence \( v_i[k'] \) with a sampling rate \( f_{sig} = I \times f_{s, dop} \).

\[
v_i[k'] = \begin{cases} w_i[k'] / I & \text{for } k' = I, 2I, \ldots, NI \\ 0 & \text{otherwise} \end{cases}
\]

The image signal of \( v_i[k'] \) is removed by an interpolation low pass filter with unit impulse response \( h_i[k] \).

#### Register Bank

The interpolated fading envelope signal \( r_i[k'] \) is stored in the register bank \( R_i \).

\[
r_i[k] = \sum_{l=-\infty}^{\infty} v_i[l] h_i[k-l], k' = 1, 2, \ldots, NI
\]

where the sampling interval of \( r_i[k] \) is

\[
\Delta t = \frac{1}{f_{sig}}
\]

#### Multipath Fading Signal Generator

The block diagram of multipath fading signal generator is shown as in Fig. 1, which is a tap delay line filter. When the multipath fading signal generator of SDR channel simulator is reconfigured, the path delay \( D_i \) at the \( i \)th path in the circuit is determined by (3) and is stored in the parameter buffer of the configuration processing unit in advance. Both the interpolated fading envelope signal \( r_i[k'] \) and the path delay \( D_i \) for the twelve paths [10] are loaded into the multipath fading signal generator to generate the fading signal \( m_i[k] \) requested by the reconfigurable controller.
\[ m_j[k'] = \sum_{k=1}^{k'} s_j[k' - D; k], j = 1, 2; \]

where one of the waveform code modules, \( s_j[k'] \), \( j = 1, 2 \), is selected and loaded from the memory of the application interface processing unit.

V. COMPARISON WITH MEASUREMENT RESULTS

The combinations of waveform and fading channel code modules are chosen from the application interface processing unit to measure the fading channel characteristics. First, we compare the Doppler spectra of the simulated DSRC fading channel with the empirical spectra as shown in [6], which was measured at 2.4 GHz and 90 km/hr vehicle speed, and scaled by a factor of 3.78 to a DSRC frequency band of 5.9 GHz and the corresponding relative vehicle speed of 280 km/hr [6]. Figure 2(a) and (b) show the Doppler spectra of the first Rician fading tap and the ninth Rayleigh fading tap, respectively. It is noted that the Doppler spectra (dotted curve) generated from the SDR channel simulator are almost identical to the measured empirical spectra (solid curve). The correctness of the designed SDR channel simulator is validating.

The two dimensional discrete channel frequency responses \( H[k', q] \) at different relative vehicle speeds are shown in Fig. 3, which is a function of frequency bins \( q \) and sample points \( k' \) for the DSRC channel. The detail derivation of \( H[k', q] \) is shown in Appendix A. It is easily found that the amplitude variation of the DSRC channel frequency responses in the sample point axis at a relative vehicle speed of \( v=60 \text{ km/hr} \) is slower than that at \( v=280 \text{ km/hr} \). The fast fading channel shows faster amplitude variation of discrete frequency response in sample point axis than slow fading channel.

Simulation results of impulse channel response and impulse frequency spectrum of DSRC channel are shown in Fig. 4, where the maximum Doppler spreads are 1311Hz and 281Hz for relative vehicle speeds 280 km/hr and 60 km/hr, respectively. As shown in Table 1, DSRC system will operate in the frequency selective fading channel. When the relative vehicle speed is 280 km/hr, DSRC system will operate in the frequency selective/fast fading channel; when the relative vehicle speed is 60 km/hr, DSRC system will operate in the frequency selective/slow fading channel. The BER performance of the DSRC receiver using 64 QAM-OFDM in different vehicle speeds are shown in Fig. 5, where the proposed channel simulator is employed to generate DSRC channel in the terms of \( v=30, 60, 120, 200 \text{ km/hr} \) and \( r_{\text{rec}}=100 \text{ nsec} \). The bit error rates (BERs) of the DSRC system with vehicle speeds 30, 60, 120, 200 km/hr (not including the case of 200km/hr vehicle speed) are less than \( 10^{-5} \) at the minimum signal-to-noise ratios (SNRs), which meet the requirements specified in 802.11p standard. It is noted that the BER of the DSRC receiver increases with the vehicle speed. For the 200km/hr vehicle speed, the severer fast fading results in an unacceptable BER level.
VI. CONCLUSIONS

In this paper, the reconfiguration features of SDR is applied for the design of a channel simulator, which is capable of simulating four multipath fading channels and various mobile radio channels according to the demands of users. The same hardware of processing modules can be reconfigured to perform different computations, following the selected fading channel and waveform software modules and the set of system parameters. The air interface specification of the DSRC system is chosen as an example to describe the reconfiguration structure and channel algorithms of the SDR channel simulator. The empirical spectra of DSRC channel taps are compared with the simulated spectra generated from the proposed SDR channel simulator to validate its correctness. On the other hand, the proposed SDR channel simulator may enhance its function in the migration of a new or modified air interface specification by adding a new fading channel code module and the relevant system parameters to the application interface processing unit. The waveform and fading channel code modules can be generated by the users and are user-selectable to simulate the channel fading signal for various mobile radio systems. In addition to the advantage of application flexibility, the cost and power consumption of the proposed SDR channel simulator can be reduced by a significant amount through hardware reconfiguration.

Appendix A Derivation of $H[k', q]$

Refer to [11], the impulse response of the mobile radio fading channel can be described as

$$h(t, \tau) = \sum_{i=1}^{L} r_i(t) \delta(\tau - \tau_i)$$  \hspace{1cm} (A1)

where $\tau_i$ is the delay of $i$th path and $r_i(t)$ is the corresponding complex amplitude. Let the sampling frequency of the multipath fading signal generator be $f_{sig} = \frac{1}{\Delta t}$, then the discrete impulse response is expressed as

$$h(t, \tau) \bigg|_{t = k\Delta t, \tau = \Delta t} \approx \sum_{i=1}^{L} r_i(k'\Delta t) \delta(l\Delta t - \frac{\tau_i}{\Delta t})$$  \hspace{1cm} (A219)

Based on relationship between (3) and (17), without loss of generality, (A2) can be expressed in the discrete-time form.

$$h[k', l] = \sum_{i=1}^{L} r_i[k'] \delta[l - D_i]$$  \hspace{1cm} (A3)

where

$$D_i = \left\lfloor \frac{\tau_i}{\Delta t} \right\rfloor \text{ and } D_i \in Z$$  \hspace{1cm} (A4)

Using (A1), the continuous frequency response of the time varying mobile radio fading channel at time $t$ is [10]

$$H(t, f) = \int_{-\infty}^{\infty} h(t, \tau) e^{-j2\pi f \tau} d\tau = \sum_{i=1}^{L} r_i(t) e^{-j2\pi f \tau_i}$$  \hspace{1cm} (A5)

Similarly, the discrete frequency response of the time varying fading channel can be determined by $N$ point FFT of $r_i[k']$.

$$H[k', q] = \sum_{i=0}^{N-1} a_i[k'] e^{-j\frac{2\pi q i}{N}} \quad \forall q = 0, 1, \ldots, N-1$$  \hspace{1cm} (A6)

where

$$a_i(k') = \begin{cases} r_i(k') & \forall i = D_1, D_2, \ldots, D_L \\ 0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (A7)

References