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DMT transmission in the context of industrial telecontrol applications

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Abstract. In this paper, we discuss the use of Discrete Multi Tone (DMT) modulation in the context of industrial telecontrol applications. We highlight the specific requirements and characteristics of the telecontrol settings and present methods to cope with the environmental challenges posed. It turns out that DMT is ideally suited for the tasks at hand. Further enhances enable our proposed system to provide superior connection stability even under the most adverse conditions.

1 Introduction

DMT is the wireline application of the well-known Orthogonal Frequency Division Multiplexing (OFDM) transmission scheme. In recent years, commercial applications of DMT such as Asymmetric Digital Subscriber Line (ADSL) have gained immense popularity. Those applications are characterized by high data rates and relatively short transmission loops. The use of DMT in industrial process data communications and metering applications has not found wide-spread acceptance yet, despite its obvious beneficial aspects. This is mainly due to the fact that conventional DMT systems suffer from relatively high transmission latency. Industrial settings are characterized by relatively low data rates but long transmission loops, require a high degree of reliability, and pose real-time constraints.

At our chair, a DMT transceiver for deployment in industrial settings was developed (Bauer, 2004) tackling the shortcomings of conventional DMT systems. Sophisticated signal processing methods lead to a latency-optimized design with online adaptation facilities to suddenly occurring deteriorations of the transmission channel. Thus, both low latency and high adaptivity are combined to demonstrate the viability of DMT transmission for telecontrol applications with superior connection reliability.

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2 System model

A basic model of the transmission system is depicted in Fig. 1. The binary input data stream is parallelized and partitioned into so-called sub-carriers. Each sub-carrier i can transmit a certain number of bits b_i. The block denoted QAM performs a quadrature amplitude modulation (QAM) of the bits b_i, yielding one complex value $u_i[k]$ for each sub-carrier i and DMT symbol k. The transmit signal in time domain is generated by computing the inverse discrete Fourier transform (IDFT) over the complex frequency domain signal. Transmission takes place in the baseband. Thus, only real-valued information can be transmitted. To generate a real IDFT result, a complex conjugation of the frequency-domain transmit signal has to be executed and appended to the original vector (Bingham, 1990).

The IFDT and DFT operations are usually executed with a power of 2 as input and output lengths which allows an efficient computation in the form of the fast Fourier transform (FFT). Specifically, we use an FFT length of 128. Thus, at most 64 sub-carriers can be modulated independently.

The resulting transmit vector of 128 real values is prepended by a so-called cyclic prefix of 32 values which is used to prevent inter-symbol and inter-carrier interference (ISI and ICI)due to the channel impulse response. The vector is converted to serial and transmitted over the channel with impulse response h_c. In this paper it is assumed that the length of the channel impulse response does not exceed the length of the cyclic prefix to preclude the occurrence of ICI and ISI.

Transmission is impaired by noise stemming from both additive white Gaussian noise (AWGN) and narrow bandwidth interference (NBI). At the receiver the operations per-

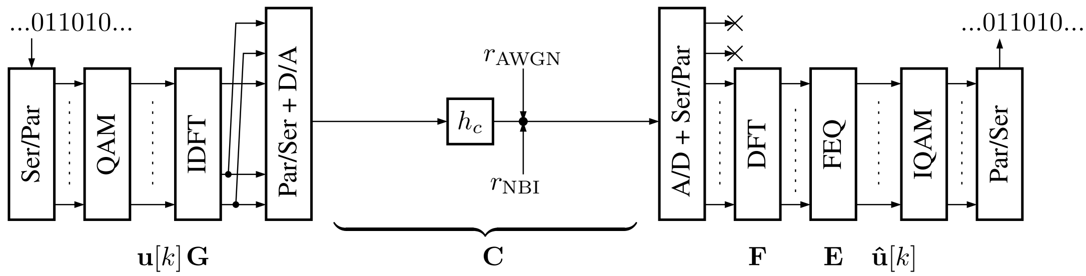

Fig. 1. DMT transmission scheme.

