Bit-loading Algorithm for DMT Broadband Indoor Power Line Communications

José A. Cortés, Luis Díez, Francisco J. Cañete, J.Tomás Entrambasaguas
Departamento de Ingeniería de Comunicaciones, E.T.S.I. de Telecomunicación,
Universidad de Málaga, Campus de Teatinos s/n, 29071 Málaga, Spain
[1]Tel: +34 952 13 71 81, e-mail: jaca@ic.uma.es

ABSTRACT

In this paper, a bit-loading algorithm for DMT (Discrete MultiTone) broadband indoor power line communications is proposed. In noisy channels with high attenuation values, most of the carriers remain empty after the application of conventional strategies. This is due to the limitation in the power spectral density (PSD) mask for the transmitted signal imposed by regulations. Under these circumstances, MBA (Multibin Bit Allocation) algorithm offers significant bit-rate improvements. Based on this framework, a modification of this method and its performance is presented. Simulation results show that, even with a reduced computational load, important bit-rate gains can be obtained.

Key words: Bit-loading, DMT, power line, broadband.

I. INTRODUCTION

In the last years, the use of the existing power line distribution grid as a broadband data transmission medium has aroused considerable interest. To this end, international regulations that extend current limits in the available spectrum [1] are under development [2]. Two main applications are proposed for power line communications: to utilise the link between the medium/low voltage transformer and the user premises as the access part to other telecommunication networks (i.e. the so-called “last mile”); and to make use of the indoor mains in small offices and houses as a local area network. This paper is concentrated on the latter alternative.

Indoor power line channels are adverse media for high-speed data transmission [3]. Because of the branched structure of the network they present deep notches, large variation of the attenuation with frequency and great dispersion of the frequency response characteristics among different channels of the same site. In addition, the connection and disconnection of electrical appliances to the grid provokes time variation in both the frequency response and the noise PSD. Regardless of the properties of the adaptive DMT modulation to cope with these impairments, the non-continuity of the available spectrum, due to electromagnetic compatibility problems, make it specially suited for power line channels.

One of the main aspects of DMT modulation is the criterion used to allocate energy to the different carriers, which is done by means of bit-loading algorithms. When conventional techniques [4]-[6] are applied in situations with large attenuation values and high noise levels, a large number of carriers have no bits assigned because the required power would exceed the PSD limit imposed by regulations. In these circumstances, the use of the MBA algorithm [7] after classical strategies offers significant bit-rate improvements. It groups some of the unused tones in fixed-size sets and transmits the same data bit in all the carriers of each cluster. Based on this framework, a modification of this method that discards tones with very low SNR (Signal to Noise Ratio) prior to the grouping process and uses variable-size sets is presented. Simulation results show that, even with a reduced computational load, important bit-rate gains can be obtained.

The rest of this paper is organised as follows. In section II, the power line channel model employed throughout of the study is depicted. This helps to understand the problems of the bit-loading for this application and, therefore, the necessity for the modifications in the MBA scheme, that was designed with major attention to ADSL (Asymmetrical Digital Subscriber Loop) systems. This algorithm, along with the proposed and conventional [4] ones, is explained in section III. Simulation results are described in section IV. Finally, main conclusions are given in section IV.

II. CHANNEL MODEL

Power line network inside buildings can be considered as the interconnection, in a tree-like structure, of multiple transmission lines terminated in loads of diverse nature [3]. Each device connected to the grid represents a load and can be modelled with a complex impedance value and a noise source. These frequency and time (depending on whether the device is in working state or not) variant values are obtained from characterisation of typical electrical appliances.

As an example, Fig.1 shows the amplitude frequency response, in the frequency range up to 30MHz, of three channels generated using the software model from [3]. All of them correspond to the same residential configuration but with the transmitter and the receiver placed in different positions at distances of 4, 13.4 and 33m, respectively. The effects of the coupling circuits are also included.

