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COMMUNICATIONS

A SIMPLE APPROACH TO OFDM–BASED SYSTEMS DYNAMIC OPTIMIZATION

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Link adaptation techniques have recently emerged as a powerful tool to perform radio interface optimization, a key feature of future mobile/wireless systems allowing to dynamically find the best trade-off among high throughput, QoS and low power. In this framework a reduced-complexity algorithm for fast, joint optimization of OFDM indoor wireless systems operating in frequency selective environments, is proposed. Based on the sub-carrier switching concept and the channel state information, the algorithm dynamically selects the transmission parameters, as far as modulation and channel coding are concerned, that guarantee the required QoS (bit rate and BER) with the minimum transmission power. The algorithm is handled by a "Supervisor" unit, which is the unit responsible for real-time information processing and control in any adaptive and/or re-configurable transceiver.

Keywords: radio interface optimization, mobile/wireless systems

1 INTRODUCTION

The requirement for high-performance, flexible, QoS-aware, low-power digital transceivers is one of the key challenges for future mobile/wireless systems. Link adaptation techniques, where modulation, coding rate, and/or other transmission parameters are dynamically adapted to the changing channel condition, have recently emerged as a powerful tool to pursue a given system optimization. So far, link adaptation techniques have been mainly focused on modulation (*eg* bit and power loading techniques for OFDM systems as described in [1], [2], [3], [4]) and, in general, on the different blocks of the transmission chain separately (source coding adaptation, channel coding adaptation, adaptive modulation, and so on). Moreover, the classic considered problem is the maximization of the rate or the minimization of the BER, given the channel condition and the fixed transmission power. Finally even if some of these techniques are proven to be highly effective from the theoretical point of view, most of them still appear too complex to be implemented in real wireless systems.

Within this framework a reduced-complexity algorithm for real-time, joint optimisation of coding and modulation parameters in OFDM indoor wireless systems is proposed. The algorithm, based on the sub-carrier switching concept, determines dynamically the modulation and channel coding parameters for an OFDM-based system operating in frequency selective environments. Based on the channel state information, the algorithm selects the transmission parameters that guarantee the required QoS (bit rate and BER) with the minimum transmission power.

This work has been developed in the context of the Wind-Flex project, an European IST project aiming at the definition of a new flexible and high-performance radio interface for indoor applications [5].

2 ALGORITHM DESCRIPTION

The Minimum Transmission Power Supervisor Algorithm, hereafter SA, is meant to perform in real-time the adaptive system optimization through the Supervisor unit.

The core of the SA calculates the optimum set of constellation size, channel code rate, number and position of active sub-carriers (SCs) and transmission power. "Optimum" here means that the parameters chosen by the SA guarantee, for the current channel condition, the bit rate and the BER requested by the MAC sub-layer with the "minimum" transmission power. The power has to be considered the "minimum" obtainable with respect to the low complexity of the algorithm. The SA exploits the idea of discarding those highly attenuated SCs that are not strictly necessary to get the requested rate (SC switching technique) and, for that reason, also the current number and position of ON SCs are given as output.

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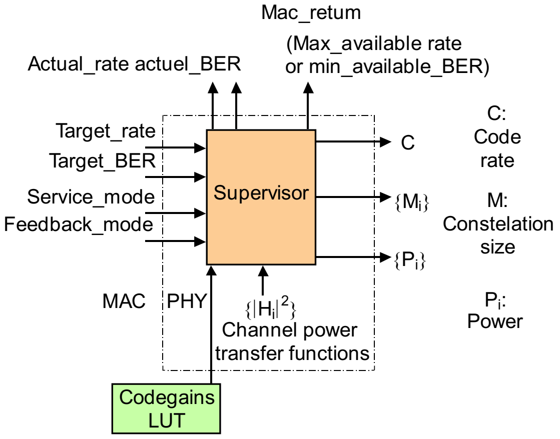

Fig. 1. I/O of the Supervisor Algorithm

If the “minimum” power computed is greater than the maximum available in the system, this maximum value is assumed to be the current ”minimum” power and the algorithm provides one out of two possible sub-optimum solutions, depending on the required service. If the service is BER sensitive (*eg* file transfer) the SA provides the maximum available bit rate for the required BER along with the corresponding set of parameters. If the service is rate sensitive (*eg* real-time voice/video) the SA provides the value of the minimum BER for the required bit rate and the corresponding parameters.

