DESIGN CONSIDERATIONS AND INITIAL PHYSICAL LAYER PERFORMANCE RESULTS FOR A SPACE TIME CODED OFDM 4G CELLULAR NETWORK

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Abstract - The exponential growth of cellular radio, WLANs and the Internet sets the context for a discussion on the role and objectives of 4G. In this paper OFDM is proposed as a leading candidate for a 4G cellular communications standard. The key design considerations and link parameters for a 4G OFDM system are identified and initial physical layer performance results are presented for a number of transmission modes and channel scenarios. Additionally, space-time techniques are considered as a means of enhancing the performance of the coded OFDM system.

Keywords - OFDM, 4G, Space-Time Coding.

I. INTRODUCTION

The rapid growth of world-wide cellular subscribers (expected to exceed one billion in 2003 and two billion in 2005 [1]) and the increasing number of Internet users suggest that higher data rates are needed, especially for multimedia traffic. Transmission rate is one of the most fundamental parameters in the radio access network. The amount of information will increase because of complex graphics and video required by anticipated future applications [2]. 4G systems are also expected to fulfil the requirements of next generation Internet, featuring QoS and Mobile IP. Furthermore, WLANs can be connected to the 4G system. "Smart" antenna technologies can be applied to 4G to further improve performance and reduce interference. In this paper, novel work performed under the framework of the IST SATURN project is presented that considers the application of wide area OFDM to 4G.

OFDM is an effective technique for mitigating the effects of delay spread in frequency selective channels. This paper identifies and describes the key link parameters of OFDM for a potential 4G cellular standard. These include the number of carriers, the subchannel spacing, the choice of modulation scheme and channel coding, and the choice of the guard interval. Since 4G systems will be deployed in a wide range of environments, a fixed set of parameters is not capable of achieving high performance in all cases. A system capable of dynamically adapting one or more of the above parameters may offer superior performance.

A simple space-time coded diversity technique for wireless communications over frequency selective fading channels is also investigated in this paper [3-5]. Performance results with and without space time coding will be presented in Sections VI and V respectively.

II. CHANNEL SCENARIOS

In order to study the performance of 4G systems it is essential that the transmission channels are satisfactorily characterized. The radio link performance in a mobile environment is primarily limited by Doppler and delay spread. In order to establish some assessment scenarios, the channels proposed in the Evaluation Report for ETSI UMTS Terrestrial Radio Access (UTRA) [6] are considered (Table 1). The channel is time varying, with Doppler rates, f_D, as high as 220 Hz for vehicular operation in the 2GHz band. For the indoor and pedestrian channels, f_D of ~5 Hz are expected.

Table 1. Rms delay spreads.

Number	Test Environment	Rms (ns)
1	Indoor A	70
2	Indoor B	125
3	Outdoor to indoor and pedestrian A	65
4	Outdoor to indoor and pedestrian B	655
5	Vehicular A	370
6	Vehicular B	4000

III. OFDM FOR 4G

From Table 1 it can be seen that the channel models considered have a wide range of possible delay spreads. Tables 2 and 3 show the values that were chosen for the proposed OFDM parameters and transmission modes respectively.

The operating frequency dictates the channel characteristics of a specific environment. For this study an operating frequency of 2 GHz and a channel bandwidth of 4096 kHz was assumed. In order to eliminate ISI for most channels, a guard time T_g =15.625μs and a useful symbol duration of T=62.5μs were chosen ($T_g = T/4$). This results in T_{symbol} = 78.125μs. However, a variable guard time can be employed in order to either improve efficiency or handle more ISI.

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Table 2. OFDM Parameters for 4G.

Parameter	Value 1	*Value 2*
Operating Frequency	2GHz	*2GHz*
Bandwidth (B)	4096 kHz	*4096 kHz*
Useful Symbol Duration (T)	62.5 μs	*125 μs*
Guard Interval Duration (T_g)	15.625 μs ($T/4$)	*31.25μs (T/4)*
Total Symbol Duration (T_{symbol})	78.125 μs (with GI =$T/4$)	*156.25 μs (with GI =T/4)*
Inner Channel Coding	Punctured 1/2 rate convolution code, Constraint length 7, $\{133, 171\}_{octal}$	*Punctured 1/2 rate convolution code,* *Constraint length 7,* $\{133, 171\}_{octal}$
FFT Size	256	*512*
Number of data sub-carriers (N_D)	216	*432*
Sub-carrier spacing (Δ_f)	16 kHz	*8 kHz*

Table 3. Mode dependent parameters.