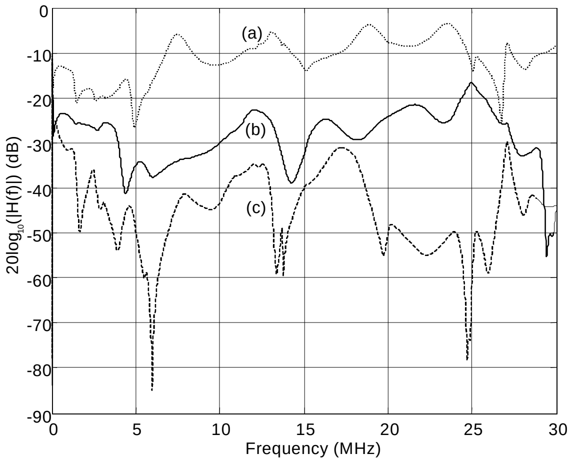

Figure 1. Amplitude frequency response of three power line channels: (a) 4m length, (b) 13.4m length and (c) 33m length

Although the noise in these channels is not white, for a worst-case analysis, a flat PSD of –65dBm/kHz can be considered as an upper bound of the worst noise scenario measured in a residential environment [3].

For channels like (a) and (b) from Fig. 1, conventional bit-loading algorithms perform reasonably well, even in the adverse noise conditions of -65dBm/kHz. Nevertheless, for the ones comparable to (c), most of the carriers have no bits allocated because of their low SNR values. For the subsequent analysis, eight long and branched channels (in the range up to 30MHz), with frequency responses similar to (c), and an Additive White Gaussian Noise with the aforementioned PSD are used. Impulsive noise has not been included.

III. BIT-LOADING ALGORITHM

There are two basic types of bit-loading algorithms: those that try to minimise the total energy employed subject to the transmission of a fixed data rate, called MA (Margin Adaptive); and the RA (Rate Adaptive) one, in which the goal is to distribute the available energy among the carriers such that the overall bit-rate is maximised. This work is focused on the latter one, whose optimal solution, the water-pouring scheme, leads to non-integer numbers of bits per carrier. However, when the bit assignment is constrained to be integer this distribution has to be modified. Thus, denoting by ε_n the energy allocated to carrier *n*, the number of bits that can be transmitted, b_n, using uncoded QAM modulation with an error probability P_e, can be approximated by

$$b_n = \left\lfloor \log_2\left(1 + \frac{\varepsilon_n \cdot |H_n|^2}{N_n \cdot \Gamma_n}\right)\right\rfloor \tag{1}$$

where $\lfloor x \rfloor$ stands for the lesser integer closest to x, H_n and N_n are the frequency response of the channel and the noise and distortion (caused by ISI -Intersymbol Interference- and ICI -Intercarrier Interference-) PSD in carrier *n*, respectively. Γ_n is the SNR gap that appears because of the use of practical signal constellations, and for QAM can be approximated by [8]

$$\Gamma_n = \frac{1}{3}\cdot\left[Q^{-1}\left(\frac{P_e}{4}\right)\right]^2 \tag{2}$$

