MIMO CHANNEL TIME VARIATION AS A FUNCTION OF MOBILE USER VELOCITY

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ABSTRACT

The analysis of multiple-input multiple-output (MIMO) communication systems often assumes a static, or quasi-static, environment. Platform motion and changes in the environment makes this an unreasonable assumption for many telemetry applications. This paper uses computer simulations to characterize the time variation of MIMO channel parameters when there is relative motion between the transmitter and receiver. These simulation results yield explicit time intervals over which a MIMO channel can be considered static for a given relative velocity and propagation environment. These results can be used to predict the practical limitations of proposed MIMO system algorithms.

KEYWORDS

MIMO Channels, simulation, coherence time, and dynamic channel.

INTRODUCTION

The literature on MIMO communication systems often assumes a static, or quasi-static, environment. While this leads to mathematically tractable solutions, platform motion and changes in the propagation environment make this an unrealistic assumption for many telemetry applications. This paper uses computer simulations to characterize the time variation of the MIMO channel matrix elements when there is relative motion between the transmitter and receiver. These simulation results yielded a new estimator for the coherence time of the 3GPP MIMO channel model [1] which the authors believe is superior to three other common channel coherence time estimators. This estimator can be used to predict practical limitations of MIMO communication system algorithms.

The following section discusses a detailed MIMO channel model, and associated terminology. Three common estimates of channel coherence time for Rayleigh fading channels are discussed next. Finally, the channel coherence time simulation results and a new channel coherence time estimator for this specific channel are presented.

MIMO CHANNEL MODEL

Huang [1] investigated channel models for suburban macrocell, urban macrocell, and urban microcell MIMO propagation environments. The difference between these environments, as well as detailed steps for generating their channel matrices, is omitted here for brevity, but is available [2]. Regardless of the environment, the channel between the base station (BS) and mobile station (MS) is described by a time varying MxN matrix, where M is the number of BS antennas and N is the number of MS antennas.

Each entry of the MxN matrix is a time varying complex quantity which describes the gain and phase shift between a specific pair of BS and MS antennas. For example, the complex quantity h_{12} in Figure 1 describes the gain and phase shift between antenna 1 of the basestation and antenna 2 of the mobile. The channel matrix element dependence on time, i.e. $h_{12}(t)$, has been omitted in the figure for simplicity. The time varying nature of each channel matrix entry depends on the velocity of the MS with respect to the BS. Channel matrix elements of stationary mobiles do not change, whereas channel matrix elements for mobiles with high velocity change quickly. An example of this can be seen in Figure 2 where the magnitudes of the channel matrix elements are plotted against time for two different mobile velocities.

Figure 1 – MIMO Channel Model

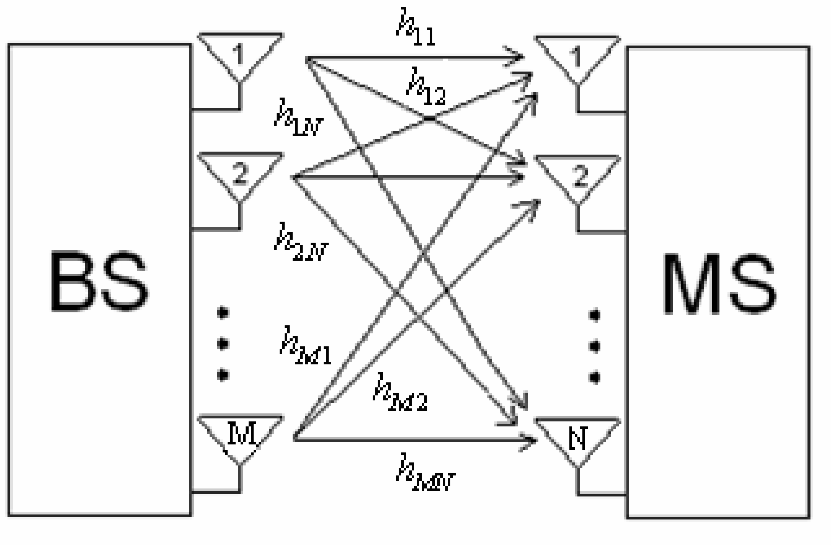
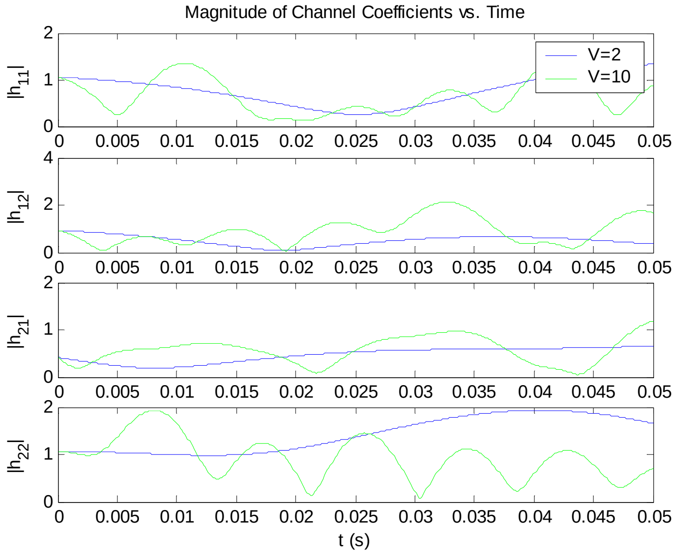


