Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**Performance of the Proposed 802.16e OFDM PHY for Supporting Mobile Operation**
Date Submitted	**2002-03-07**
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Re:	The document is submitted in response to “Call for Proposals on IEEE Project 802.16e: Mobility Enhancements to IEEE Standard 802.16/802.16a” (IEEE 802.16e-03/02).
Abstract	The performance of the proposed OFDM/OFDMA PHY layer for mobile operation is analyzed.
Purpose	The document is submitted for consideration in the 802.16e WG.
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Performance of the Proposed 802.16e OFDM PHY for Supporting Mobile Operation

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1. Introduction

In [1], a new OFDM/OFDMA PHY was proposed for consideration by the 802.16e WG. The new PHY is an extension of the 802.16a 256FFT OFDM mode, and is designed for mobile operation. The PHY is based on downlink OFDM and uplink OFDMA with 24 subchannels. This document analyzes the performance of the proposed PHY, in downlink and uplink.

The document is organized as follows: The DL is considered in section 2. The DL scheme is briefly described, and a channel estimation scheme is proposed based on a 2-D Wiener filter. Simulation results show the performance of the DL operation in several mobile scenarios. A discussion on the suitable FEC for mobile operation concludes the DL section.
The UL is discussed in section 3, where a brief system overview and simulation results are presented.

2. Performance of the Downlink scheme

2.1 Notations

E_s	Average signal power per subcarrier
E_d	Average signal power per <u>data</u> subcarrier
N_0	Thermal noise power per subcarrier
N_{tot}	Noise power per subcarrier (thermal + estimation noise)
p_i	Received (and demodulated) pilot
RS	Reed-Solomon code

CC Convolutional code

2.2 Proposed Scheme

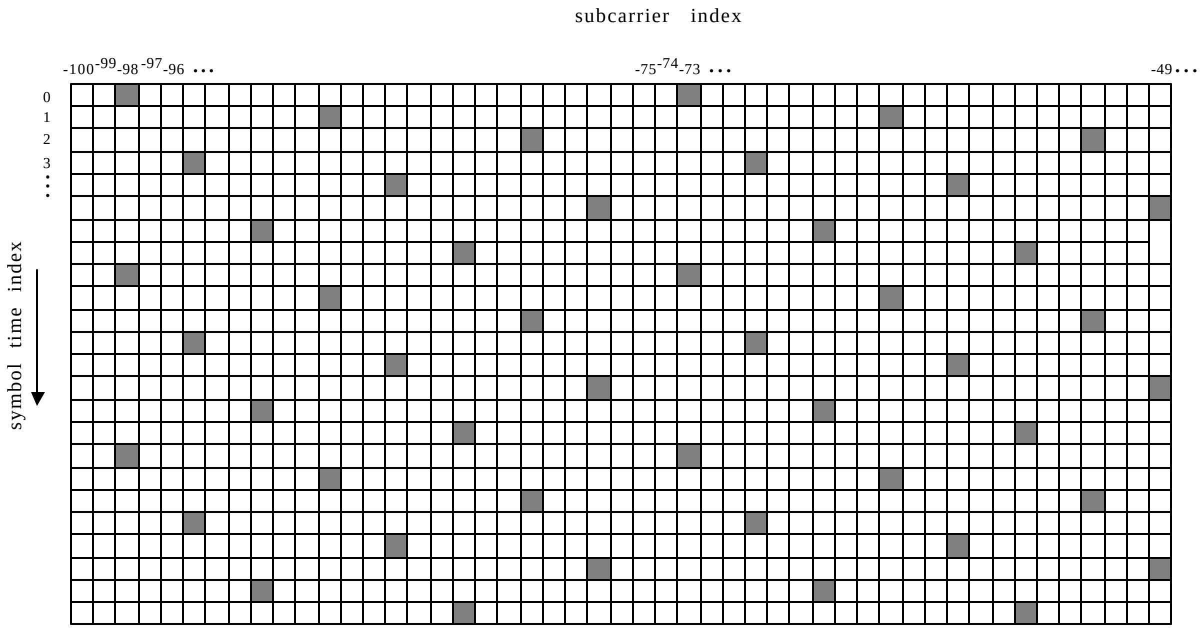
The downlink IEEE 802.16a OFDM mode implements an FFT-256 OFDM symbol with 200 active subcarriers, out of which 8 are pilot subcarriers at fixed locations and 192 are data subcarriers.