Hence, the discrete RA problem for a system with M carriers is stated as follows

$$\max_{\varepsilon_n} \sum_{n=1}^{M} b_n \tag{3}$$

subject to the constriction

$$\sum_{n=1}^{M} \varepsilon_n \leq \mathrm{E} \tag{4}$$

A. Basic RA algorithm

The Hughes-Hartogs algorithm [4] achieves the optimal solution for the discrete RA loading problem. For the application under study, in addition to the limitation in available energy, a PSD constraint for the transmitted signal (imposed by regulations) and a restriction in the maximum number of bits per carrier, b_{max}, are also considered. In order to apply the algorithm, the use of a memory stored look-up table, *SNR(k,P$_e$)*, that contains the required SNR to transmit *k* bits with an error probability lower than P_e is very convenient. Therefore, the bit-loading procedure can be summarised as follows:

```
1: Estimate the values of $H_n$ and $N_n$ for $n=1...M$
2: For $n=1...M$ calculate the necessary energy to add
   one bit to each carrier:
      $\Delta E(n) = \frac{SNR(b_n+1,P_e)\cdot N_n}{|H_n|^2} - \frac{SNR(b_n,P_e)\cdot N_n}{|H_n|^2}$   (5)
   where $b_n=0$ $\forall n$ in the first iteration and
   $SNR(0,P_e)=0$
3: Initialise the expended energy, $E_{expended}=0$
4: While (none of the constraints is violated) do
    -Find the minimum $\Delta E(n)$
    -$E_{expended} \leftarrow E_{expended}+\Delta E(n)$
    -If ($E_{expended}<E$) and ($\Delta E(n)<PSD\_mask(n)$),
        where $PSD\_mask(n)$ is the PSD constraint in
        the frequency of carrier $n$
            $\varepsilon_n \leftarrow \varepsilon_n+\Delta E(n)$
            $b_n \leftarrow b_n+1$
            Compute the new $\Delta E(n)$
     else $\Rightarrow$ some constraints have been violated
```

This process has $\mathcal{O}(B_{TOTAL}\ x\ M)$ complexity, where

B_{TOTAL} is the total number of bits that have been assigned during the execution.

B. MBA algorithm

After the application of the basic RA scheme in very hostile channels, like the ones that concern us (e.g. (c) in Fig. 1), a large number of carriers remain empty, even if the energy budget is not exhausted, because of the PSD constraint. The MBA is executed in a second phase, following the basic RA, when there is still available energy to expend and some carriers have no bits allocated. Energy needed to transmit the minimum number of bits (one, in our case) in the non-occupied carriers is sorted in ascending order. Groups of *m* carriers are formed and the same information bit, with energy *1/m* times lower than the minimum one, is assigned to all the carriers in a set. This process continues while none of the constraints is violated, i.e. the energy budget is fully expended or the allocated power would exceed the PSD mask. The value of *m* is fixed and determined by simulation to maximise the bit-rate [7]. The bit allocation profile must be communicated to the receiver in order to recover the information spread over multiple carriers. Algorithmically, the method can be described as:

```
1: Sort, in ascending order, the $\Delta E(n)$ values of all the non-occupied carriers. Let us express the output of this step as a vector of pointers to the indexes of the sorted carriers $P(i)$, such that $\Delta E(P(i)) \le \Delta E(P(j))$ if $i<j$
2: Initialise iteration counter, $k=1$
3: While (none of the constraints is violated) do
    -$E_{expended} \leftarrow E_{expended} + \Delta E(P(k \cdot m))$
    -If $\left( \frac{\Delta E(P(k \cdot m))}{m} < PSD\_mask(P(k \cdot m)) \right)$
     and ($E_{expended} < E$)
            -For $j=0$ to $m-1$
                $\varepsilon_{P(k \cdot m+j)} \leftarrow \Delta E(P(k \cdot m+j))/m$
            -Assign the same bit to carriers with indexes $P(k \cdot m)$ to $P(k \cdot m+m-1)$
            -$k \leftarrow k+1$
      else $\Rightarrow$ some constraints have been violated
```

The complexity of the MBA is dominated by the sorting of the $\Delta E(n)$ values that, using binary sort algorithms, can be executed with average running time proportional to $\mathcal{O}(M_o \cdot \log_2 M_o)$, where M_o is the number of empty carriers after the application of the basic RA scheme.

C. MBA-modified algorithm

The MBA technique was designed with major attention to ADSL channels, whose attenuation can be considered monotonically increasing with frequency. Although it can be directly applied to power line channels, their special characteristics suggest that various modification of this strategy may report important improvements in the bit-rate with minimum effect in the computational load.