Mode	Modulation	Coding Rate, R	Bit rate [Mbit/s]	Coded bits per sub-carrier
1	BPSK	1/2	1.3824	1
2	QPSK	1/2	2.7648	2
3	QPSK	3/4	4.1472	2
4	16QAM	1/2	6.2206	4
5	16QAM	3/4	8.2944	4
6	64QAM	3/4	12.4416	6

The subcarrier spacing is $\Delta_f = 1/T =$ 16 kHz. The number of sub-carriers can be found by dividing the available bandwidth B_s by the subcarrier spacing:

$$N = B_s / \Delta_f = B_s * T = 256$$

The symbol duration may be increased by employing a larger FFT in the modulation process. However, this results in increased complexity of implementation and increased sensitivity to Doppler and phase noise. A FFT size of N=512 is also under consideration, since it will improve guard interval efficiency and can handle more ISI. The OFDM parameters for N=512 are shown in Table 2 (*italic*). However, in this paper performance results for the case of N=256 will be presented. The individual carriers will be modulated by either BPSK, QPSK, 16QAM, or 64QAM with coherent detection. In order to employ coherent detection, channel estimation must be performed. For the simulations in this paper, a preamble before every packet was used to estimate the channel and it was assumed that the channel does not change over the duration of the packet. (In practise this method would be suitable only for the pedestrian and indoor channels. For the vehicular channels, channel estimation techniques, such as pilot symbol assisted modulation should be employed).

Channel coding can be performed on a service type basis. The following options could be available: (a) Convolutional coding, (b) Outer Reed Solomon (RS) + Outer interleaving + Convolutional coding, (c) Turbo coding.

Additionally, Automatic Repeat Request (ARQ) schemes can be employed for packet services with no delay constraints (for example, data services). High peak rate modes (such as mode 6) that have high PERs can be used in conjunction with ARQ protocols for non delay sensitive services. Turbo codes also allow the modem to trade off improved PER at the cost of latency. Interleaving is used to ensure that the channel coding performs well in the presence of burst errors introduced by the fading channel. This paper considers the case of convolutional coding with soft decision Viterbi decoding.

The raw bit rate depends on the chosen modulation scheme. Channel coding also affects bandwidth efficiency. Different modes with different modulation and coding rates will provide a number of data rates. These modes can be selected by a link adaptation scheme. Table 3 shows the bit rate for the different transmission modes considered in this paper.

IV. MULTIPLE ACCESS

The multiple access scheme considered here is TDMA. The TDMA scheme is capable of accommodating multirate traffic, which is essential to multimedia applications. Note that in general, within a given time slot, a mobile station may use all or some of the allocated subcarriers. Hence, the transmission rate of each mobile station may dynamically vary from slot to slot. This situation is known as orthogonal frequency division multiple access (OFDMA) [7,8]. Although this technique provides the means for extended flexibility and multirate transmission, it requires precise synchronisation between the mobile stations and thus high implementation complexity. However, OFDMA provides better coverage by allocating a power level that is a function of user distance on the downstream and concentrating the available user terminal power on a few carriers in the upstream. This gain is increased with the number of subcarriers. Hence, both multiple access schemes are under consideration in the SATURN project. For this paper, the simpler OFDM/TDMA scheme will be considered, where each time slot is dedicated to a mobile terminal. However, the physical layer OFDM results are not dependent on the multiple access scheme.

If we assume a TDMA/TDD approach the base station informs the ‘Mobile Terminals’ (MTs) at which point in time in the MAC frame they are allowed to transmit their data. Time slots are allocated dynamically depending on the need for transmission resources. Multiple virtual connections with different bit rates and QoS requirements can be established. If a frame duration of 10ms is assumed then the number of OFDM symbols in a frame is N_{frame}= 128. This approach is similar to that taken in the 802.11a and HIPERLAN/2 standards [13].