We propose [1] to modify this scheme so that the location of the 8 pilot subcarriers will vary from symbol to symbol cyclically with a period of 8 symbols. In this way, interpolation of the complete channel response from these pilots is made possible.

Let $k=0\ldots Ns\text{-}1$ be the time index of the current symbol relative to the beginning of a packet, and let the active subcarriers be indexed from –100 to +100. The symbol's pilots will be spaced every 25 subcarriers at the following subcarrier indices:

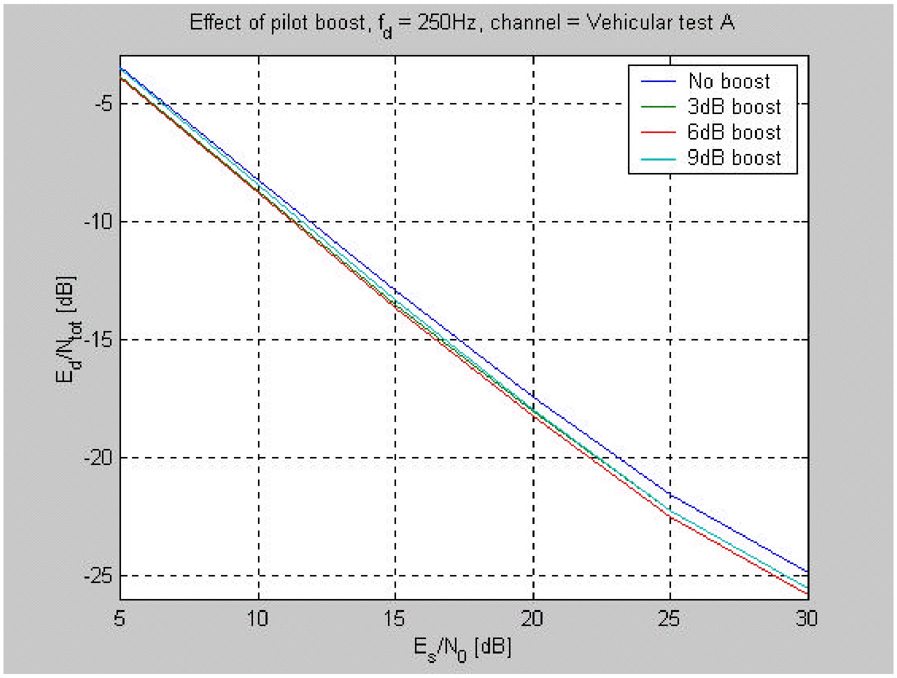
$$P_k = \{-98,-73,-48,-23,+2,+27,+52,+77\} + \mathrm{mod}(9k,24)$$

Pilots cover all in all 64 distinct subcarrier locations (ratio of ~1:3) over a complete cycle. The diagram below illustrates this scheme.



Pilot Boosting

It is further proposed to boost the power at the pilot locations by 3dB relative to the power at the data subcarriers. This boost reduces estimation noise at the expense of reducing the average data subcarrier power. The following figure shows, for several boost levels, the SNR due to estimation + thermal noise at the data subcarriers for velocity of 75km/h, as a function of thermal SNR:



The improvement from 3dB to 6dB is not significant. A boost of over 6dB leads to a rise in the overall noise.

2.3 Channel Estimator

The channel can be estimated from the scattered pilots by 2-D MMSE interpolation [2][3]. In the following, the method is briefly summarized.

The channel estimator at each subcarrier of a symbol is a linear combination of the received (and demodulated) pilots in the subcarrier's vicinity, i.e.