Mainly because of the presence of deep notches, a considerable amount of carriers will never be used because of their extremely low SNR. In addition to this, it should be also noted that the H_n and N_n estimation procedures have a limited resolution that prevents us from using these carriers, otherwise the objective error probability would be exceeded. The process of discarding them before the ordering of the $\Delta E(n)$ values has $\mathcal{O}(M_o)$ complexity, but may greatly reduce the sorting time, which is proportional to $\mathcal{O}(M_o \cdot \log_2 M_o)$. On the other hand, the optimum *m* for these channels is two. Notable bit-rate gains can be achieved if variable-size sets, with $m=2 \ldots m_{max}$, are allowed. The most appropriate m_{max} is assessed by means of simulations. Even though this latter step involves extra computational load, in section IV it will be shown that the overall running time of this algorithm is lesser than the one of the MBA. The resulting MBA-modified algorithm can be summarised as:

```
1: Discard empty carriers with $\Delta E(n)/m_{max} > PSD\_mask(n)$
2: Sort, in ascending order, the $\Delta E(n)$ values resulting from step 1. Again, the output is expressed with the vector $P(i)$
3: Initialise iteration counter, $k=1$ and the size of the groups, $m=2$
4: While (none of the constraints is violated) and ($m \le m_{max}$) do
    -If $\left( \frac{\Delta E(P(k \cdot m))}{m} < PSD\_mask(P(k \cdot m)) \right)$
            -$E_{expended} \leftarrow E_{expended} + \Delta E(P(k \cdot m))$
            -If ($E_{expended} < E$)
                -For $j=0$ to $m-1$
                    $\varepsilon_{P(k \cdot m+j)} \leftarrow \Delta E(P(k \cdot m+j))/m$
                -Assign the same bit to carriers with indexes $P(k \cdot m)$ to $P(k \cdot m+m-1)$
                -$k \leftarrow k+1$
            else $\Rightarrow$ one constraint has been violated
    else
            -$m \leftarrow m+1$
```

The description of the algorithm has been done trying to facilitate its readability. However, in a practical implementation some operations will be performed in a more efficient way, e.g. instead of evaluating $\Delta E(P(k\cdot m))/m<PSD\_mask(P(k\cdot m))$, which contains a division, $\Delta E(P(k\cdot m))<m\cdot PSD\_mask(P(k\cdot m))$ would be calculated.

IV. SIMULATION RESULTS

The bit-rates and implementation complexity of the different bit-loading algorithms presented in the previous section are now evaluated and compared. To this end, the sampling frequency is fixed to 60MHz and a DMT system with 1024 carriers and 228 samples of cyclic prefix is considered. The latter parameter setting has proved to be adequate to maximise the bit-rate [9]. Although regulations regarding the energy budget and the PSD mask for the transmitted signal are still under development [2], a -20dBm/kHz flat PSD (this value is used as a design criterion by many modem manufacturers in the area), from which the energy constraint is derived, has been adopted for the simulations. Uncoded QAM constellations with an error probability of 10^{-6} and a number of bits in the range of one to 10 are utilised.

The reasons for the poor results given by the basic RA algorithm and for the improvements reported by the MBA-modified are illustrated in Fig. 2. There, the SNR (including distortion caused by ISI and ICI) experienced by the 1024 carriers of the system in the channel of Fig.1 (c), have been sorted in descending order. Five regions have been depicted: (a) contains those with a SNR higher enough to carry, at least, one bit; (b) includes the extra ones that would be employed by the MBA method ($m=2$); when the MBA-modified with $m_{max}=6$ is applied, this limit is extended up to region (c) and to (d) in the case of $m_{max}=30$. Finally, (e) comprises those that would need an m_{max} larger than 30.

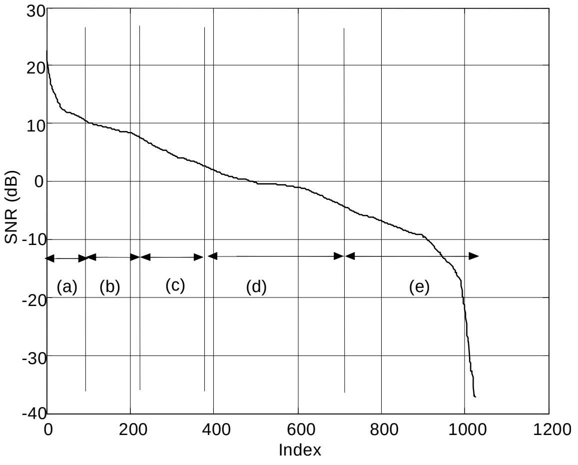

Figure 2. SNR (including distortion from ISI and ICI) per carrier, sorted in descending order, for the channel configuration of Fig.1 (c)

As seen, area (a), the one used by the basic RA, is very narrow. The number of carriers in (b) doubles the one in (a), but each one carries just half a bit. Region (c) is nearly twice as larger as (b) and, as $m_{max}=6$, still significant number of bits is gained. The convenience of the use of (d) (extending the m_{max}) is not straightforward and should be evaluated by means of simulations, but it seems clear that very little performance would be lost if (e) is not considered.

