Time-Domain Equalization in Broadband DC-PLC Sensor Networks

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***Abstract*—An application of time-domain equalization (TEQ) is discussed in the context of multi-carrier sensor networks. Designed as a DC power-line communication system (DC-PLC), the exemplary underwater sensor network of a sonar array uses a linear bus topology of the power distribution network for data transmission. Simulations show the advantages of a TEQ-enabled system, both using rate-maximizing or a classical shortening TEQ, in different bus configurations. As a result, the complexity of the corresponding modem implementations could be greatly reduced by using a shorter DFT, while still keeping the high data rate.**

I. Introduction

The progress in communication research of the last decades provides an incredibly rich set of methods that can be used to design very sophisticated transmission systems. This, together with the rapid technological progress, is of a great importance in the world of embedded design. The high-speed real-time acoustical sensor network of a sonar is a good example of the communication system with distributed embedded signal processing, which can benefit from this recent research.

A sonar, which consists of a number of spatially distributed acoustic sensors and operates in a frequency range of a few Hz to hundreds of kHz, is usually the only device, capable of sensing the far-field environment under water. The transmission of digitalized acoustic data from outboard sensors to the inboard signal processing units is a great challenge, as the number of acoustic sensors, the distances between them, and their sampling rate and bit resolution increases. A typical sonar system consists of hundreds of single sensors producing a data flow of around 10 MBit/s per node, or 1-2 GBit/s per system. Such sonar systems do not only mean high data rate and synchronization requirements for a data transmission system, but also some mechanical restrictions, due to high pressure conditions under water.

The appropriate data transmission system is forced to be wire-line based: because of the high attenuation of radio or optical waves under water, a wireless system would be very inefficient [1], especially on the typical sensor-array lengths of 100 to 1000 meters. Because of mechanical restrictions, the use of active components outboards (like switching nodes) should be limited or avoided and the wiring should be reduced. Power Line Communications (PLC) can fulfill both requirements by using the power distribution network with a linear bus topology.

The origins and the most frequent application of PLC is over AC power wiring [2], [3], but there are also DC-PLC examples for on-board control networks inside aircrafts [4], ground vehicles [5], or as part of embedded robotic systems [6]. While all existing DC-PLC systems concentrate on low-throughput narrow-band applications, a new MC-TP (Multi-Carrier Twisted-Pair) broadband transmission system, described in Section II, is developed for high-speed sensor networks, with a sonar as an example application.

Time-domain equalization (TEQ) in multi-carrier systems is a method used to shorten the effective channel impulse response and optimize the overall capacity or to minimize the bit-error rate [7]. It is widely used in different DSL applications, but seems to be less effective in PLC. The DC-PLC channel is supposed to be much more static than a typical PLC channel, due to its deterministic structure. The goal of this work is to analyze the behavior of different equalizers and to argue their usage in the DC-PLC environment. In a special case of a sensor network the purpose of the TEQ is rather to keep the constant effective data rate than to maximize it and reduce the overall implementation cost (e.g. by reducing the FFT size in DMT implementation).

An overview of TEQ designs is given in Section III, followed by the simulation results with and without different TEQs are compared and discussed in Section IV.

II. Broadband DC-PLC Sensor Network: System Design

A linear bus structure is the main topology option in a PLC transmission system, used to transmit both data to and from sensors and power to the sensors, connected in parallel. The resulting channel is frequency-selective and will introduce inter-symbol interference, due to the multi-path nature of a linear bus. The harsh environment may affect cable properties and introduce slow fading [8].

Channel Sharing Strategy

In the general case of a multi-user multi-access channel (MAC, upstream in a bus system), CDMA can be shown to reach the optimum capacity. Giving users equal priorities results in equivalence of all three multiple access strategies [9]. This is also a typical requirement in a homogeneous sensor network.

In practice, TDMA sharing is widely used in bus systems. It is not only the implementation simplicity that speaks for this solution – the passive high-impedance mode of all currently unused transceivers allows the active transceiver to achieve higher data rates due the lower bus load. The higher bus load can hardly be compensated in the FDMA case, when transceivers' output impedances are static.