$$c_n^{(k)} = sum_i \; w_i^{(n,k)} p_i$$

where n is the subcarrier index and k is the symbol time index. The coefficients $\{w_i^{(n,k)}\}$ are determined via linear MMSE interpolation using a 2-D Weiner filter. Assuming worst-case channel statistics, i.e. a flat Doppler power spectrum with maximum Doppler frequency of $f_{d,max}$ and a uniform delay power spectrum with maximum delay spread of t_{max}, the 2-D channel correlation function, $r(\, , \,)$, is given by:

$$r(n_1-n_2,k_1-k_2) = sinc\,(2f_{d,max}\,(n_1-n_2)T_s) \cdot sinc(2\; t_{max}(k_1-k_2)F_{sc})$$

where T_s is the symbol duration and F_{sc} is the subcarrier spacing. The Wiener filter solution is

$$\underline{w}^{(n,k)} = \underline{D}^{(n,k)\,T} \cdot \underline{\underline{R}}^{-1}$$

where

$$R_{i,j} = E_p\, r\,(n_i-n_j\,,\, k_i-k_j) + N_0\;\; d(n_i-n_j\,,\, k_i-k_j)$$

is the correlation between the received pilots p_i and p_j, E_p is the power in which the pilots are transmitted, and

$$D_i^{(n,k)} = E_p^{1/2}\, r(n-n_i\,,\, k-k_i)$$

is the cross-correlation between the channel at (n,k) and received pilot p_i.

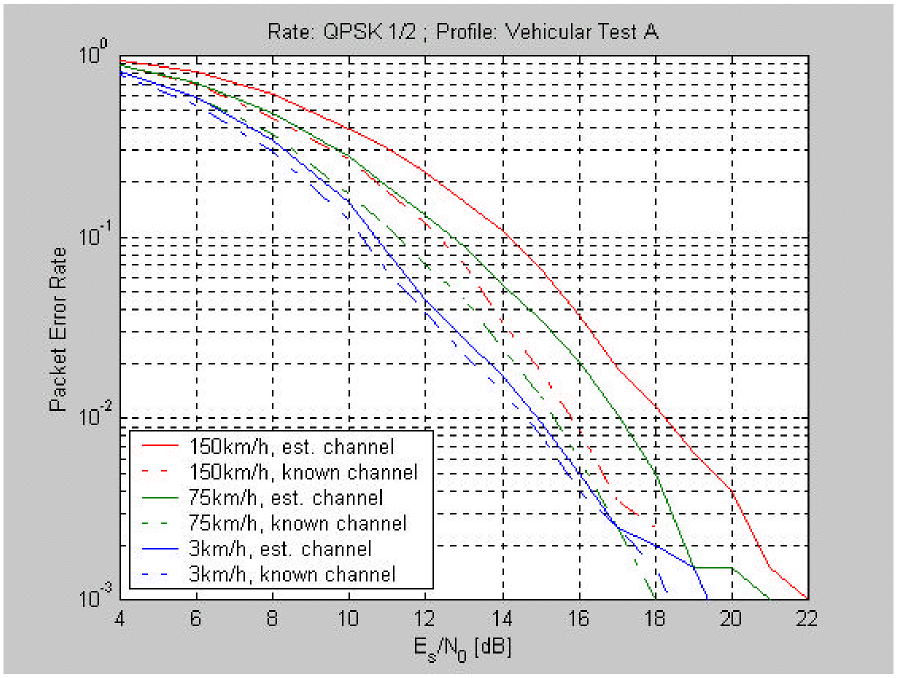
2.4 Simulation Results

The performance of an IEEE 802.16a based system with the above modification was analyzed through simulation. Due to the varying nature of the channel response and the high probability of fades over the duration of a 1000-byte packet at medium to high velocities, we break a single 1000-byte packet to 5 packets of 200-bytes. We therefore simulate transmission of 5x200 byte sequences.