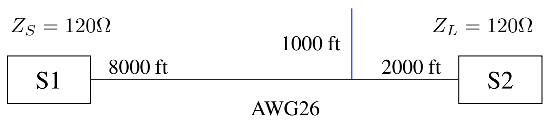

Fig. 2. Topology of example transmission channel.

formed at the transmitter are reversed. Additionally, a one-tap frequency domain equalizer removes distortions due to the transmission channel. QAM demodulation should yield the same binary sequence that was sent by the transmitter.

3 Transmission channel

In telecontrol communications over wire lines one is faced with frequency selective channels. The impulse response of the transmission channel is determined by material constants of the medium and by the topology of the transmission network. Sophisticated models exist that allow derivation of the transfer function for arbitrary topologies. Usually, telecontrol applications in industrial settings use rather long transmission lines. Possibly, there are unterminated or imperfectly terminated bridge taps resulting in reflections of the transmitted data. The superposition of several reflected waves leads to a pronounced frequency selectivity of the encountered transfer functions. However, the transfer function is slowly time-variant for wire lines. This is a great advantage compared to wireless communication channels which fluctuate very quickly.

The slow time variance of the transfer function allows efficient use of the available resources by means of adaptation to the respective channel characteristics. Before actual data transmission starts, the channel is estimated during the initialization phase. A special training sequence with content known to both stations is transmitted and comparison with the received sequence allows estimation of the channel attenuation factors g_i and noise powers n_i per sub-carrier. Together with the reference power p_{ref} per sub-carrier used to transmit the training sequence, the signal to noise ratios

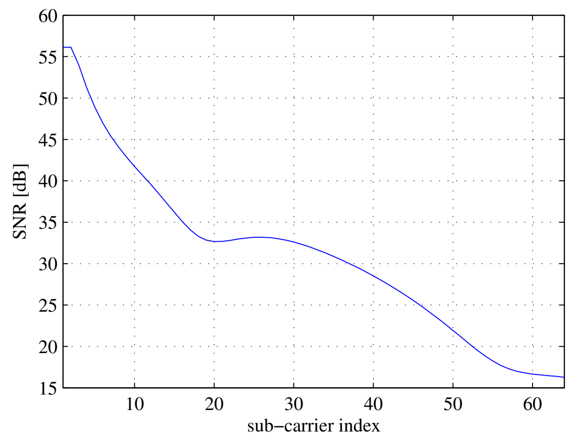

Fig. 3. SNR for example transmission channel.

(SNR) per sub-carrier i can be computed as

$$\text{SNR}_i = \frac{p_{\text{ref}} \cdot g_i}{n_i} \qquad (1)$$

4 Initial adaptation

For the rest of the paper, we will consider two stations connected by the topology shown in Fig. 2. Both stations are terminated with a resistance of 120 Ω. One unterminated bridge tap is present. Lengths of the line segments are given in feet (1 ft = 30.48 cm). The transmission wire is 26AWG. This transmission channel will be used to illustrate the techniques explained in this paper.

We assume white Gaussian background noise with power $n_i = 120$ dBm/Hz. The total transmit power of the system is limited to $p_{\text{tot}} = 25$ dBm. This power is equally distributed over all sub-carriers during the channel estimation phase, thus $p_{\text{ref}} = p_{\text{tot}}/128$. The sampling frequency of the DMT system is $f_S = 1024$ kHz. The rather high sampling frequency and the short FFT length effectively reduce the latency of the system due to block oriented signal processing. The DMT symbol rate equals $r_S = 6400$ Hz.

With all these parameters, the SNR can be computed as described in the last section and are depicted in Fig. 3.

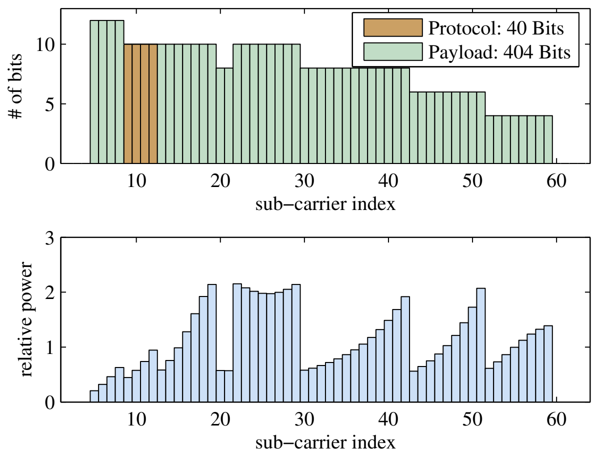

Fig. 4. SNR for example transmission channel.