Depending on the application, the downstream channel can be either MAC or broadcast. The sharing in a full duplex mode between the upstream and downstream channels is chosen to be FDD, which allows to realize two independent channels.

Physical Layer System Parameters

The bandwidth in the DC-PLC environment is practically not limited by interference with other systems - using shielded twisted-pair cabling and differential signaling reduces the electro-magnetic emissions to a minimum. The frequency-dependent cable attenuation and its linear dependency on the cable length limits the effective bandwidth to a few hundred MHz for cable lengths around 100 m. The MC-TP uses, for instance 100 MHz bandwidth - also because of practical considerations like less expensive cabling (Cat5e) and the analog front-end hardware.

In case of a multi-carrier system, the lengths of the FFT and the cyclic prefix are essential. The classical way to define these parameters is to estimate the longest possible channel impulse response (in samples), the system has to cope with - then set the cyclic prefix equal to it and the FFT length at least five times as long, so that the cyclic prefix overhead is 20 % at maximum. An optimum approach is to choose a shorter cyclic prefix and tolerate some inter-symbol and inter-carrier interference to get a higher effective data rate due to less overhead [10]. Yet another possibility (and the MC-TP system choice) is to use a time-domain equalizer (TEQ) that allows to use a very short cyclic prefix and a smaller FFT - this way hardware resources usage can be reduced.

III. Time-Domain Equalization in Multi-Carrier Systems

Multi-carrier systems are known to be particularly well suited for a frequency-selective channel with ISI [11], and thus the primary transmission system candidate for the multipath channel of a linear bus structure. The basic idea behind any multi-carrier system is to partition the available channel bandwidth into a set of independent narrow-band sub-channels, transmitting a high number of bits in parallel at a low symbol rate.

DMT and OFDM are two most frequently used multi-carrier modulation methods, used in both wire-line (e.g. DSL) and wireless (e.g. LTE) transmission systems, respectively. An example of a simplified DMT system is shown in Fig. 1. The complex input vector $\mathbf{X_k}$ of length N for a DMT-symbol k is typically a result of QAM-mapping. The columns of the IDFT matrix are used as transmit basis vectors to generate the time-domain sequence $\mathbf{x_k}$. For the channel input signal $\mathbf{x_k}$ to be real, the DFT input sequence $\mathbf{X_k}$ has to be Hermitian (conjugate) symmetric. In practice, this means that the FFT size should be twice the length of $\mathbf{X_k}$, that is $2N$, in the case of baseband transmission. The system uses a cyclic prefix, repeating the last ν time-domain samples at the beginning of each symbol, consisting of $2N$ samples, such that $x_{-n} = x_{2N-n},$ for $n = 1, ..., \nu$. As long as the channel impulse response L_h is shorter than or equal to cyclic prefix length ν, the linear convolution becomes cyclic and the receiver can easily zero the noise-free ($\mathbf{n_k} = 0$) error between $\mathbf{X_k}$ and $\hat{\mathbf{X}}_\mathbf{k}$ by applying constant scaling (frequency-domain 1-tap equalizer, FEQ) at the DFT output. Obviously, this would also completely eliminate both inter-symbol and inter-carrier interferences (ISI/ICI).

In the opposite case $L_h > \nu$, the frame is affected by both ISI and ICI. The need to keep N relatively low in order to reduce the implementation cost means also keeping the cyclic prefix length short to reduce the overhead. The channels with high dispersion (e.g. in DSL applications) require special handling to achieve high data rates without implementation penalties.

A. Shortening TEQ

A method that can be called classical nowadays is to introduce an equalizer before performing the FFT, with FIR coefficients w defined such that for the overall effective impulse response $h_{eff}(n) = h(n) \star w(n)$ the expression $L_h \leq \nu$ is valid. The first algorithms to calculate such a shortening time-domain equalizer (TEQ) for a multi-carrier system were introduced by Chow and Cioffi in [12]. The main idea of this group of algorithms is to introduce a reference system with the desired impulse response and find a solution, which minimizes an error (MMSE) between the reference and the actual TEQ.