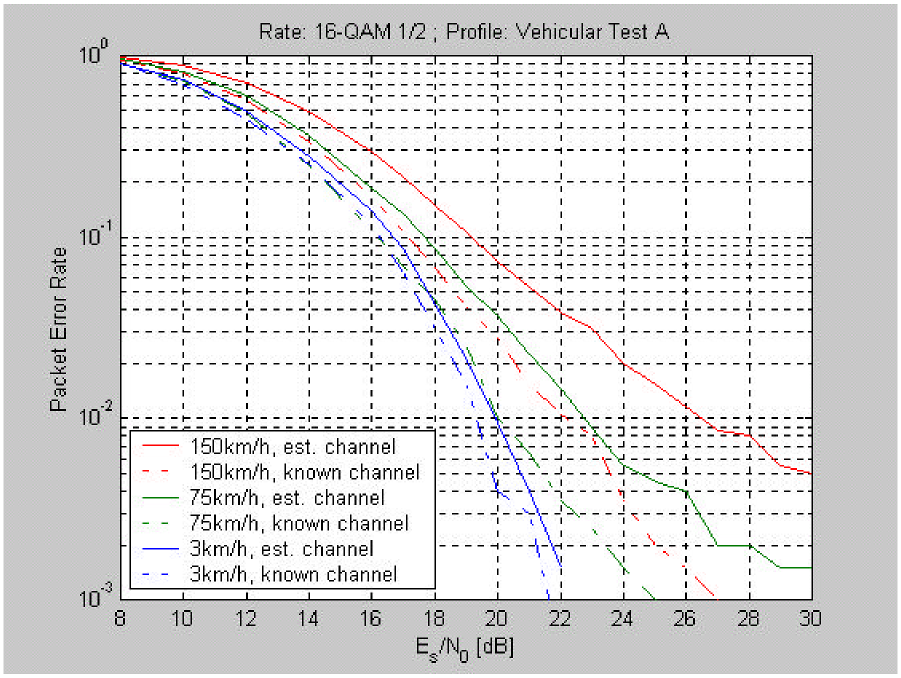
The simulation conditions are as follows:
OFDM Symbol: FFT-256, full bandwidth, FFT rate is 4 Msamples/sec.
Carrier frequency: 3.5 GHz.
MMSE estimator is matched to a maximum delay spread of 4μsec and to true Doppler frequency.
Data: 400 sequences are transmitted, each sequence comprised of 5 x 200-byte packets.
FEC: concatenated RS + zero tail CC (K=7), following IEEE 802.16a. The use of a zero tail CC (K=7) alone was also examined.
Channel profile: Vehicular Test A, defined in [4].
The following rate / velocity combinations were examined:
QPSK ½: 3 km/h, 75 km/h, 125 km/h.
16-QAM ½: 3 km/h, 75 km/h, 125 km/h.
64-QAM ¾: 3 km/h, 38 km/h, 75 km/h.

Results are shown for two scenarios: 1) The channel is estimated via MMSE interpolation, 2) The true channel is known to the receiver.

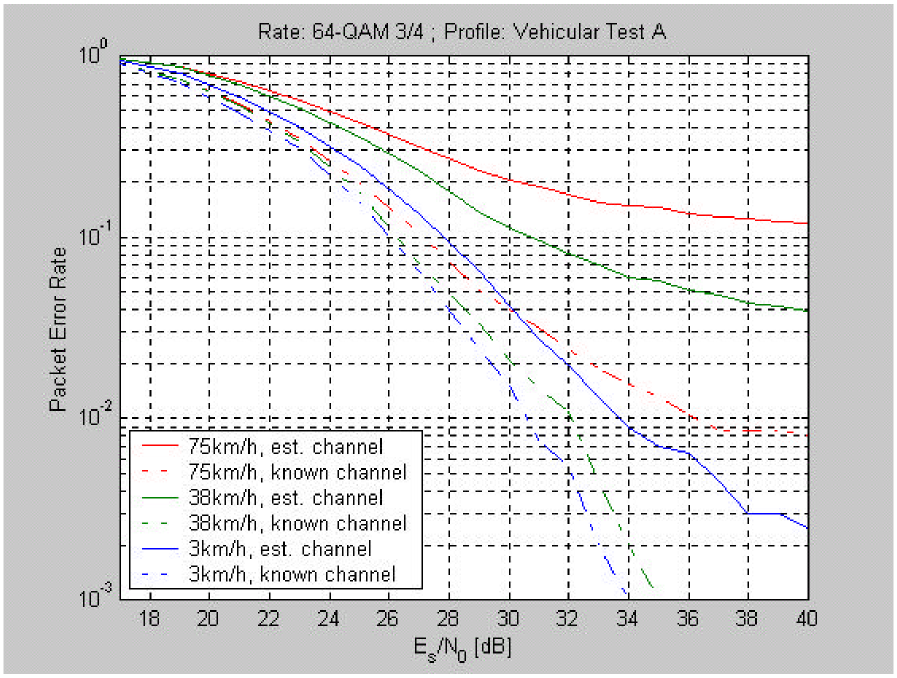
Rate: QPSK ½


Rate: QPSK 1/2 ; Profile: Vehicular Test A
Packet Error Rate
10^0
10^{-1}
10^{-2}
10^{-3}
4 6 8 10 12 14 16 18 20 22
E_s/N_0 [dB]
150km/h, est. channel
150km/h, known channel
75km/h, est. channel
75km/h, known channel
3km/h, est. channel
3km/h, known channel