Figure 2 – Time Variation of Channel Matrix Elements



The rate of change of channel matrix coefficients is described by the *channel coherence time* [3]. This is a generic term, which indicates the length of time a channel can be approximated by a static model. Different definitions and estimates of channel coherence time are used in different applications. The importance of knowing the channel coherence time is discussed in the following section, followed by a brief discussion of some channel coherence time estimates used for Rayleigh single-input single-output (SISO) fading channels.

MIMO CHANNEL TRAINING

MIMO communication systems are of current interest due to their increased spectral efficiency as compared to SISO communication systems. Since most literature regarding MIMO communication systems assumes the MS knows the channel perfectly, it is essential that the MS be able to estimate the channel matrix elements accurately. Without a proper estimate of the channel, the MS will not be able to demodulate received data correctly.

Several pilot training systems [4,5] have been proposed recently that allow estimation of the channel matrix elements to be performed at the MS. These pilot training systems assume a block-fading environment. This means that the channel is constant for a discrete time interval T, after which it changes to a new and independent channel realization. These pilot schemes dedicate a fraction of the first T time instants to sending known data symbols, i.e. pilot symbols. Transmission of these pilot symbols allows the receiver to form an estimate of the channel matrix elements and demodulate the subsequent data correctly. These works [4,5] also develop important theorems that specify the type of training signals to use for MIMO channel training, the optimal fraction of total transmit power to assign to the training period, and the fraction of total block length time T to spend training.

MIMO channel training on a continuously varying channel was investigated in [6]. Since the channel changes continuously (as do the channels for each propagation environment of the 3GPP channel model [1]) a static estimate of the channel formed at the MS becomes worse as time evolves. This occurs since as time progresses the channel changes continually and becomes less correlated to the original estimate. This results in an error between the estimate and true value of the channel that grows with time. For both the block-fading and continuously varying channel there is a simple tradeoff between the channel estimate and the throughput that can be attained. This tradeoff is discussed next.

Let $T_{transmit}$ denote the total length of time downlink transmission takes place between the BS and MS. Let $p_{train} = \frac{T_{train}}{T_{transmit}}, 0 \le p_{train} \le 1$ be the percentage of time the BS spends sending pilot training symbols and $p_{data} = \frac{T_{data}}{T_{transmit}}, 0 \le p_{data} \le 1$ be the percentage of time spent sending data symbols. For $p_{train} = 1$ (i.e. $T_{train} = T_{transmit}$), no data symbols are ever transmitted so the effective throughput is 0 bits/s. If $p_{data} = 1$ (i.e. $T_{train} = 0$), no training is ever performed, the MS cannot form an accurate estimate of the channel and hence cannot demodulate any received data. Once again this results in an effective throughput of 0 bits/s. For any given channel, there is an optimal value of p_{train} with $0 < p_{train} < 1$ that maximizes the average effective throughput. This optimal value of p_{train} is large enough for the MS to form a “good“ estimate of the channel, but is small enough to allow a large portion of time to be dedicated to transmitting data.

Also, it is clear that p_{train} for a channel with a small coherence time is greater than p_{train} for a channel with a large coherence time. For example, consider a channel with a coherence time of 5 minutes. The first few seconds of transmission could be used to form an excellent estimate of the channel at the MS, and a majority of the 5 minutes would be used for sending data, yielding a p_{train} value of approximately 0.05. On the contrary, channels with a small coherence time may change so quickly that pilot symbols would need to be transmitted every second or third time instant. This would yield a larger value of p_{train} on the order of 0.5.

