An Adaptive Channel Model for VBLAST in Vehicular Networks

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The wireless transmission environment in vehicular ad hoc systems varies from line of sight with few surroundings to rich Rayleigh fading. An efficient communication system must adapt itself to these diverse conditions. Multiple antenna systems are known to provide superior performance compared to single antenna systems in terms of capacity and reliability. The correlation between the antennas has a great effect on the performance of MIMO systems. In this paper we introduce a novel adaptive channel model for MIMO-VBLAST systems in vehicular ad hoc networks. Using the proposed model, the correlation between the antennas was investigated. Although the line of sight is ideal for single antennas systems, it severely degrades the performance of VBLAST systems since it increases the correlation between the antennas. A channel update algorithm using single tap Kalman filters for VBLAST in flat fading channels has also been derived and evaluated. At 12 dB $E_s/N_0$, the new algorithm showed 50% reduction in the mean square error (MSE) between the actual channel and the corresponding updated estimate compared to the MSE without update. The computational requirement of the proposed algorithm for a $p \times q$ VBLAST is $6p \times q$ real multiplications and $4p \times q$ real additions.

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1. Introduction

Crash prevention, road traffic control, route guidance, internet on the road as well as multimedia services, and others are the promising applications of vehicular ad hoc networks (VANET). Such applications require high data rates and high reliability with minimum human interaction. Although the technology used in wireless communication such as IEEE 802.11 has reached a high level of maturity and is capable of providing high bit rates, its performance in high speed transmission and adaptability to channel conditions ranging from strong line of sight to Rayleigh fading are of concern. Multiple-input multiple-output (MIMO) systems, including diversity, space-time coding, and BLAST algorithms, have been thoroughly studied and have shown superior performance [1] compared to single antenna systems for mobile communications in rich scattering, no line of sight, and slowly varying channel conditions. However, the conditions are different in VANET, and an accurate channel model is required to study the performance of MIMO systems. Moreover, since MIMO algorithms require accurate channel state information, the issue of channel tracking is raised.

In this paper, we adapt the elliptical model introduced in [2] to simulate the MIMO channel in VANET. The channel Doppler spectrum was calculated and compared to that of the classical Jakes model [3]. As will be shown, the Doppler spectrum is different from that of Jakes’ model due to the movement of the scatterers. The correlation between antennas was also studied under various line of sight conditions. The results show that an antenna separation of $3\lambda$ or more, $\lambda$ represents the wavelength, can achieve a correlation less than 0.5 unless a very strong line of sight exists. A novel channel update algorithm to track the channel is then introduced. The new algorithm improves the bit error rate (BER) performance of MIMO systems with a minor increase in hardware complexity.

The paper is organised as follows. Some of the existing models and their applications are discussed in the next section. Section 3 is a detailed description of the proposed channel model. In Section 4, a comparison between the proposed model and Jakes’ model is provided as well as correlation results for a broadside antenna array. The channel update algorithm is derived and assessed in Section 5. Finally, Section 6 concludes the paper.
2. An Overview of Existing Channel Models

Several models have been developed to approximate the mobile wireless channel. The main parameters in designing a channel model are the heights of transmit and receive antennas, the position of the surroundings relative to the antennas, the Doppler spectrum as well as the parameters intended for calculation. The early work on wireless channel modelling showed that the envelope of the received signal has a Rician distribution and becomes Rayleigh distributed when no line of sight exists [4]. The well-known Jakes analysis showed that the autocorrelation \(R(\tau)\) and Doppler power spectrum \(P(f)\) of the channel are given by [3]

\[
R(\tau) = J_0(2\pi f_D \tau),
\]

\[
P(f) = \begin{cases} \frac{1}{\pi f_D} \frac{1.5}{\sqrt{1 - (f/f_D)^2}}, & |f| < f_D, \\ 0, & \text{otherwise}, \end{cases}
\]

where \(f_D\) is the maximum Doppler shift, \(v\) is the relative transmitter receiver speed, and \(J_0\) is the zero-order Bessel function.