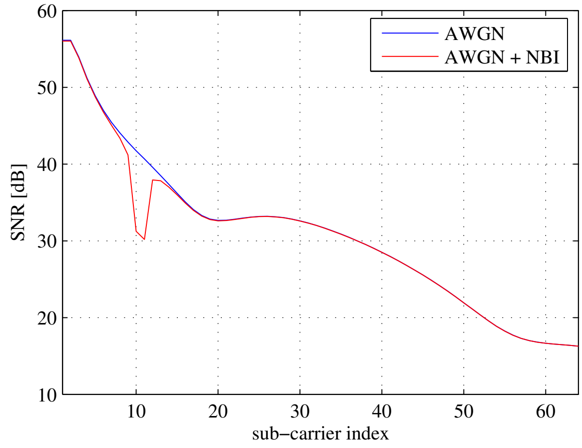

Fig. 5. SNR with and without additional NBI.

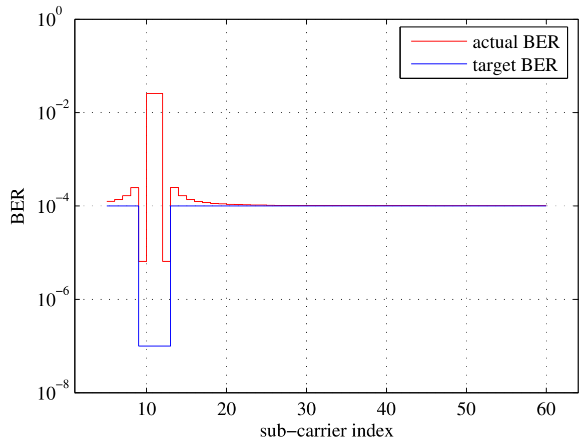

Fig. 6. Change of BER due to NBI.

According to the SNR values computed during the initialization phase, a so-called bit-loading algorithm determines how many bits should be transmitted and what transmit powers should be used per sub-carrier. The result of the loading algorithm are two tables, one indicating the bit-load (bit allocation table, BAT) and the other indicating the powers relative to the reference power (power allocation table, PAT).

Our DMT system applies a modified version of the well-known Hughes Hartogs bit-loading algorithm (Hughes-Hartogs, 1989) to compute these two tables. The modification allows to specify two data classes with different protection (Hoo et al., 1999b). In transmission systems, protection is usually measured and given in terms of bit error rate (BER), the number of erroneous bits divided by the total number of transmitted bits. Our system makes a distinction between protocol information used to establish and maintain the point-to-point connection of the two stations and between payload data that is transparently transmitted. Note that a temporary increase in the BER of payload data does not harm the connection itself. However, erroneous protocol information will lead to the use of defective transmission parameters and after a short time to the breakdown of the connection.

In telecontrol applications, high stability of the connection is of great concern. Hence, we provide increased protection for the protocol data. For illustration purposes, we fix the amount of protocol data to 40 bits per DMT symbol, and we call these data the embedded service channel (ESC). The target BER for the ESC is fixed to 10^{-7}. For payload data, we set the target BER to 10^{-4}. Again, these parameters are application dependent values. We chose values that allow for easy simulation of results. One might think of the payload information as voice data or video surveillance information, where rather high BER is acceptable.

Figure 4 shows the BAT and PAT for the above parameters that results in the maximum number of payload bits per DMT symbol $b_{\max}$, in this case $b_{\max} = 404$.

Note that due to the use of imperfect anti-imaging and anti-aliasing filters, some sub-carriers at low frequencies and high frequencies can not be used. The actual number of independently modulated sub-carriers is thus reduced to 55.

5 Appearance of disturbances

Once optimal BAT and PAT are computed and exchanged, the actual data transmission starts using these transmission parameters. The occurrence of a disturbance, e.g. an increase of noise power on some sub-carriers, can significantly deteriorate the transmission quality for the affected sub-carriers. An exemplary disturbance, NBI centered between sub-carriers 10 and 11, is shown in Fig. 5.