Several key points can be made from the discussion above: 1) The MS must be able to form an accurate estimate of the channel. Without an accurate estimate the MS cannot correctly demodulate received data. 2) The amount of time spent training has a significant impact on the effective throughput of the MIMO communication system. 3) The percentage of time spent training is dependant on the channel coherence time.

From these key points it is clear that knowledge of the channel coherence time is an essential part to designing MIMO communication systems. If the estimate of the channel coherence time is larger than the actual channel coherence time, the value of p_{train} chosen will be too small. This will result in poor channel estimates at the MS, possibly preventing the MS from being able to accurately demodulate received data. If the estimate of the channel coherence time is smaller than the actual channel coherence time, the value of p_{train} chosen will be too large. This will result in excellent channel estimates at the MS, but the amount of time available for data transmission will be reduced, lowering the effective throughput. It is thus important to have accurate channel coherence time estimators. Several common channel coherence time estimators for Rayleigh fading channels are discussed in the following section.

COHERENCE TIME OF RAYLEIGH FADING CHANNELS

There are several common estimates used for the channel coherence time of Rayleigh fading channels. One of these estimates is based on the worst case Doppler shift. Under the dense-scatterer model, the largest Doppler shift occurs when a scatterer is directly aligned with the direction of the moving mobile station. In this case, the Doppler shift is defined as:

$$f_d = \frac{V}{\lambda} \tag{1}$$

where f_d is the Doppler shift in Hz, V is the magnitude of the mobile velocity in m/sec and λ is the signal wavelength in meters. The channel coherence time, T_0, can be estimated [3] as

$$T_0 \approx \frac{\lambda / 2}{V} \tag{2}$$

The length of time a channel's response to a sinusoid has correlation greater than 0.5 is another method of defining channel coherence time. In this case, the channel coherence time can be approximated [3] as

$$T_0 \approx \frac{9}{16\pi (V / \lambda)} \tag{3}$$

A coherence time definition used by Sklar [3] is the geometric mean of estimates (2) and (3), or

$$T_0 \approx \frac{0.423}{V / \lambda} \tag{4}$$

The accuracy of these channel coherence time estimators for the 3GPP MIMO channel is investigated in the following section.

TIME VARIATION OF THE MIMO CHANNEL

Simulations were performed in each propagation environment of the MIMO channel model at a carrier frequency of 1.9 GHz and with mobile velocity magnitudes of 0.1, 1, 10, and 100 m/sec. For each simulation, the 50 percent correlation time for each matrix element (i.e. each h_{ij} $1 \le i \le M, 1 \le j \le N$) was calculated. This yielded the exact value of T_0 based on the definition of Equation (3) for each matrix element. The mean value of these T_0 was then calculated to obtain an average channel coherence time. The average channel coherence time as a function of mobile velocity was then plotted and compared with the estimates of Equations (2)-(4). These comparisons for the suburban macrocell and non-line-of-sight urban microcell environment can be seen in Figures 3 and 4. Comparisons for the other propagation environments are similar and have been included in the appendix.

Figure 3 – Suburban Macrocell Channel Coherence Time

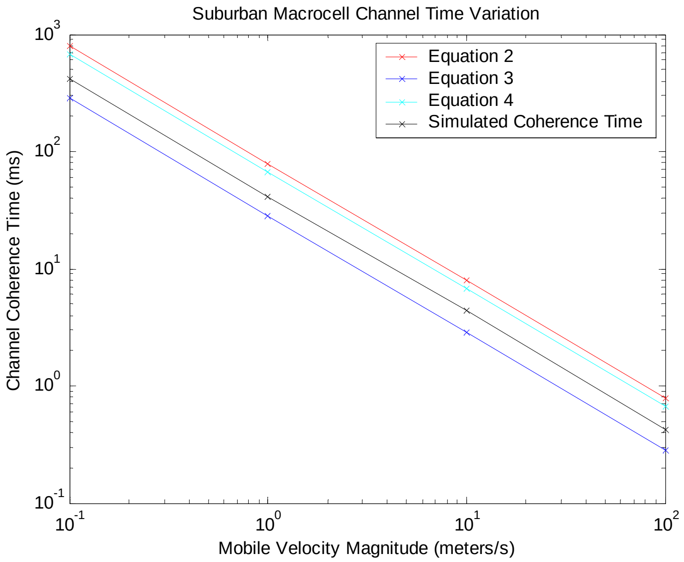
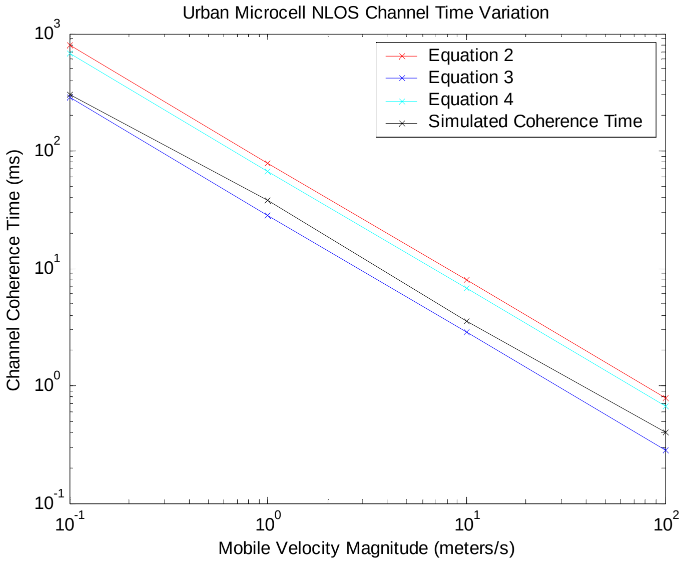