A. Bit-rate comparison

Fig.3 depicts, for eight indoor power line channels, bit-rate values obtained with the MBA-modified strategy, relative to the ones achieved by the basic RA algorithm, for different values of m_{max}. Notice that when $m_{max}=2$, results of the MBA-modified are equal to those of the MBA method with optimum m, which provides important gains over the RA one. The use of an $m_{max}=8$ may even double these gains and, in general, minimum improvements are accomplished by using values greater than 12. However, the maximum m_{max} is limited, as previously explained, by the resolution of the SNR estimation process.

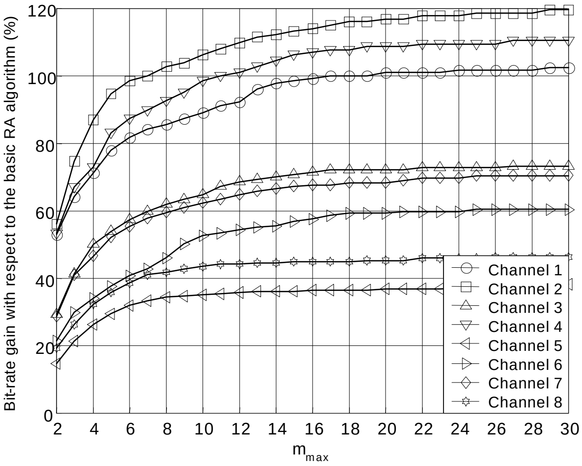

Figure 3. Bit-rate gains, with respect to the basic RA algorithm, obtained with the MBA-modified for different values of m_{max}

Absolute values, in Mbps, are shown in Table 1 For the MBA-modified $m_{max}=8$ has been employed.

Channel	Basic RA	MBA	MBA-modified
1	3,30	5,04	6,12
2	3,01	4,69	6,09
3	3,95	5,11	6,41
4	3,08	4,72	5,93
5	7,09	8,12	9,52
6	4,38	5,30	6,38
7	4,24	5,46	6,78
8	5,83	6,93	8,25

Table 1. Bit-rate (Mbps) values for the basic RA, MBA and MBA-modified with $m_{max}=8$

B. Complexity comparison

To assess the complexity of the MBA-modified algorithm with respect to the MBA one, the number of operations required by both of them has been estimated.

Table 2 summarises the results obtained by counting, line by line, the pseudo-code from section II.

Line	MBA	MBA-modified
1	$M_o \cdot \log_2(M_o)$	$2 \cdot M_o$
2	1	$M_o^1 \cdot \log_2(M_o^1)$
3	$\sum_{i=1}^{L}(6+2\cdot m)$	2
4	-	$\sum_{i=1}^{L}(7+2\cdot m_i)+m_{\max}$

Table 2. Number of operations estimated for the pseudo-code of the MBA and MBA-modified algorithm

where L is the total number of groups that have been formed, M_o^1 is the number of carriers that have not been discarded in line 1 of the MBA-modified and m_i is the number of carriers in a group (for the MBA $m=2$).

Fig. 4 displays the total number of operations of the MBA-modified algorithm with respect to the MBA with optimum m (negative values indicate that less number of operations are required) when applied in the eight channels considered in Fig. 3. Trends in the curves are easily explained considering Fig. 2. The enormous difference between both methods when $m_{max}=2$ is due to the fact that for the MBA-modified line 2 just includes the carriers in region (b), whereas the equivalent process in the MBA (line 1) comprises carriers from regions (b) to (e). For very large m_{max} values, the MBA-modified gives higher computational load because, although $M_o^1 \approx M_o$, the extra process in line 1 is performed.