Rate: 16-QAM ½


Rate: 16-QAM 1/2 ; Profile: Vehicular Test A
Packet Error Rate
Es/N0 [dB]
10^0
10^-1
10^-2
10^-3
8
10
12
14
16
18
20
22
24
26
28
30
150km/h, est. channel
150km/h, known channel
75km/h, est. channel
75km/h, known channel
3km/h, est. channel
3km/h, known channel

Rate: 64-QAM ¾



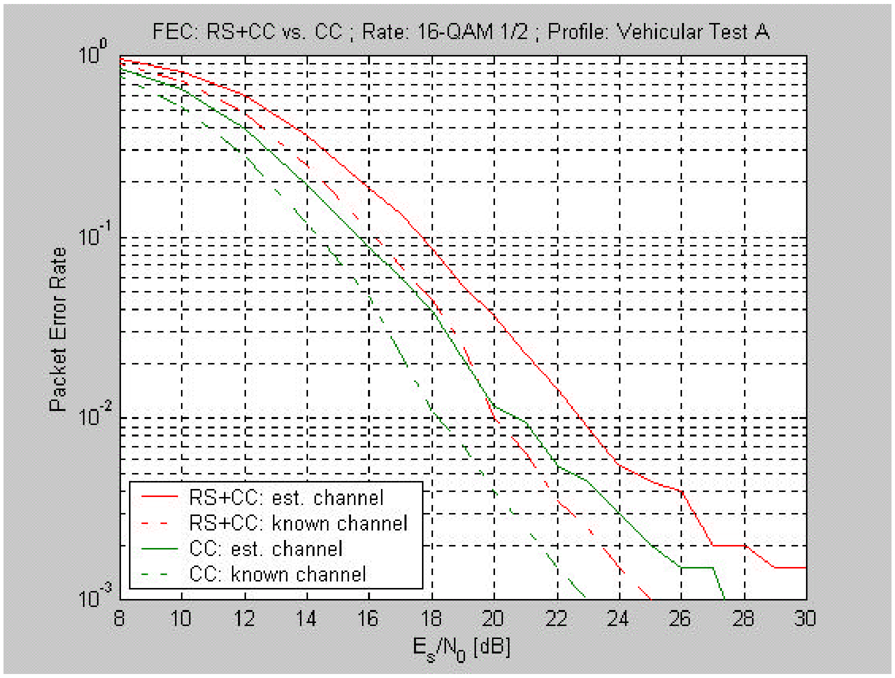
2.5 Effect of FEC on performance

In this section the suitable FEC scheme for the wireless is considered. In 802.16a a concatenated Reed-Solomon and K=7 convolutional (RS-CC) code is employed. This scheme is efficient for low error probabilities. However for regions of low-mid error probabilities, it is outperformed by a convolutional code (CC) scheme. RS-CC scheme performs in high SNR situations.

The performance in mobile situations is dominated by occasional fades in which the signal level drops towards the threshold. In such situation CC scheme will outperform the RS-CC. This effect is analyzed next.

The CC scheme is compared with an RS-CC for the for the case of 16-QAM with overall rate ½ and velocity of 75km/h. The RS –CC scheme used a (64,48) RS and a K=7 rate ½ CC punctured to 2/3. The results are shown in the following figure.

As can be observed, the CC outperforms the RS+CC by about 2dB even at low probabilities of error.



2.7 Conclusions

Based on the above results, we can conclude the following (performance criterion is SNR @ ~1% PER):
The system performance degrades as velocity increases due to objective channel conditions. This is evident from the rate of errors in the known channel case.
At 3km/h, estimating the channel using hopping pilots degrades performance by less than 1dB for QPSK ½ and 16-QAM ½ compared to assuming a known channel. For 64-QAM ¾, performance is degraded by 3dB.
At 75km/h, the use of hopping-pilots for estimation degrades performance by 2dB for QPSK ½ and by 3dB for 16-QAM ½ compared to the known channel case. The degradation at 150km/h is 2dB for QPSK ½ and 4dB for 16-QAM ½.
For 64-QAM ¾ at 38km/h and 75km/h, the degradation is much more significant. A steady packet error rate of over 4% (38km/h) / 10% (75km/h) was observed at over 35dB SNR. This may be due to the ICI noise floor of –

39dB (-33dB at 75km/h) that exists at these speeds due to Doppler spread and that hampers the estimator's performance as well as the overall system performance.
At 75km/h and 16-QAM ½, the FEC defined in IEEE 802.16a (concatenated RS+CC) performed worse than a pure CC with the same overall code rate. The observed degradation was 2dB.