For packet based services, if the parameters of Table 3 are assumed then a packet size of 162 bytes will result in an integer number of OFDM symbols for most transmission modes. Of course, if additional Reed Solomon coding is employed then the packet size will be reduced according to the number of redundant bits in the outer code. In each packet, 3 bytes can be used for error detection, using CRC (Cyclic Redundancy Check) codes.

V. PERFORMANCE RESULTS

Figures 1 and 2 present the BER and PER (Packet Error Rate) performances of the different transmission modes (specified in Table 3) versus the average SNR for channel model 4 (see Table 1). An outer RS code or an ARQ scheme (in combination with CRC codes) - depending on the QoS requirements of the application - can be employed to reduce the application error rate. These codes can reduce the residual PER to approximately 10^{-9} - 10^{-11} for PERs of 10^{-1} - 10^{-3} for a code rate in the region of 0.9.

Figure 3 shows the simulated PER performance versus SNR for mode 4 under all considered channels. It can be seen that as the delay spread increases the performance improves. This continues until the delay spread becomes so large that ISI and ICI become limiting factors (channel 6). It is important to point out that the symbol duration, T=78.125μs, is much smaller than the channel coherence time, even in the case of fast variation (vehicular model), where the coherence time is approximately Tc≈3ms. Therefore, channel time variations can be neglected within each OFDM symbol. Thus, a time invariant impulse response can be associated with each transmitted OFDM symbol, which may change between OFDM symbols [12].

Channels 1 and 3 have similar performances due to their similar values of rms delay spread (see Table 1). Channels 2, 5 and 4 have increasingly better performances relative to channels 1 and 3 due to the increased frequency diversity of the channels. In channel 6 the excess delay (~20 μs) of the channel is larger than the guard interval (~16 μs) so ISI cannot be completely eliminated. Thus, performance starts to deteriorate for excess delays more than ~16 μs. Employing an FFT size of 512 instead of 256 with T_g=31.25μs (see Table 2) can solve this but at the expense of increased implementation complexity and sensitivity to Doppler and phase noise.

It can be observed from Figures 1 and 2 that modes 3 and 4 have similar performances for the case of channel 4. Hence, approximately the same degradation in performance results from increasing the code rate or changing the modulation scheme. The similar performance of QPSK ¾ rate and 16-QAM ½ rate is due to the fact that the latter is able to tolerate more erroneous subcarriers, which compensates for the smaller distance between constellation points [9].

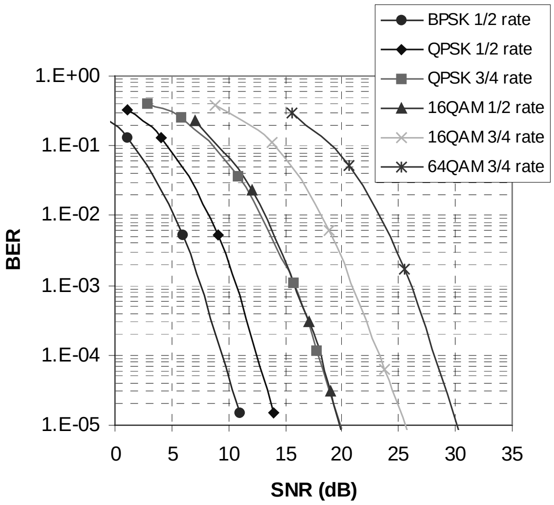

Fig. 1. BER Performance of the 4G system.

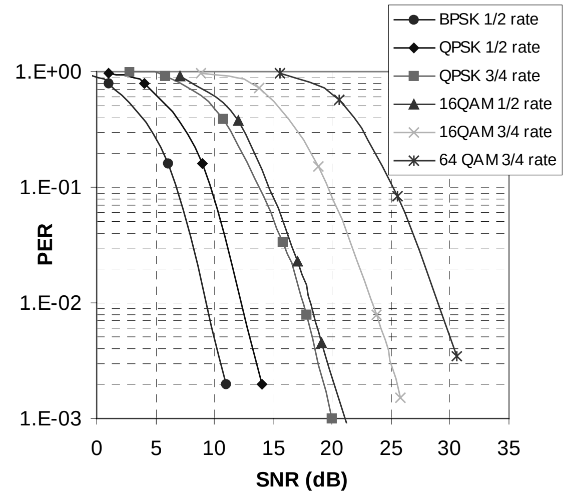

Fig. 2. PER Performance (Packet size =162 bytes).