Due to the deterioration of the SNR of the affected sub-carriers, the BER for these carriers rises too. The increase of BER is shown in Fig. 6, together with the target BER.

It can be seen that despite the increased protection for the ESC, the disturbance heavily impairs the transmission system.

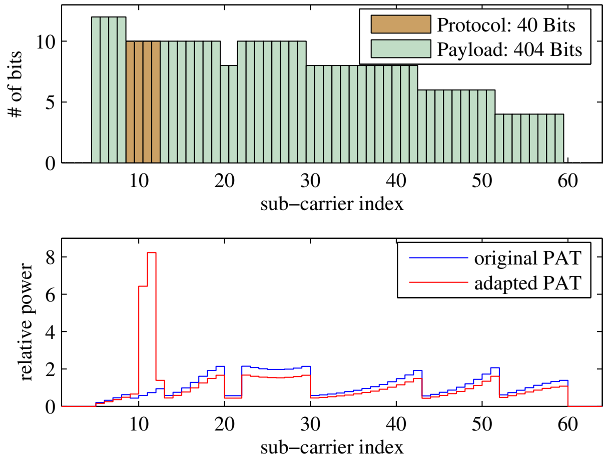

Fig. 7. Increase of transmit power.

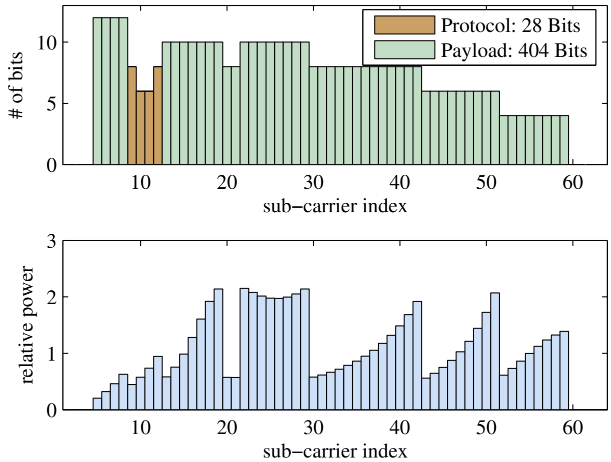

Fig. 8. Reduction of constellation size.

This situation calls for dynamic adaptation, that is, adaptation of the system to changed channel conditions during runtime. In ADSL, for example, a sequence of bit-swap commands can be exchanged to redistribute bits away from heavily disturbed sub-carriers to less disturbed sub-carriers (Hoo et al., 1999a). However, such methods require an exchange of protocol information over the ESC. If the ESC itself is affected by a disturbance, as is the case in our example, the protocol information might be faulty. In ADSL, the protocol data is protected by a five-out-of-nine repetition code (ADSL). We could show in Edinger et al. (2005b) that even such protection is not sufficient. The use of faulty transmission parameters will lead to a loss of connection.

The next section examines methods to restore acceptable BER for the ESC, and thus restoring reliable information exchange, by means of signal processing.

6 Securing the ESC

A number of methods can be applied, to restore ESC quality and reliability if it is impaired by a disturbance. Some of these methods can be applied blindly, others imply the exchange of information. Some methods work on individual sub-carriers, others work on several or all sub-carriers. The amount of information exchange should be as small as possible.

6.1 Increase of transmit power

If the noise power on a sub-carrier increases by factor δ_n, the transmit power on this sub-carrier can be increased by the same factor to restore the target BER. Fig. 7 shows the transmit powers necessary to restore a BER of 10^{-7} for the ESC in the presence of the example disturbance.

Note the large power peaks at affected ESC carriers. If power spectral density (PSD) constraints restrict the maximum transmit power level, the above constellation might violate those constraints. Additionally, since total transmit power is limited, the additional power for the ESC must be collected from payload sub-carriers, which further increases their BER. Another drawback of this method is that good estimates of the noise power must be available for determining the additional transmit power required. These estimates are not immediately available but must be gathered from observations of the noise process which adds to the time required for adaptation.