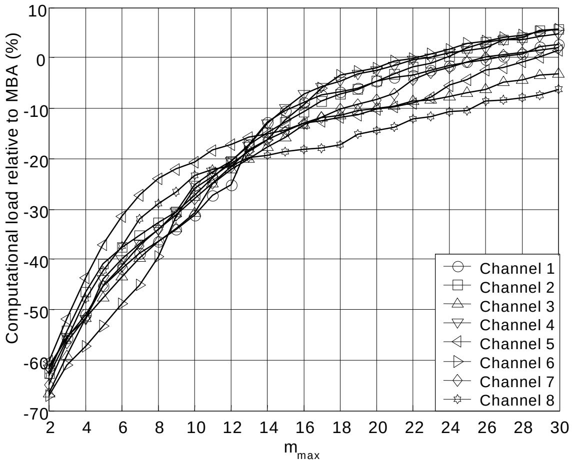

Figure 4. Number of operations of the MBA-modified, with respect to the MBA, for different values of m_{max}

It should be noted that Fig. 4, in conjunction with Fig. 3, gives an additional criterion to select the maximum m_{max}. In this sense, although the use of m_{max} larger than 12 provides insignificant bit-rate gains in most cases, it may increase the running time considerably.

V. CONCLUSIONS

The performance of a conventional bit-loading algorithm for DMT systems has been assessed in indoor power line channels with severe attenuation values and high noise levels. In these scenarios most of the carriers have no bits allocated because of the limitation in the PSD for the transmitted signal imposed by regulations. It has been shown that, under these circumstances, the use of the MBA scheme, that spreads the same information bit over multiple carriers that would otherwise be empty, provides important bit-rate gains.

Based on this framework, a modification of this method, adapted to the special characteristics of power line channels, has been proposed. The performance, in terms of bit-rate and number of operations, of both algorithms has been compared. It has been proved that, even with a reduced computational load, significant bit-rate improvements can be achieved.

ACKNOLEDGEMENTS

The authors would like to thank Ove Edfors, from the Department of Electroscience, Lund University (Sweden), for his support and encouragement at the beginning of this work.

This work has been supported by the Spanish Ministry of “Ciencia y Tecnología” under CICYT Project No. TIC2000-1110.

REFERENCES

[1] EN 50065, “*Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz*”. CENELEC, 1991.

[2] ETSI Power Line Telecommunications (PLT). http://portal.etsi.org/Portal_Common/home.asp

[3] Francisco J. Cañete, Luis Díez, José A. Cortés, J.T. Entrambasaguas, “*Broadband Modelling of Indoor Power-Line Channels*”, IEEE Transactions on Consumer Electronics, February 2002, Vol. 48, No. 1, pp. 175-183.

[4] D. Hughes-Hartogs, “*Ensemble modem structure for imperfect transmission media*” U.S. Patent 4 679 227, July 1987.

[5] J. Campello, “*Practical Bit Loading for DMT*”, Proceedings of the ICC, 1999, pp. 801.805.

[6] Peter S. Chow, John M. Cioffi, John A. C. Bingham, “*A Practical Discrete Multitone Transceiver Loading Algorithm for Data Transmission over Spectrally Shaped Channels*”, IEEE Transactions on Communications, Vol. 43, No. 2/3/4, February/March/April 1995. pp. 773-775.

[7] R. Sonalkar and R Shively, “*An Eficient Bit-Loading Algorithm for DMT Applications*”, IEEE Communications Letters, Vol.4, No.3, March 2000, pp. 80-82.

[8] Kalet, I., “*The Multitone Channel*”, IEEE Transactions on Communications, Vol. 35, No. 2, pp. 109-124, February 1989.

[9] José A. Cortés, Luis Díez, Francisco J. Cañete, J.T. Entrambasaguas, “*System Parameters Effect on DMT-Based Indoor Broadband Power Line Communications*”, Proceedings of the ISPLC 2002, pp. 48-52.