Another approach, MSSNR, first introduced by Melsa in [13] maximizes the energy in the part of the effective impulse response, covered by the available cyclic prefix (h_{win}) or alternatively minimizes the energy of its tail (h_{wall}).

Quite some other algorithms exist that improve or generalize these two approaches. The paper by Martin et al. [7] is a good reference that not only lists many of those algorithms but also introduces a unified mathematical framework for almost all of them. Considering an optimization problem

$$\hat{\mathbf{w}}^{opt} = \arg \max_{\hat{w}} \frac{\hat{\mathbf{w}}^T \mathbf{B} \hat{\mathbf{w}}}{\hat{\mathbf{w}}^T \mathbf{A} \hat{\mathbf{w}}} \; , \tag{1}$$

with vector $\hat{\mathbf{w}}$ containing the estimated TEQ, the solution turns to be the generalized eigenvector of the matrix pair $(\mathbf{B}, \mathbf{A})$ and requires the computation of $\hat{\mathbf{w}}$, corresponding to the largest generalized eigenvalue λ

$$\mathbf{B}\hat{\mathbf{w}} = \lambda \mathbf{A} \hat{\mathbf{w}} \; .$$

The values for matrices $(\mathbf{B}, \mathbf{A})$ depend on the channel (attempt to model the sub-channel SNR) and different constraints: the MMSE-TEQ in [12] is described, for instance, by

$$\mathbf{A} = \mathbf{R}_y - \mathbf{R}_{yx} \mathbf{R}_x^{-1} \mathbf{R}_{xy} \; ,$$
$$\mathbf{B} = \mathbf{e}_j \mathbf{e}_j^T \; ,$$

with elementary vector $\mathbf{e}_j$ and (co-)variances R of input x and channel and noise distorted output y. The MSSNR-TEQ is defined by

$$\mathbf{A} = \mathbf{H}_{wall}^T \mathbf{H}_{wall} + \mathbf{R}_n \; , \tag{2}$$
$$\mathbf{B} = \mathbf{H}_{win}^T \mathbf{H}_{win} \; , \tag{3}$$

with $\mathbf{H_{win}}$ and $\mathbf{H_{wall}}$ constructed as Toeplitz matrices of h_{win} and h_{wall}, respectively, and $\mathbf{R}_n$ is a noise correlation matrix [7].

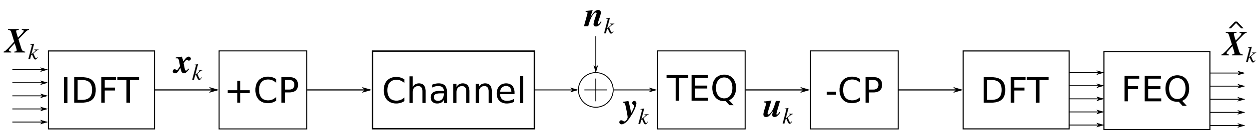

Fig. 1. DMT system with a time-domain equalizer (TEQ) at the receiver. The serial/parallel conversions are included in the DFT implementation (FFT).

B. Bit Rate Maximizing TEQ

By shortening the impulse response a TEQ can indirectly improve the resulting data rate by eliminating the ISI and ICI noise. Some time after the first TEQ designs were introduced it has been recognized that data rate maximization could be the ultimate goal of TEQ design. Early attempts to follow this strategy include [14] and [15]. In the unified framework this could be formulated as an optimization problem with multiple generalized Rayleigh quotients

$$\hat{\mathbf{w}}^{opt} = \arg \max_{\hat{w}} \log_2 \left(\prod_{j \in S} \frac{\hat{\mathbf{w}}^T \mathbf{B}_j \hat{\mathbf{w}}}{\hat{\mathbf{w}}^T \mathbf{A}_j \hat{\mathbf{w}}} \right) , \quad (4)$$

where S is the set of active data-loaded carriers and $\mathbf{A}_j$ and $\mathbf{B}_j$ are model-dependent matrices, used to represent the SNR. An optimum solution to such an optimization problem is not yet formulated, such that the existing algorithms use approximations and gradient-descent strategies to find at least a local optimum.