6.2 Reduction of constellation size

When the number of bits on a sub-carrier is reduced by 2, this corresponds to an increase of transmit power by ≈ 6 dB. Thus, the constellation size of disturbed ESC sub-carriers can be reduced until the amount of bits equals zero or the required transmission quality is met again. However, dynamically reducing the amount of ESC information per DMT symbol significantly increases the complexity of the underlying protocol. Information might need to be spread over several symbols and recombined after reception.

Figure 8 shows the changed BAT that is required to reach BER of the ESC of equal or less than target BER. A reduction of the ESC by 12 bits is necessary.

Figure 9 compares the two above methods in terms of the actual BER they obtain. It can be seen that power adaptation exactly reaches the target BER. Due to limited transmit power the BER of payload sub-carriers is increased. Note that the BAT does not change. Only the updated PAT values for the ESC must be exchanged, the remaining PAT entries can be computed from those values.

On the other hand, payload BER is not increased for the method of reducing ESC constellation sizes. The PAT is not changed. The only information that must be transmitted are the updated BAT values for the ESC which can be

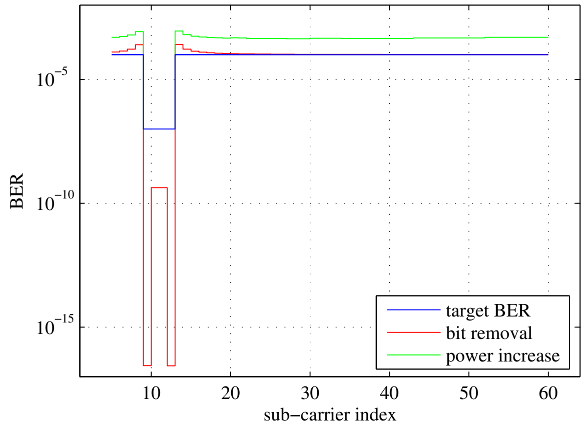

Fig. 9. Comparison between ESC protection methods.

represented more compactly than PAT entries. However, the resulting BER are much lower than actually required. This indicates an inefficient use of the available resources.

6.3 Change of ESC location

So far, we have only considered methods that leave the spectral location of the ESC untouched. Clearly, this is unfavorable if this spectral location is affected by a disturbance. Therefore, a mere re-allocation of the ESC at sub-carriers further away from the disturbed frequency range can significantly improve the BER for the ESC. One possible alternative ESC location is depicted in Fig. 10. Note that complete updated BAT and PAT are used. The spectral range previously occupied by ESC information is now filled with payload data.

Figure 11 shows the resulting BER. Requirements are almost perfectly met for the ESC. Now, payload data is heavily affected by the disturbance. However, this does not lead to a loss of connection. Additionally, due to the use of a new BAT, the amount of payload bits is reduced by 2. This payload rate reduction must either be handled by higher protocol layers, or one can insert dummy bits at the receiver which will have BER 0.5 in the mean.

6.4 Precomputation of alternative ATs

The main drawback of the last alternative was the necessity to exchange complete BAT and PAT. The amount of information is considerable and impractical if the connection is disturbed. One solution for this problem is to precompute a number of alternative BAT and PAT with the ESC located on disjunct and coherent sets of sub-carriers. These allocation tables (AT) are then exchanged and stored for later use in both stations. If the ESC is disturbed in its present location, an alternative AT can be used instead. The information required is then just an index pointing out the respective AT that should be chosen.

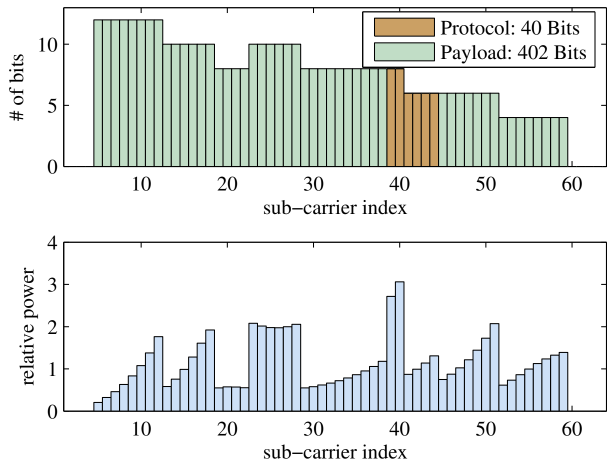

Fig. 10. New spectral location for ESC.