3. Uplink

3.1 System Overview

The uplink channel is divided into 24 OFDMA subchannels. The following principles apply:
A subchannels is composed of 4 clusters.
A clusters is rectangle in time-frequency of 2 subcarrier, by 7 OFDM symbols. See XXX.
A clusters is composed of 12 data subcarriers and 2 pilot subcarriers.
This structure allow independent processing of the clusters, simplifying the decoding process at the BS.
The clusters are assigned so that each Subchannel is a subset of one and only one 802.16a Subchannel. Thus backward compatibility is maintained.
The pilot within a sub-channel are staggered to allow some pilot boosting.

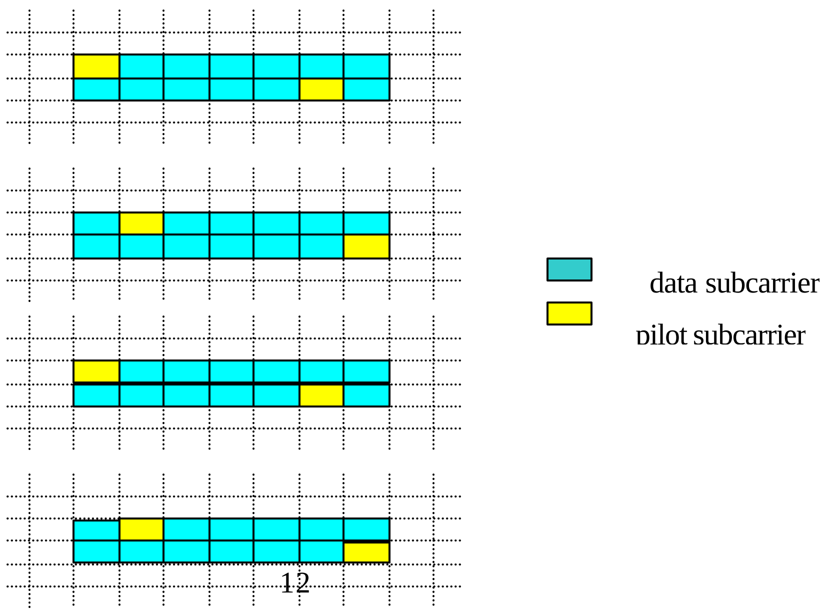
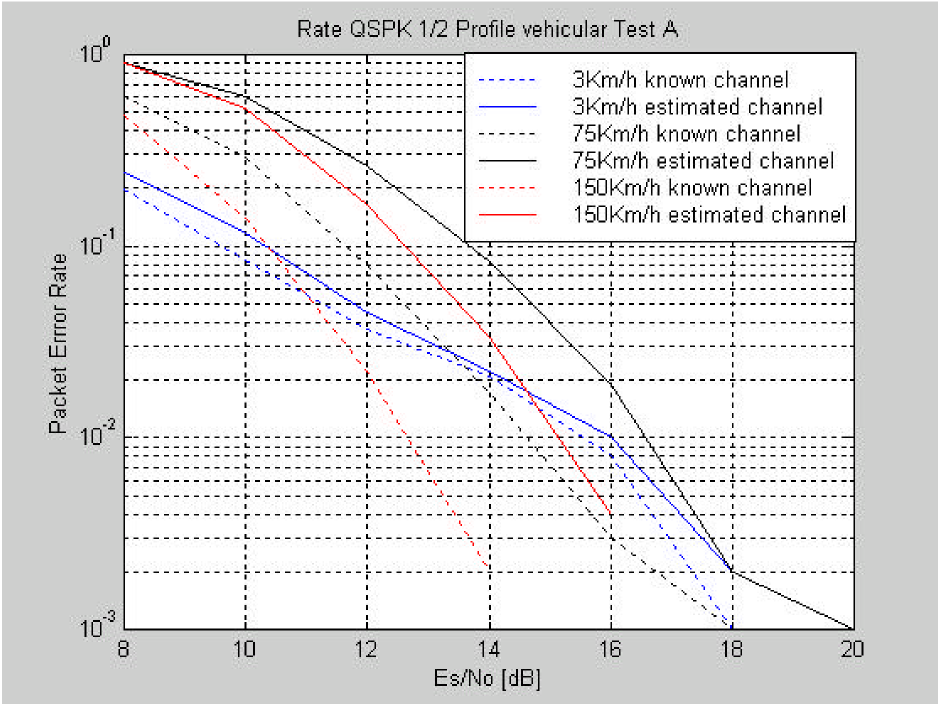