To simulate the received signal at a mobile terminal from a basestation, or vice versa, in marccells, Lee’s model is usually used [5]. Since the basestation is positioned over high buildings, the number of surroundings is small, while for a mobile terminal at street level, a large number of surroundings are available. Therefore, Lee modelled the channel by a ring of scatterers uniformly distributed around the terminal which affects both the terminal and basestation [6]. Lee’s model was extended to model ad hoc networks in [7]. Since in ad hoc networks the transmitter and receiver are usually peers, both are assumed to be surrounded by scatterers; therefore, the authors of [7] developed a two-ring model which uses one ring of scatterers around the transmitter and another around the receiver. The two-ring model was extended to three dimensions in [8] to study the performance of vertical antenna arrays. The three-dimensional model assumes that the terminals are surrounded by scatterers of various heights, and the authors used cylinders instead of rings to model the channel. An elliptical model was introduced in [2] to study the angle of arrival (AOA) and angle of departure (AOD) as well as the performance of antenna arrays at basestations in microcells. Basestations in microcells are at street lights heights and, therefore, are more affected by the surroundings than those in macrocells. The probability of line of sight communication in microcells is also much greater than in macrocells. The model places the transmitter and receiver at the foci of an ellipse. The two-ring and three-dimensional channel models are ideal for urban areas under heavy traffic conditions where there are a large number of surroundings and no line of sight. However, in suburban areas, open areas, or light traffic conditions, the assumptions of large number of surroundings and no line of sight become invalid and, therefore, a more realistic channel model is required.

3. Proposed Channel Model

The proposed channel model, shown in Figure 1, is based on the elliptical channel model first introduced in [2]. The original model was intended for modelling a mobile to basestation channel in a microcell, where the basestation is not very high as in macrocells and a line of sight may exist. Similar conditions are common in vehicular networks. The number and position of the surroundings depend on the terrain type. For highways, we expect a small number of surroundings; the scatterers increase as we approach the city where a large number of scatterers are more appropriate. The surroundings are placed uniformly within two ellipses. The parameters, \(a_m\) and \(b_m\), of the outer ellipse are calculated from the delay spread using the following equations [6], while the inner ellipse is specified by the road geometries.

\[
\begin{align*}
    a_m &= \frac{c T_m}{2}, \\
    b_m &= \frac{1}{2} \left( c^2 \tau_m^2 - D^2 \right), \\
    \tau_m &= 3.244 \sigma + \tau_0,
\end{align*}
\]

where \(\tau_m\) is the maximum delay to be considered, \(\sigma\) is the delay spread, \(\tau_0\) is the minimum delay (line of sight delay), \(D\) is the distance between the transmitter and receiver, and \(c\) is the speed of light. The delay spread of VANET has been measured for various roads and traffic conditions in [9, 10]. The minimum mean delay spread measured was 103 nanoseconds. We adopt this value in our model as a worst-case scenario since a larger delay spread leads to smaller antenna correlation.

We assume that the existence of objects (cars) between the transmitter and receiver leads to blockage of line of sight. When a line of sight exists, a ground reflection is added if the distance between the transmitter and the receiver satisfies the following equation:

\[
D \geq \frac{4 \pi \cdot h_t \cdot h_r}{\lambda},
\]

where \(h_t\) and \(h_r\) are the heights of the transmitter and receiver antennas, respectively, and \(\lambda\) is the wavelength. The right-hand side of (3) is the minimum distance for the first Fresnel zone to touch the ground, and thus a ground reflection may exist only if (3) is satisfied [11, 12].
The surroundings are not assumed fixed but their speeds are uniformly distributed between 0 and a maximum limit. For simplicity, we set the speed of the transmitter and surroundings relative to the speed of the receiver. Surroundings above the transmitter in Figure 1 are either fixed or moving in a direction opposite to the transmitter (negative speed) while those below the transmitter are either fixed or moving in the same direction as the transmitter (positive speed). It can be easily shown that the Doppler shift for any path \((i)\) is given by (4) or (5) [13, 14]. Equation (5) follows from (4) since the last term in (4) is much smaller than the first. Considering the elliptical model in Figure 1, the maximum Doppler shift is no longer defined only by the relative speed of the transmitter/receiver \((v_T - v_R)\) as in Jakes’ model because the surroundings are not fixed [3, 14].