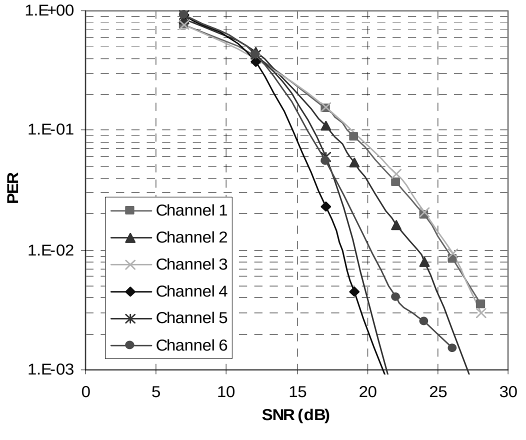

Fig. 3. PER Performance of mode 4 for all the channels.

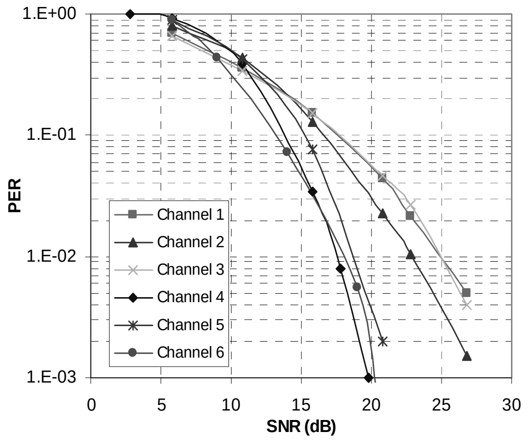

Fig. 4. PER Performance of mode 3 for all the channels.

However, it can be seen from Figures 3 and 4 that these two modes do not have the same performance for all channels. It can also be observed that the performance of mode 3 is much better than that of mode 4 in channel 6. The error floor in mode 3 appears for much lower PER values. This is due to the fact that lower order modulation schemes cope better with ISI.

VI. SPACE TIME CODING

In [3] Alamouti proposed a simple transmit diversity scheme which was generalized by Tarokh [10] to form the class of Space-Time Block Codes (STBC). These codes achieve the same diversity advantage as maximal ratio receive combining (allowing for a -3dB offset for the case of 2 Tx antennas due to power normalization) [5].

In [4], Lee and Williams applied a 2Tx-1Rx antenna, transmit diversity scheme to OFDM in order to achieve diversity gain over frequency selective fading channels. In this paper, STBC will be applied to the OFDM system with convolutional coding as described in the previous sections in order to enhance system performance. Figure 5, shows a block diagram of the 2Tx, *m*Rx ($m = 1,2$), proposed space-time coded OFDM system for the case $m = 1$. In Alamouti's encoding scheme two signals are transmitted simultaneously from the two transmit antennas. The transmission matrix, is given by [3-5,11]:

$$X=\begin{bmatrix} X_1 & -X_2^* \\ X_2 & X_1^* \end{bmatrix} \tag{1}$$

where in the case of OFDM, X_1, X_2 are two consecutive vectors (forming a pair of vectors) to be input to the IDFT after the serial to parallel conversion (S/P) of the QAM modulated data [4]. At the first antenna, X_1 is transmitted during the first symbol period followed by $-X_2^*$ in the second symbol period. At the second antenna, X_2 is transmitted during the first symbol period followed by X_1^* in the second symbol period.

At the receiver, after the DFT and the cyclic prefix removal, the received vectors are given by [4,5]:

$$\begin{aligned} Y_1 &= H_1X_1+H_2X_2+N_1 \\ Y_2 &= -H_1X_2^*+H_2X_1^*+N_2 \end{aligned} \tag{2}$$

where N_1, N_2 are AWGN and H_1, H_2 are diagonal matrices whose diagonal elements are the frequency responses (DFT of h_1, h_2) of the channels between Tx1 and Rx1 and between Tx2 and Rx1 respectively (see Figure 5). It is assumed that the channel responses are constant during the period of two OFDM symbols, something that is reasonable for the OFDM parameters chosen here, where $T_{symbol} = 78.125\mu s$.