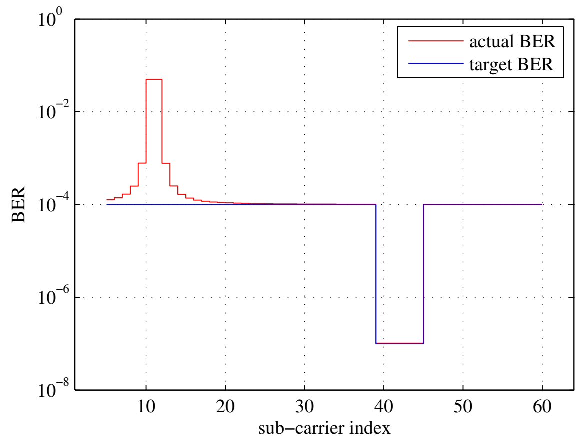

Fig. 11. BER with new spectral location for ESC.

Even if no reliable communication is possible for some time, both stations can cycle through all possible transmit and receive combinations to finally guess the optimal choice of AT blindly.

If some a-priori information is available about the types and likely locations of disturbances to be expected for the transmission channel or environment that the stations are presented with, this information can be used to design the alternative AT especially for those situations.

A more detailed description of the protocol design for our system can be found in Edinger et al. (2005a). It uses a special automatic repeat request (ARQ) protocol that protects only the ESC information. Faulty ESC bits can be detected and the respective information can be retransmitted. If errors occur, the protocol tries to increase the probability of correct reception by applying the methods described above. The protocol works incrementally, that means, it starts with simple methods changing as few parameters as possible and if these changes do not bring about the desired results, the

Table 1. Duration of adaptation tasks.

Task	# of DMT symbol clock cycles
Detection of disturbance	10
Securing the ESC	30
Channel estimation	400
BAT/PAT computation	200
BAT/PAT transmission	130
Total time	770

protocol continues with other methods, until the connection is finally secured.

7 Completing the adaptation process

After BER of the ESC has been restored to allow reliable information exchange, the adaptation process continues with estimating the transmission channel again. Data about the changed noise conditions can be gathered using decision feedback methods. However, this might lead to misestimation especially for heavily disturbed sub-carriers. A better but more costly alternative is to insert known training patterns into the DMT symbol. The effective payload data rate will be reduced by this method.

After information about the changed SNR conditions have been gathered, a new BAT and PAT with respect to these new SNR values are computed and exchanged over the ESC together with a time stamp indicating when the new transmission parameters will take effect. Most probably, the new amount of payload data that can be transmitted per DMT symbol will be reduced. Thus, higher protocol layers must provide some capability to accommodate changes in data rate. The BER for both payload and ESC data will perfectly meet the target values, provided the channel estimation is sufficiently accurate.

8 Simulation results

Our simulations have shown that the above protection methods in connection with the incremental ARQ are extremely robust and powerful. The complete adaptation process runs also very fast. Table 1 lists the individual tasks required for the adaptation together with the number of DMT symbol clock cycles typically required for these tasks.

At the rate of 6400 DMT symbols per second used by our system, the complete adaptation requires only 0.12 seconds. In comparison, re-establishing a lost connection requires at least one second. Additionally, during that time, no payload data at all can be transmitted while our system still allows transmission of considerable amounts of payload data even during adaptation.

For the example disturbance and power increase for the ESC, the mean BER for the payload data equals $5.0 \cdot 10^{-4}$. For the method of changing the ESC location, this mean BER equals $3.17 \cdot 10^{-3}$. However, the former method requires accurate data about the disturbance which will not be available immediately. Additionally, information exchange must take place over the disturbed ESC. Both factors require time which is not needed for the latter method. Thus, both will be approximately equal in the amount of erroneous bits received but the latter will complete sooner.

Whichever method is applied, it becomes clear that even in the presence of disturbances, the mean BER of payload might allow relatively unhampered transmission during the adaptation process.

9 Conclusions

Our proposed system makes effective use of the multiple benefits of DMT modulation and alleviates its few disadvantages. The system has superior connection stability even in the presence of strong disturbances. It can recover extremely quickly from such disturbances. Finally, it is very flexible and can easily be fine tuned to meet specific requirements.

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