\[
f_d(i) = f \left[ \left( 1 + \frac{v_T - v_i}{c} \cdot \cos(\alpha_i) \right) \cdot \left( 1 + \frac{v_i - v_R}{c} \cdot \cos(\beta_i) \right) \right] - f,
\]

\[
f_d(i) = \frac{f}{c} \left[ \left( v_T - v_i \right) \cdot \cos(\alpha_i) + \left( v_i - v_R \right) \cdot \cos(\beta_i) \right]
+ \frac{f}{c^2} \left( v_T - v_i \right) \left( v_i - v_R \right) \cos(\alpha_i) \cos(\beta_i),
\]

\[
f_d(i) \approx \frac{f}{c} \left[ \left( v_T - v_i \right) \cdot \cos(\alpha_i) + \left( v_i - v_R \right) \cdot \cos(\beta_i) \right].
\]

The channel response \((h(t))\) at time \((t)\) can be represented by

\[
h(t) = \sum_{i=0}^{N} g_i \cdot \exp \left( j \left( \frac{2\pi}{\lambda} f_d(i) \cdot t + \theta_i + \phi_i \right) \right) \cdot u(t - t_i),
\]

where \(g_i\) is the reflection coefficient, \(t_i\) and \(\theta_i\) are the excess distance delay and phase, respectively, \(\phi_i\) is a random phase, \(N\) is the number of paths, and \(u(t)\) is the unit step function. The line of sight is represented by the \(i = 0\) term.

\[\]
where \( d \) is the spacing between the antennas and \( \psi \) is the angle of orientation of the array (set to \( \pi/2 \) for broadside and 0 for end fire). For mobile terminals, the surroundings are usually assumed to be uniformly distributed in a circle around the terminal (Lee’s model) leading to the AOA distribution of the following equation [19]:

\[
p(\varphi) = \begin{cases} 
\frac{1}{2\pi}, & 0 \leq \varphi \leq 2\pi, \\
0, & \text{otherwise.}
\end{cases}
\]  

(8)

Figure 3 compares the correlation between the antennas under various line of sight strengths and no line of sight conditions using the elliptical model with the correlation from (7). As can be seen, (7) gives an optimistic estimate of the correlation due to the assumption of uniform angle distribution which is realistic only in rich scattering channels. We also note that the correlation increases as the line of sight strength increases since the received signal becomes dominated by the line of sight component. The ground reflection reduces the correlation since the attenuation for ground reflection, the correlation becomes higher, and it is not possible to reduce it unless very large, impractical antenna spacings are used.

Although the line of sight condition is ideal for single antenna systems, it can lead to severe degradation in the performance of BLAST systems [19–21]. To illustrate this, we used the channel model without ground reflection to simulate a \( 2 \times 4 \) VBLAST system using PSK modulation, 1 MHz bandwidth, and perfect channel knowledge. As shown in Figure 4, the performance drops as the line of sight increases. This is due to the correlation between the antennas which leads to the loss of the diversity since the antennas receive similar signals. In the next section, we introduce the proposed channel update algorithm.

5. Channel Update

The performance of MIMO systems depends on the accuracy of channel state information (CSI). In a fast-varying channel, the channel estimate must be updated more frequently. Generally, a training sequence is used for channel estimation [22–24]; however, under fast-varying conditions, the interval between successive training sequences becomes small, and thus the efficiency is reduced. Our aim in this section is to develop an algorithm to update the channel estimate using the received signal in order to increase the interval between successive training intervals.