Figure 4 – Urban Microcell NLOS Channel Coherence Time



In the discussion that follows, the channel coherence time obtained via simulation is called the *actual* channel coherence time since it is calculated from channel data and a precise definition based on correlation. The estimates of Equations (2)-(4) are based on approximations, worst case scenarios, or a rule of thumb.

The channel coherence time comparison in Figures 3 and 4 show that the channel coherence time estimator of Equation (2) is an optimistic estimator of the channel variation, as it consistently overestimated the length of time the channel was approximately invariant. The estimator of Equation (3) is seen to be a worst case estimator as it consistently underestimates the length of time the channel is approximately invariant. The estimator of Equation (4) also consistently overestimated the channel coherence time, but the over-estimation error was smaller than that of Equation (2). The average percent difference between each estimate and the actual channel coherence time are tabulated in Table 1.

Table 1 – Average Estimator Percent Difference

Estimator	Average Percent Difference
Optimistic Estimator (2)	97.3
Worst Case Estimator (3)	-29.4
Geometric Mean Estimator (4)	66.9
New Estimator (5)	-0.18

This table shows that the percent difference between the estimated and actual channel coherence times for the estimators of Equations (2)-(4) are large. Thus, a new estimator proportional to $\frac{1}{V/\lambda}$ was defined to minimize the average percent difference. The new estimator is:

$$T_0 = \frac{0.253}{V/\lambda} \tag{5}$$

As seen in Table 1, the average percent difference for this new channel coherence time estimator is only -0.18 percent, significantly better than the previous best average percent difference of -29.4 percent.

CONCLUSION

Computer simulations have been performed to characterize the time variation of the 3GPP standard MIMO channel due to relative motion between the transmitter and receiver. The simulations were performed for a variety of propagation environments and mobile station velocity magnitudes. The simulation results were compared to three common channel coherence time estimators. This comparison shows that two of the estimators provide optimistic estimates of the channel coherence time, and one provides a pessimistic or worst case estimate of channel coherence time. The average percent difference between the estimated and simulated channel coherence times for each estimator have been tabulated in Table 1. The simulation results were also used to define a new channel coherence time estimator for the 3GPP MIMO channel model that has significantly smaller average percent difference then the other estimators. This new estimator can be used to predict the length of time a MIMO channel can be considered static, or quasi-static, and thus is useful in determining practical limitations of proposed MIMO communications system algorithms.