A similar optimization approach has been used in the one of the first attempts [15] to achieve the highest possible data rate. The algorithm calculates the overall capacity at all carrier locations, taking into account noise and channel response, shaped by the equalizer. A multidimensional optimization algorithms is then used to find the FIR coefficients of the equalizer which result in the maximum data rate.

Yet another approach is to maximize the bit rate on every single carrier independently, thus maximizing also an overall capacity – the so-called per-tone equalization [16], [17]. The filters are implemented after the DFT, so that they in fact are frequency-domain equalizers. Being possibly an optimal solution in terms of the capacity, it is the most demanding approach in terms of complexity.

IV. SIMULATIONS

The simulations with both shortening (MSSNR) and bit-rate maximizing (SIM-TEQ from [15]) TEQs were performed to motivate the application of time-domain equalization in DC-PLC sensor networks. The linear bus channel is modeled according to the "bottom-up" approach, shortly described in [8]. Two different cable types are used to build the example underwater sensor network (Fig. 2): main cable type, used between the branch segments and to connect the bus to a base station (with cable lengths l_M and l_R, respectively); branch cable type with length l_B. The cable model parameters are given in Table I. The identification for different cable configurations has the form $l_R.l_M.l_B$ for cable lengths in meters. The main goal of such a sensor network is to provide data from spatially distributed sensors to a single base station, so that the data transmission from sensors to a single receiver is considered here.

The sensor bus is used in TDMA mode with constant load and termination impedance $Z_L = Z_T = 100\ \Omega$ and configurable source impedances:

$$\begin{aligned} &Z_S^n = 100\ \Omega\ , \\ &Z_S^m = 30\ \mathrm{k}\Omega\ , \\ &m \neq n, \quad m, n \in [1, M]\ , \end{aligned}$$

simulating active state of the current sensor n in a system with $M+1$ nodes.

The simulated noise environment includes quantization and clipping from ADC/DAC (n_{DAC}) and fixed-point arithmetic (n_{FP}) as white noise sources. The main external source of colored noise is the power supply chain, modeled by [18]

$$n_{ext} = -25 \log 10(\mathrm{f_{MHz}}) - 94\ \frac{\mathrm{dBm}}{\mathrm{Hz}}\ , \quad (5)$$

Both ISI and ICI (n_I) caused by the tail of the effective impulse response, not covered by the cyclic prefix, are modeled according to [19]. The contribution to $\mathbf{R}_n$ in Eq. (3) is limited to n_{ext} and n_{DAC}.

The achievable bit distribution $b_i\ , i \in [1; N]$ per frame is calculated by an optimum discrete loading algorithm (Levin-Campello, [20]) for a fixed bit error ratio (10^{-7}), zero margin and coding gain and -20 dBm mean power. The effective data rate in $\left[\frac{\mathrm{bit}}{\mathrm{s}}\right]$

$$R_i = \frac{f_S}{2N + \mathrm{l_{cp}}} \sum_{j=1}^{N} b_j\ , \quad (6)$$

with sampling frequency $f_S = 250$ MHz takes into account the length of the cyclic prefix $\mathrm{l_{cp}}$. An optimum constant cyclic

MAR-Model Parameter	Main	Branch
R_0, [Ω/km]	250.76	240.94
L_∞, [H/km]	5.513e-04	5.867e-04
a	2.25	2.04
b	3.35	3.33
c	6.05	6.08
δ	7.33e-03	1.29e-02
C_{1MHz}, [F/km]	4.83e-08	5.10e-08

TABLE I. CABLE MODEL PARAMETERS.

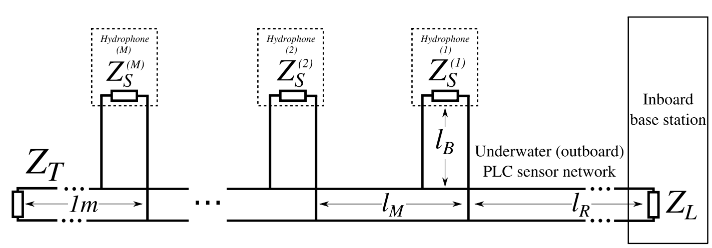

Fig. 2. An example bus system for simulations.