Several channel tracking algorithms are available for single and multiple antenna systems. In [25], a maximum likelihood channel tracking algorithm has been proposed. Kalman filters have been considered in several papers. In [26], the authors combined a Kalman filter with a decision feedback equaliser (DFE). The DFE is used to estimate the transmitted signal, and its output is fed to the Kalman filter for channel tracking. In [27], an autoregressive moving average (ARMA) filter was used to model the channel response based on Jakes’ channel power spectral density; this was then used to design a Kalman filter for tracking. The main limitation of these algorithms is complexity. The decoding algorithms for MIMO systems are usually very complicated and, therefore, it is desirable to minimise the channel estimation and tracking complexity. In this section, we develop a simple single tap Kalman filter to update the channel and thus reduce the BER while keeping the increase in hardware complexity to minimum.

For a \( p \times q \) VBLAST system with \( p \) transmit and \( q \) receive antennas, \( q \geq p \), in a flat fading channel, the received signal vector of length \( q \) \((r_{n-1})\) at time index \( n - 1 \) can be written as

\[
r_{n-1} = H_{n-1}s_{n-1} + m_{n-1}.
\]  

(9)

where \( H_{n-1} \) is the \( q \times p \) channel matrix, \( s_{n-1} \) is the column vector of \( p \) transmitted symbols, and \( m_{n-1} \) is the column vector of \( q \) white noise samples at time \( n - 1 \). Unless otherwise specified, bold upper-case characters represent matrices and bold lower-case characters represent vectors while normal lower-case characters represent elements within the matrix/vector of the same character. Our analysis assumes that the antenna separation is large enough for the received signals to be uncorrelated.

Let the estimated channel matrix be \( \hat{H}_{n-1} \). The simplest BLAST receiver (zero-forcing receiver) calculates an estimate of the transmitted symbols \((\hat{s}_{n-1})\) using the pseudoinverse of the channel matrix \((\hat{H}_{n-1})\) as [28]

\[
\hat{s}_{n-1} = \hat{H}_{n-1}^+ r_{n-1},
\]  

(10)

Define \( \Delta H_{n} \) as

\[
\Delta H_{n} = (r_{n-1} - \hat{H}_{n-1} \hat{s}_{n-1}) \times \hat{s}_{n-1}^+.
\]  

(11)
Substituting (9) in (11) and assuming correct decoding, we find
\[
\Delta H_n = (H_{n-1} - \tilde{H}_{n-1}) \times s_{n-1}s_{n-1}^* + m_{n-1}s_{n-1}^*.
\] (12)

Note that the term \((r_{n-1} - \tilde{H}_{n-1}s_{n-1})\) is calculated in the
cancellation step of the VBLAST decoding algorithm. \(\Delta H_n\) can be used with a first-order Kalman [13] filter to improve
the channel estimation as
\[
\tilde{H}_n = \tilde{H}_{n-1} + K \cdot \Delta H_n,
\] where \(K\) is a \(q \times p\) matrix of update parameters and the dot
in (13) represents the element-by-element multiplication.

We now need to find the optimum value of \(K\), however,
since we assume that the receive antennas are not correlated;
we need to optimise for only one antenna. Equation (12) can be
rewritten for the elements of the matrix \(\Delta H_n\) as
\[
\Delta h_{ij}^n = \left( r_{ij}^{n-1} - \sum_{l=1}^p \tilde{h}_{il}^{n-1} \cdot \tilde{s}_{lj}^{n-1} + m_{ij}^{n-1} \right) a_{ij}^{n-1}.
\] (14)

The subscripts identify the row \((i)\) and column \((j\) or \(l)\)
which represent receive and transmit antennas, respectively,
while the superscript \((n)\) denotes the time index. \(a_{ij}\) is the
element at column \(j\) of the row vector \(s^n\). Equation (14)
can be expanded using (9) as
\[
\Delta h_{ij}^n = \left( \sum_{l=1}^p (h_{il}^{n-1} \cdot s_{lj}^{n-1} - \tilde{h}_{il}^{n-1} \cdot \tilde{s}_{lj}^{n-1} + m_{ij}^{n-1} ) \right) a_{ij}^{n-1},
\] (15)
and assuming correct decoding as
\[
\Delta h_{ij}^n = \left( \sum_{l=1}^p (h_{il}^{n-1} - \tilde{h}_{il}^{n-1}) \cdot \tilde{s}_{lj}^{n-1} \right) a_{ij}^{n-1} + m_{ij}^{n-1} a_{ij}^{n-1}
\] = \(\beta\) \(s_{ij}^{n-1} \cdot s_{ij}^{n-1} \cdot a_{ij}^{n-1} + m_{ij}^{n-1} a_{ij}^{n-1}.
\] (16)