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APPENDIX

Figure A – Urban Macrocell (8 degree angular spread) Channel Coherence Time

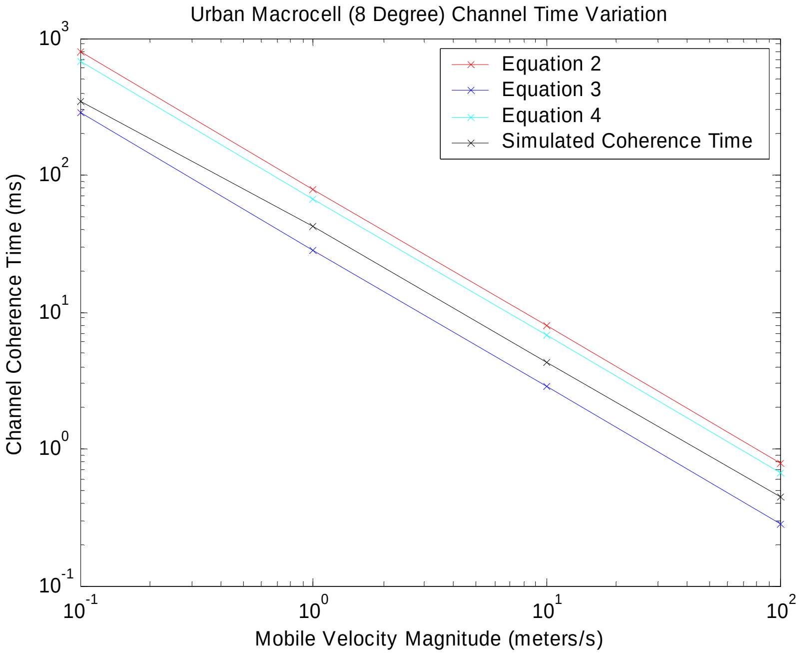

Figure B – Urban Macrocell (15 degree angular spread) Channel Coherence Time

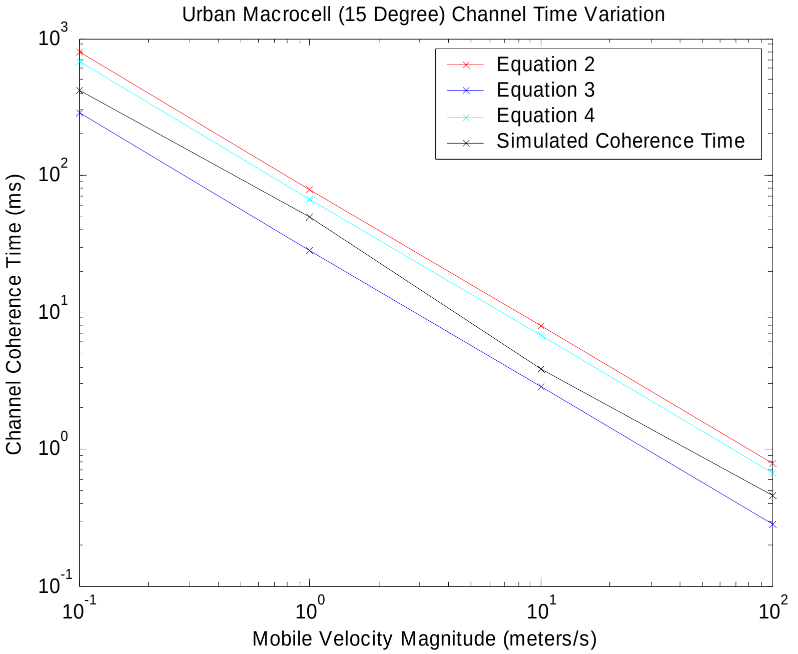

Figure C – Urban Microcell LOS (K=1) Channel Coherence Time

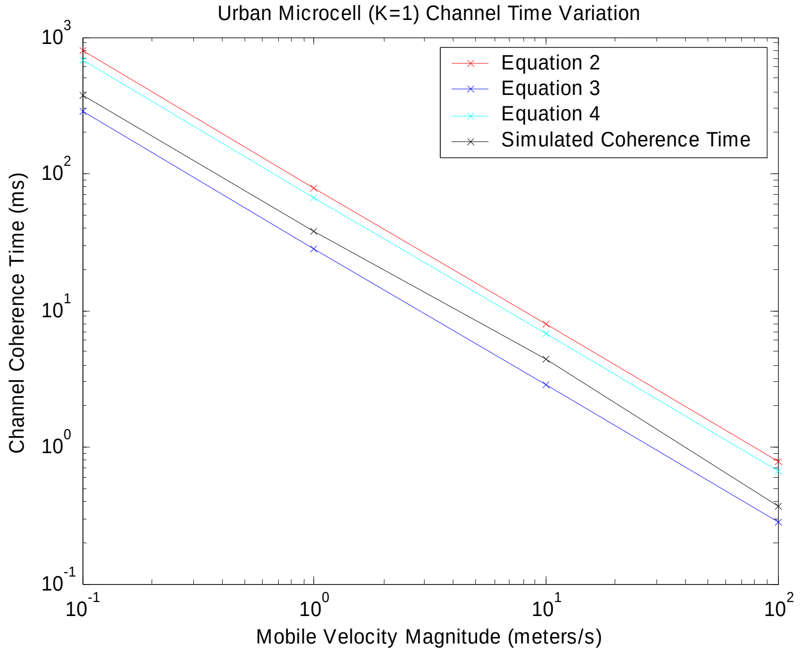

Figure D – Urban Microcell LOS (K=100) Channel Coherence Time