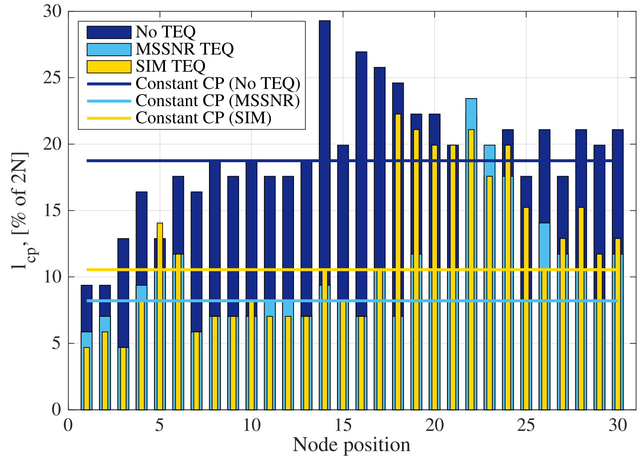

Fig. 3. Estimated optimum cyclic prefix lengths in a 30-nodes bus system, cable configuration $l_R.l_M.l_B = 50.1.1$, $N = 128$.

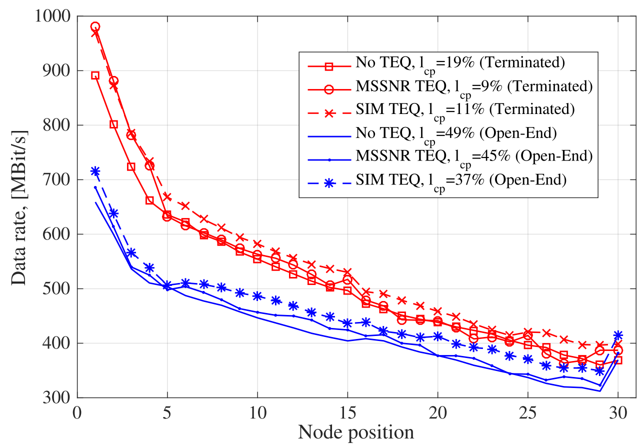

Fig. 4. Data rates in a 30-nodes bus system with constant CP, with and without termination, cable configuration $l_R.l_M.l_B = 50.1.1$, $N = 128$.

prefix length in samples (see Fig. 3), common for all nodes, is calculated as

$$\hat{\mathrm{l}}_{\mathrm{cp}}^{\mathrm{opt}} = \arg\max_{\hat{\mathrm{l}}_{\mathrm{cp}}} \sum_{i=1}^{M} R_i \ , \tag{7}$$

with R_i as from Eq. (6).

A. Bus Termination Influence

According to transmission line theory the far end of a bus system should be terminated (Z_T in Fig. 2) to avoid reflections. The absence of termination will result in a longer impulse response but will also increase mean signal power at the receiver, as a consequence of elimination of the voltage divider. In a case of such termination fault, it is important to be able to retain the operation of a sensor network.

A multi-carrier system, especially equipped with a TEQ, is in fact flexible enough to cope with such problems. The comparison of data transmission performance in an exemplary 30-nodes sensor network with different cable configurations is shown in Figs. 4-6.