After channel estimation, the channel parameters are known to the receiver, and the signals Y_1, Y_2 can be combined at the receiver according to [4,5]:

$$\begin{aligned} S_1 &= H_1^*Y_1+H_2Y_2^* \\ S_2 &= H_2^*Y_1-H_1Y_2^* \end{aligned} \tag{3}$$

Substituting for Y_1, Y_2 from (2), the combined signals can be written as [4,5]:

$$\begin{aligned} S_1 &= (|H_1|^2+|H_2|^2)X_1+H_1^*N_1+H_2N_2^* \\ S_2 &= (|H_1|^2+|H_2|^2)X_2+H_2^*N_1-H_1N_2^* \end{aligned} \tag{4}$$

In order to perform the soft decision Viterbi decoding, the Channel State Information of both channels (H_1, H_2) is passed to the decoder in order to calculate the metric. For the case of 1 Rx antenna, the above scheme is similar to that of two branch maximal ratio receive combining (MRRC). For the case of 2 Rx antennas, the signals from the two receivers are combined and the scheme performs similarly to four branch MRRC.

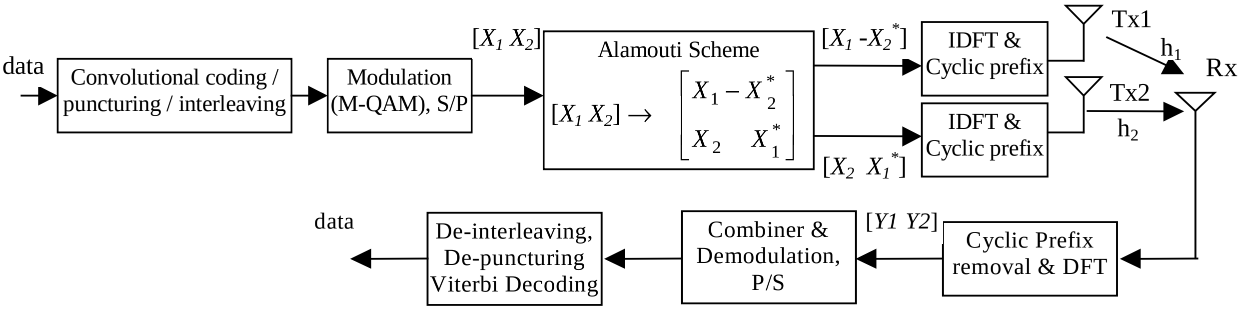

Fig. 5. Block diagram of the proposed space time coded OFDM system for the case of 2Tx, 1Rx.

However, the Alamouti scheme has a 3 dB power loss compared to MRRC because each transmit antenna transmits only half the power so that the average received power is the same when comparing receive with transmit diversity [4,5].

Figures 6 and 7 show the BER performances of modes 1 (channel 5) and 5 (channel 2) versus the average SNR with STBC respectively. It was assumed that a perfect channel estimate was available at the receiver. It can be observed that the performance is significantly improved for both the cases of 2Tx, 1Rx and 2Tx, 2Rx antennas.

From Figure 6, it can be seen that the proposed STBC provides ~ 3.5dB gain at a BER of 10^{-4} for the case of 2Tx and 1Rx antennas and a further 5.5dB gain for the case of 2Tx and 2Rx antennas (mode 1, channel 5). For mode 5 (in channel 2), an 8dB gain for the case of 2Tx and 1Rx antennas and a further 6dB gain for the case of 2Tx and 2Rx antennas can be observed from Figure 7. Hence, the gain depends on the transmission mode and channel scenario.

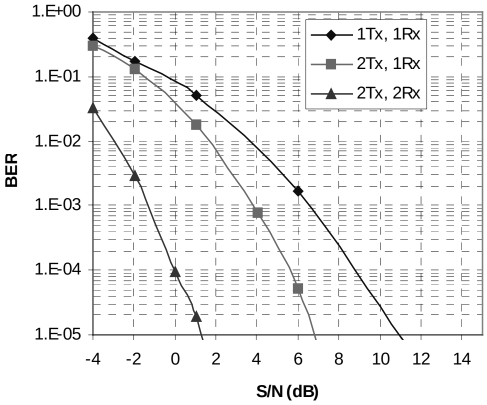

Fig. 6. BER Performance with STBC, Mode 1,Channel 5.