2.1 Assumptions/Constraints

The following simplifying assumptions/constraints have been considered:

1) OFDM transmission is equivalent to N parallel and independent single-carrier transmissions;
2) every sub-band is modelled as an AWGN channel with a flat channel response defined by a complex coefficient H;
3) the mean path loss and the channel power gain $a = |H|^2$ for every SC, experienced at the receiver, are known at the transmitter;
4) the transmission power, as well as the single-carrier constellation, are the same for every ON SC;
5) code rate is the only adjustable parameter of the coding scheme;
6) the coding gain in AWGN channels for each available constellation and code rate is known.

2.2 I/O Data

The SA receives input data from the MAC sublayer (Target_BER and Target_Rate, Service and Feedback_mode) and from the physical layer (the channel state information, *ie* the set of the channel power gains) as shown in Fig. 1. Moreover it can access static data from an internal LUT (Look-Up Table) containing the code gains for every M/C couple (constellation/code rate couple) in AWGN channel. The Service_mode flag indicates the SA the type of service. The SA algorithm also returns to the MAC, among the other parameters, the actual bit rate and BER achieved. In case the channel conditions prevent from achieving the required QoS, the SA sets up all the parameters depending on the required service. Apart from the current parameters, the algorithm always provides, under request, the MAC with the Maximum available rate or the Minimum available BER. The MAC specifies which value it is interested in by means of the Feedback_mode. Feedback information can support MAC in determining the next QoS request.

2.3 The Supervisor Algorithm

As stated above, the SA is able to solve the problem of finding the M/C couple, the number and the position of the ON SCs required to fit the Target_Rate and the Target_BER requirements with the “minimum” power, given the current channel condition. In this paper only the algorithm referring to the case in which the channel condition allows the “optimum” solution will be described.

1. Calculate the maximum bit rate achievable by every couple M/C, identified by modulation k and code-rate i, with all SCs turned on:

$$R_{\max}^{(k,i)} = N \cdot R_n^{(k,i)}\,, \quad R_n^{(k,i)} = nbit_k C^i \tag{1}$$

(1) where N is the total number of SCs, $R_n^{(k,i)}$ is the pre-coded bit rate carried by the nth SC by making use of modulation k and code-rate i, C^i is the code-rate, $nbit_k$ is the number of bits per modulation symbol. Note that this calculation can be performed off-line at initialization time.

2. Eliminate the couples M/C for which the maximum achievable bit rate is less than the requested one: $R_{\max}^{(k,i)} < R$.
3. For every couple useful M/C:
   a. calculate the minimum number of SCs required to achieve the bit rate B:

$$N^{(k,i)} = \left\lceil \frac{R}{R_n^{(k,i)}} \right\rceil \tag{2}$$

   where $\lceil\cdot\rceil$ denotes the round up to the next integer. Note that, in real implementations, the number of SCs is calculated so as to place an integer number of information bits per OFDM symbol.

   b. Derive, from simulation-based curves, the SNR necessary to obtain the required BER in the AWGN case. Let $snr_{SC}^{(k,i)}$ be the SNR required, for a single SC, to operate @BER when using modulation k and channel coding i, assuming an AWGN channel:

$$snr_{SC}^{(k,i)} = snr_{SC}^{k}/g_c^i \tag{3}$$

where snr_{SC}^{k} is the uncoded SNR required by modulation k and g_c^i is the coding gain i. Then, using $N^{(k,i)}$ SCs, the received power will be:

$$P_{r,AWGN}^{(k,i)} = P_n snr_{SC}^{(k,i)} N^{(k,i)} \tag{4}$$

P_n is the white noise power in the nth SC band, and $snr_{SC}^{(k,i)}$ the signal-to-noise ratio for modulation k and code i. This is the best way to derive the relation between BER and SNR for the single carrier coded modulation: no complex analytical relations, when obtainable, have to be worked out. It is worth to be underlined that the real channel is not supposed to be AWGN. This step is just a starting point for the algorithm and the real channel is considered in step 3c.