Here, \(\epsilon_{ij}^{n-1} = h_{ij}^{n-1} - \tilde{h}_{ij}^{n-1}\), and \(\beta\) is the product of the \(s_{ij}^{n-1}\)
and \(a_{ij}^{n-1}\) terms. The elements of the updated channel can be
written as
\[
\hat{h}_{ij}^n = \hat{h}_{ij}^{n-1} + k_{ij} \Delta h_{ij}^n,
\] (17)
\[
\hat{h}_{ij}^n = \hat{h}_{ij}^{n-1} + \beta k_{ij} e_{ij}^{n-1} + k_{ij} \sum_{l=1}^p \epsilon_{il}^{n-1} a_{lj}^{n-1} + k_{ij} m_{ij}^{n-1} a_{ij}^{n-1}.
\] (18)

With the assumption of independent identically distributed (i.i.d)
white data and equal average signal to noise ratio (SNR) for the receive antennas, the last two terms in (18) can be approximated by white noise with average power
[13]:
\[
N_{0,i,j} = \frac{P_0}{p_j} \left( 1 + \sum_{l=1}^p e_{il} \right),
\] (19)
where \(P_0\) is the original noise to signal power ratio
for receive antenna \(i\), \(e_{ij}\) is the average error covariance reduction
value, and \(p_j\) is a constant that specifies the fraction of noise
associated with stream \(j\). The optimum value of \(k_{ij}\) is
the one that minimises the expression \(E\left[ (h_{ij}^n - \hat{h}_{ij}^{n-1})^2 \right].\) For \(f_0 T_s < 0.2, T_s\) is the symbol duration, the channel autocorrelation function \((A(mT_s))\) can be approximated by (20) [29, 30].
The optimum value of \(k_{ij}\) is then found using (21) to (24),
\[
A(mT_s) \approx 1 - \pi^2 f_0^2 T_s^2 \cdot m^2,
\] (20)
\[
k_{ij} = \frac{\rho_j (f_0 T_s)^2}{\beta P_0 (1 + \sum_{l=1,l \neq j} e_{il})}
\] (21)
\[
= \frac{\beta \beta P_0 (1 + \sum_{l=1,l \neq j} e_{il})}{e_{ij} \approx \frac{0.75}{p_j} k_{ij}}
\] (22)
\[
\beta = \frac{1}{E_s/N_0}.
\] (23)

We define \(E_s/N_0\) as the total SNR if all transmitting
antennas transmit the same symbol. We set \(\beta\) and \(p_j\) equal to
1/p in (22) since we assume equal average transmit (receive)
power for each transmit (receive) antenna. The \(k_{ij}\) parameters
are calculated recursively. First, we assume no interference
from the other symbols and set \(e_{ij} = 0\). This is best suited
for the last decoded symbol in VBLAST since all the other
symbols would be cancelled out by then. We then calculate \(k_{ij}\)
and \(e_{ij}\) for this stream. Next, we substitute the new value of \(e_{ij}\)
for the next to last decoded symbol and calculate the \(k_{ij}\) then
update \(e_{ij}\). After all the initial \(k_{ij}\) parameters are calculated,
the process is repeated again with \(e_{ij}\) from the calculated \(k_{ij}\). This
process converges very quickly, and the final values of \(k_{ij}\) are
not very different from the initial ones. The parameters then
can be used to update the channel estimate. The algorithm
requires the calculation of \(p k_{ij}\) parameters, one for each
transmit antenna (21) and (24). These can be calculated
once at the beginning of the packet and held constant for the
duration of the packet. \(\Delta H_n\) requires the pseudoinverse
of the \((p \times 1)\) vector \(s\), which can be precalculated and
stored, and then multiplying it by the term \((r_{n-1} - \tilde{H}_{n-1}s_{n-1})\),
(11), which is calculated in the VBLAST algorithm. This
multiplication consists of \(p \times q\) complex multiplication.
The update algorithm, (13), requires \(p \times q\) real-by-complex
multiplication and \(p \times q\) complex addition.