Figure 1 A single UL subchannel

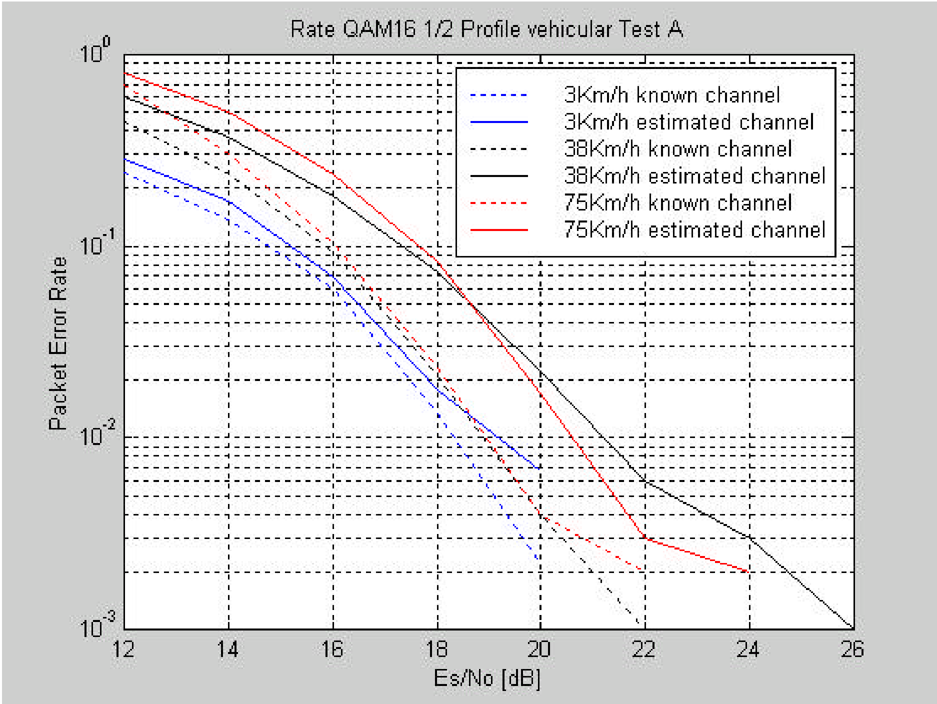
3.2 Simulation results

The performance of the UL system when a single sub-channel is used are analyzed below.
The simulation conditions are as follows:
OFDM Symbol: FFT-256, full bandwidth, FFT rate is 4 Msamples/sec.
Carrier frequency: 3.5 GHz.
Channel estimator is matched to a worst case channel and to the true Doppler frequency.
Data: 1000 sequences are transmitted, each sequence comprised of 200-byte packets.
Channel profile: Vehicular Test A, defined in [4].
No frequency and timing offsets. No phase noise. Ideal power amplifier.
The following rate / velocity combinations were examined:
QPSK ½: 3 km/h, 75 km/h, 125 km/h.
16-QAM ½: 3 km/h, 38Km/h 75 km/h.
64-QAM ¾: 3 km/h, 38 km/h,