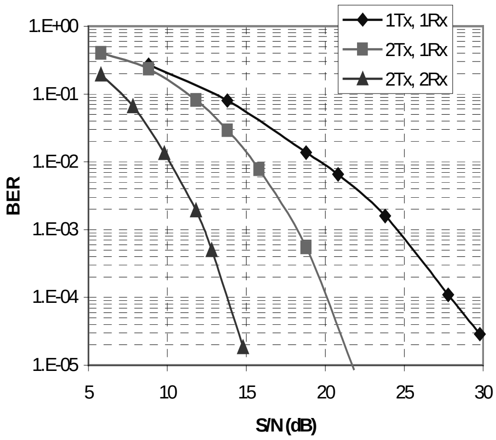

Fig. 7. BER Performance with STBC, Mode 5, Channel 2.

VII. CONCLUSIONS

In this paper, OFDM was proposed as the transmission technique for a future 4G network. The key link parameters were identified and initial physical layer performance results were presented for a number of channel models. The OFDM system provides data rates of around 1.3-12.5 Mb/s by employing different transmission modes. Hence, this system will be suitable for multimedia traffic, which is a key requirement for 4G systems. In order to achieve diversity gain and enhance performance, space-time block codes were employed. Although this scheme has low complexity and is easy to implement, it provides considerable improvements in performance without any bandwidth expansion. Gains of between 9-14 dB were observed depending on the transmission mode and channel scenario at a BER of 10^{-4} for the case where 2 antennas are used in both the transmitter and receiver.

AKNOWLEDGEMENTS

This work has been performed in the framework of the IST project SATURN.

REFERENCES

[1] J.M. Pereira, "Fourth Generation: Now, it is Personal", PIMRC 2000, Vol. 2, pp. 1009-1016, 2000.

[2] N. Nakajima, Y. Yamao, “Development for 4th Generation Mobile Communications,” Wireless Communications and Mobile Computing, Vol. 1, No.1. Jan-Mar 2001.

[3] M.Alamouti, "A simple transmit diversity technique for wireless communications", IEEE JSAC, Vol. 16, No.8, October 1998.

[4] K.F.Lee, D.B.Williams, "A space-time coded transmitter diversity technique for frequency selective fading channels", Sensor Array and Multichannel Signal Processing Workshop, 2000, pp. 149-152.

[5] B. Vucetic, "Space-Time Codes for High Speed Wireless Communications", Course on Space Time Codes, King's College London, November 2001.

[6] ETSI/SMG/SMG2, “The ETSI UMTS Terrestrial Radio Access (UTRA) ITU-R RTT Candidate Submission” ETSI Proposal for IMT-2000.

[7] J.Chuang, N.Sollenberger, "Beyond 3G: Wideband Wireless Data Access Based on OFDM and Dynamic Packet Assignment", IEEE Communications Magazine, July 2000, pp.78-87.

[8] Sony Corporation, "BDMA, The multiple access scheme proposal for the UMTS terrestrial radio air interface (UTRA)," ETSI SMG2, London, June1997.

[9] R.vanNee, R.Prasad, “OFDM for Mobile Multimedia Communications”, Boston: Artech House, Dec.1999.

[10] V.Tarokh, H.Jafarkhani, A.R.Calderbank, "Space-time block coding for wireless communications: performance results", IEEE JSAC, Vol.17 No.3, March 1999, pp.451-460.

[11] A.F.Naguib, N.Seshadri, A.R.Calderbank, "Increasing data rate over wireless channels", Signal Processing Magazine Vol. 17 No. 3, May 2000, pp.76-92.

[12] L.Hanzo, W.Webb, T.Keller, “Single and multicarrier Quadrature Amplitude Modulation”, John Wiley & Sons, 2000.

[13] A.Doufexi, *et al*. " A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless LAN Standards" IEEE Communications Magazine, Vol.40 No.5, May 2002.