c. Let $\vec{A} = \{a_1, a_2, \ldots, a_N\}$ be the vector of the channel power gains for all N SCs. Let us assume, without loss of generality, that $\vec{A}$ has been ordered in descending order and consider the leading $N^{(k,I}$ components:

$$\vec{A}^{(k,i)} = \{a_1, a_2, \ldots, a_{N^{(k,i)}}\} \, . \tag{5}$$

Then $a_{N(k,i)}$ is the lower gain among the $N^{(k,i)}$ necessary SCs: if the SNR on this SC is greater than or equal to the required $SNR^{(k,i)}$ (for modulation k and code-rate i), then the very same condition will obviously hold for all the $N^{(k,i)}$ SCs. The signal power at the receiver must be such that the above condition applies for the worst SC, *ie* the received signal power calculated in step 3 must be scaled by the factor $1/a_{N(k,i)}$:

$$P_r^{(k,i)} = (1/a_{N^{(k,i)}}) \cdot P_{r,AWGN}^{(k,i)} \, . \tag{6}$$

d. Calculate the total received power for all $N^{(k,i)}$ SCs:

$$P_{r,tot}^{(k,i)} = P_r^{(k,i)} \cdot N^{(k,i)} \, . \tag{7}$$

4. The "optimum" couple M/C ($(M,C)_{\text{min\_pow}}$) is the one which minimizes $P_r^{(k,i)}$:

$$P_{r,\text{min\_pow}} = \min_{(k,i)} \left\{ P_{r,tot}^{(k,i)} \right\} \, . \tag{8}$$

If the minimum receive power (8) is below the sensitivity threshold T_r of the receiver, then the receive power is set equal to the sensitivity threshold:

$$P_{r,\text{min\_pow}} = T_r \, . \tag{9}$$

Note that this is just an upper bound for the minimum required power. A way to derive the real BER of the whole coded OFDM symbol from the different BER of the various sub-channels is under investigation for the Wind-Flex system, and could be implemented without modifying the algorithm. Anyway, a system design based on this upper bound can be considered a good trade-off between complexity and performance.

5. The couple $(M,C)_{\text{min\_pow}}$ can achieve the actual rate $R_{\text{min\_pow}} = N_{\text{min\_pow}} \cdot nbit_k \cdot C^i$ and the BER requested by the MAC sub-layer by using $N_{\text{min\_pow}}$ SCs and with the minimum possible transmit power, given by:

$$P_{t,\text{min\_pow}} = a P_{r,\text{min\_pow}} \tag{10}$$

where a is the mean path loss.

3 SIMULATION RESULTS

Several simulations in the Wind-Flex scenario [5] have been performed. The Wind-Flex system architecture is based on Turbo channel coding, OFDM modulation scheme and provided with a "Supervisor" (SPV) unit for real-time system optimization.

The available sub-carrier modulation schemes are BPSK, QPSK, 16-QAM and 64-QAM, and are adaptively chosen. The total number of useful sub-carriers is 100 but a variable number of sub-carriers can be also adaptively switched-off (SC switching).

The coding scheme is a parallel convolutional turbo code [6]. The available code rates are 1/2, 2/3 and 3/4 and the block length is adaptive and dependent on the triplet: Code rate, Constellation size, and Number of ON sub-carriers.

The 17 GHz channel model provided by the Wind-Flex Consortium [7] has been adopted. The channel exhibits a frequency-selective behaviour, which translates into few deep fades in the 50 MHz-wide spectral response.

3.1 Results

Figures 2, 3 and 4 show some performance results obtained by applying the SA algorithm (blue), compared to the performances without SA implemented (pink). The worst-case scenario, *ie* NLOS channel and maximum distance from the transmitter (5 meters), has been considered. For each simulation 10000 channel realizations have been used, that is: the SA was run 10000 times, and for every channel realization the "optimum" couple M/C, giving the required QoS with the minimum transmit power, was found. Note that the optimum couple — and the required power — is not always the same for different channel realizations. The bottom horizontal line is the minimum power line and, in the graphs, defines the minimum average received power required. It is obtained by selecting, for each channel realization, the received power of the optimum M/C couple and then averaging over the total number of channel realizations. The graphs also show the average power required by each couple M/C. Some couples are missing because they would require a power level higher than the maximum allowed by system specifications (10 dBm EIRP transmit power).