A simple analysis shows that the algorithm requires
\(6p \times q\) real multiplications and \(4p \times q\) real additions per update. Assuming a \(2 \times 4\) system, the algorithm then requires
48 multiplications and 32 additions. If channel update is
conducted for every symbol, then a chosen 500 MHz DSP
processor, which executes a multiplication in 1 cycle, can
compute the update in 160 nanoseconds.
We ran a number of simulations using Matlab for a $2 \times 4$ VBLAST system with a symbol rate of 1 MSymbol/s and the elliptical channel model. The frequency was 5.9 GHz. In our simulations, initially the algorithm would have perfect channel knowledge rather than estimating from a training sequence. This is necessary to isolate any errors that might arise from the use of training sequence estimation. The initial values of $k_j$ were used to reduce complexity, and the channel estimate was updated for every symbol.

Figure 5 shows the mean square error in the estimated channel for the cases of 256, 512, and 1024 symbols per antenna using QPSK modulation with channel update, using (12) and from (21) to (24), compared to 256 without update. As can be seen from Figure 5, the update algorithm reduces the MSE by 50% at 12 dB $E_s/N_0$. The MSE in Figure 5 without update does not depend on the SNR because the receiver is assumed to have perfect noise-free estimate of the channel at the beginning of the packet, and this is held constant for the duration of the packet. Figure 6 shows the MSE versus the symbol number for 26 dB $E_s/N_0$. Initially, the receiver will have perfect channel knowledge (MSE $\approx 0$) but with time this estimate becomes invalid due to the high Doppler shift. If a training sequence was used, the initial MSE will be greater than 0, thus shifting the curves upwards. The difference between the curves, however, will not change and, therefore, the MSE comparison will still hold.

Figure 7 shows the BER performance of QPSK for various relative vehicle speeds. As can be seen, the performance improves considerably when the algorithm is used and is 2 dB from that of perfect channel knowledge for 60 km/h. Figure 8 shows the performance of the same system using QPSK with various packet lengths for a speed of 60 km/h.

From Figure 8, we observe that the performance degrades as the packet length increases; this is due to two reasons. The first reason is estimation error, as the estimation process proceeds, the error in the estimation accumulates, and for long packets this will lead to erroneous results near the end of the packet. The second reason is detection errors since the probability of symbol errors increases as the packet length increases. The estimation algorithm assumes correct decoding; therefore, such errors will affect the performance of the algorithm.
6. Conclusion

In this paper, we introduced a channel model for vehicular networks. The model was compared to Jakes’ model, and it was shown that the Doppler power spectrum extends beyond Jakes’ maximum frequency due to the movement of the surroundings, transmitter, and receiver. The correlation between antennas was then studied, and the results show that under very strong line of sight conditions, the correlation is high and, therefore, a small gain is expected from the use of multiple antennas while for moderate and no line of sight conditions the correlation is low. We also developed a simple recursive algorithm to keep track of changes in the channel and update the channel estimation matrix for VBLAST. The update algorithm enhances the channel estimation on a symbol-by-symbol basis, but this can be relaxed for high symbol rates and/or slow fading as the channel coherence time will be large compared to the symbol duration. The proposed algorithm improves system BER and channel estimate MSE via continuous and accurate channel updating and has less computational complexity compared to existing tracking algorithms as a result of using a simplified Kalman filter. Simulation results showed remarkable improvements when using the update algorithm compared to the training of only channel estimation. The algorithm is capable of updating the channel estimation for VBLAST for nodes moving at high speeds thus improving the bit error rate and reliability of VANET.

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