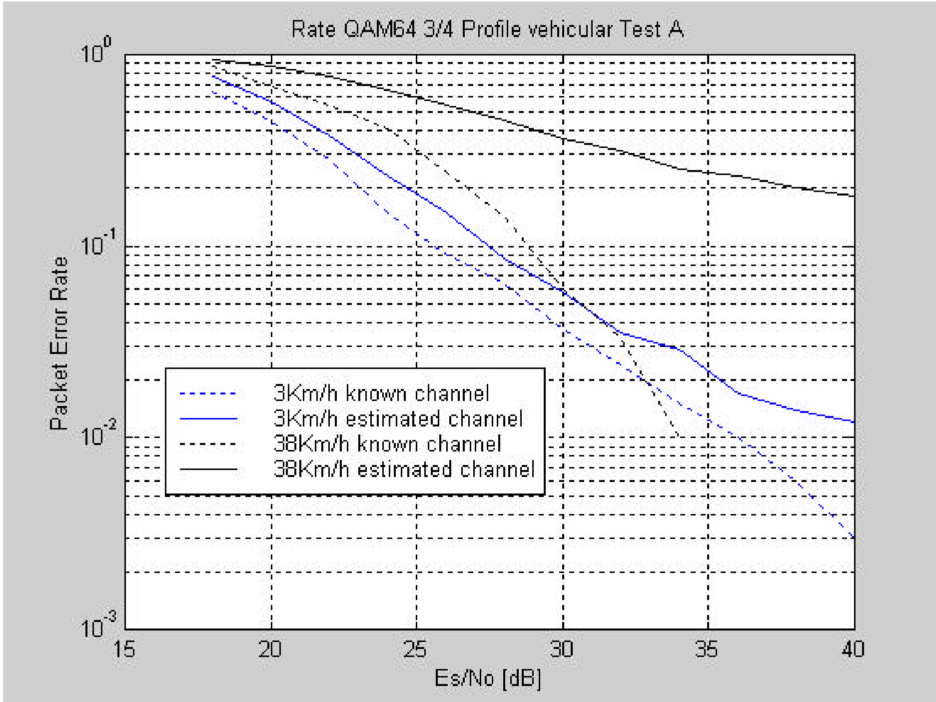
QPSK rate ½


Rate QSPK 1/2 Profile vehicular Test A
Packet Error Rate
Es/No [dB]
3Km/h known channel
3Km/h estimated channel
75Km/h known channel
75Km/h estimated channel
150Km/h known channel
150Km/h estimated channel
10^0
10^-1
10^-2
10^-3
8
10
12
14
16
18
20

QAM16 rate ½


Rate QAM16 1/2 Profile vehicular Test A
Packet Error Rate
Es/No [dB]
3Km/h known channel
3Km/h estimated channel
38Km/h known channel
38Km/h estimated channel
75Km/h known channel
75Km/h estimated channel
10^0
10^-1
10^-2
10^-3
12
14
16
18
20
22
24
26

QAM64 rate ¾



Conclusions

We can conclude the following:

1. QPSK rate ½ works well at velocities up to 150km/h. At high speeds channel estimation causes a degradation of up to 2.5dB. At low speeds, channel estimation incurs a negligible degradation.
2. QAM16 rate ½ works at speeds up to 75Km/h with degradation of 2dB relative to the known channel. At low speeds it works with negligible degradation.
3. QAM64 rate ¾ requires an SNR of more than 30dB, for proper operation even in pedestrian speeds. There is a degradation of 3dB due to channel estimation. Channel estimation fails at high speeds.

4. Summary of findings

The proposed UL and DL scheme operated robustly at high vehicular speeds. Specifically the QPSK rate ½ operated at speeds of up to 150Km/h. The QAM16 rate ½ operated at speeds of 75Km/h. The QAM64 rate ¾ operated only at pedestrian speeds (3Km/h)/

5. References

[1] J. Liebetreu, J. Tellado, T. Kaitz, N. Chayat, M. Goldhammer, A. Efron, A. Wang, A. Middleton, O. Kelman. "Modifications to OFDM FFT-256 mode for supporting mobile operation". Submitted to the IEEE 802.16e task group (IEEE C802.16x-03/12).

[2] Y. Li. "Pilot-Symbol-Aided Channel Estimation for OFDM in Wireless Systems", IEEE Trans. Vehicular Technologies, Vol. 49, No. 4, 2000.

[3] P. Hoeher, S. Kaiser, and P. Robertson. "Two-Dimensional Pilot-Symbol-Aided Channel Estimation by Wiener Filtering".

[4] ITU Recommendation ITU-R M.1225 – Guidelines for evaluation of radio transmission technologies for IMT-2000 (Question ITU-R 39/8).