Note that when no SA is applied, the optimum couple M/C is always the same for every channel realization

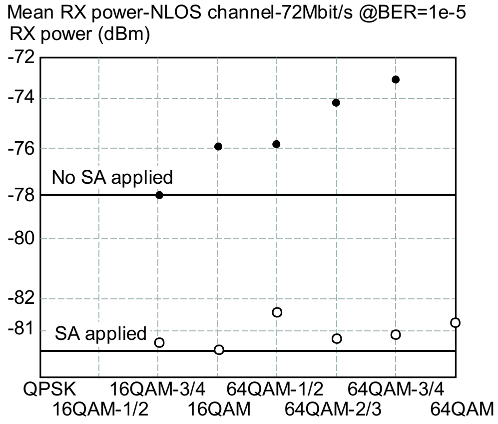

Fig. 2. Power levels required for 72 Mb/s transmission at 10^{-5} BER

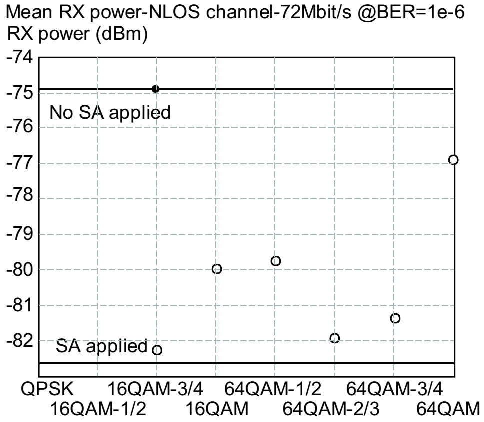

Fig. 3. Power levels required for 72 Mb/s transmission at 10^{-6} BER

(*eg* 16 QAM with 3/4-rate convolutional turbo coding in Fig. 2), therefore the level of the minimum power line is defined by the average power required by this modulation/coding scheme. When the SA is applied, on the other hand, the optimum couple may change, therefore the minimum power line does not generally correspond to the power level required by a single couple (Figs 3 and 4).

Note also the significant amount of power saved by using the SA, especially when high bit rates/low BERs are requested by the MAC layer.

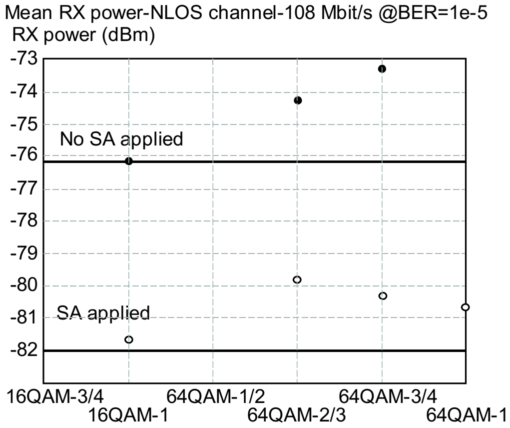

Fig. 4. Power levels required for 108 Mb/s transmission at 10^{-5} BER

4 CONCLUSIONS

A simple and effective algorithm that can be run by any adaptive, QoS-aware, OFDM receiver has been developed and proposed. The algorithm is based on the sub-carrier switching technique and is able to solve the problem of finding the modulation/coding scheme and the number and position of the ON sub-carriers required to fit the Target_Rate and the Target_ BER requirements with the "minimum" power, given the current channel condition. The proposed solution can be considered a good trade-off between complexity and performance with respect to the theoretical optimum given by the "water filling" solution [8]. Moreover, this reduced-complexity algorithm is suitable for the real-time applications. The SA, as described in this paper, gives just an upper bound for the minimum required power. A way to derive the real BER of the whole coded OFDM symbol from the different BER of the various sub-channels is under investigation in the Wind-Flex project framework.

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