The optimum l_{cp} in the case of an open-ended system (without termination) is always larger than in a terminated

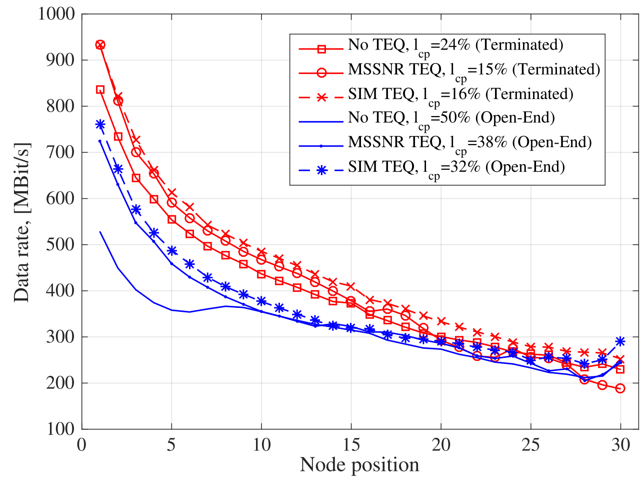

Fig. 5. Data rates in a 30-nodes bus system with constant CP, with and without termination, cable configuration $l_R.l_M.l_B = 50.1.2$, $N = 128$.

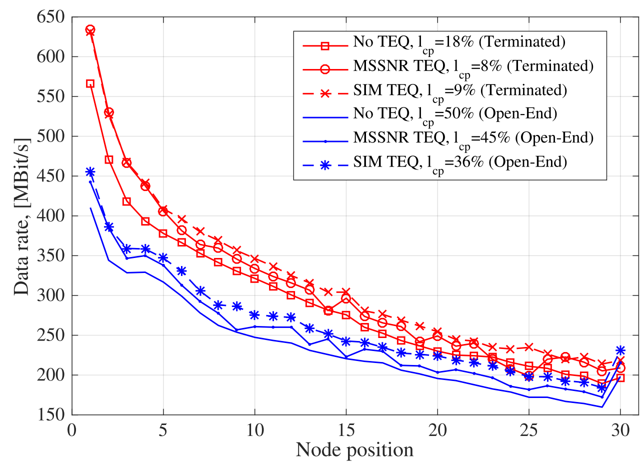

Fig. 6. Data rates in a 30-nodes bus system with constant CP, with and without termination, cable configuration $l_R.l_M.l_B = 100.1.1$, $N = 128$.

system. This is an indirect indication of a longer impulse response, as expected. Obviously, the rate-maximizing SIM-TEQ always outperforms the shortening-only MSSNR-TEQ.

Depending on cable configuration, the SIM-TEQ can increase the effective data rate up to 10 %, compared to a system without TEQ (see Fig. 7).

Both TEQ designs perform better in a non-terminated bus system, but still do not manage to match the performance of a terminated system. The better performing nodes, located closer to the receiver, loosing at most, while the farthest (20 to 30, depending on configuration) can even boost performance with a TEQ.

In a sensor network with equal sensor priorities and data rate demands (e.g. an underwater hydrophone network) the node with the lowest performance limits the overall system performance, if TDMA time slots are equally distributed. In this special case no data rate degradation due to termination fault will occur, if a data-rate maximizing TEQ is used.

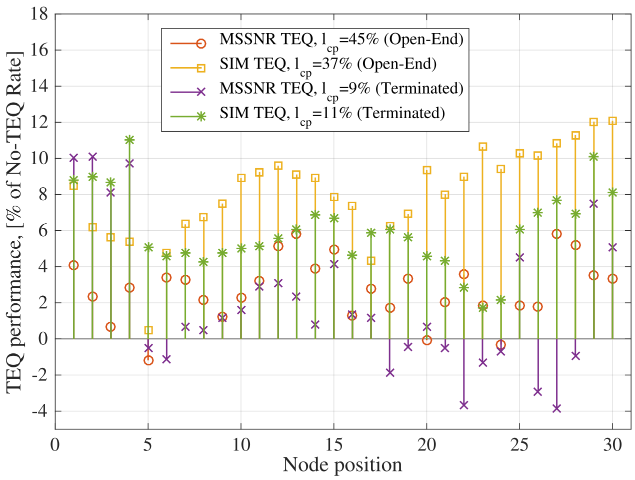

Fig. 7. Data rate gain with a TEQ compared to the corresponding data rate without TEQ in a 30-nodes bus system with constant CP, with and without termination, cable configuration $l_R.l_M.l_B = 50.1.1$, $N = 128$.

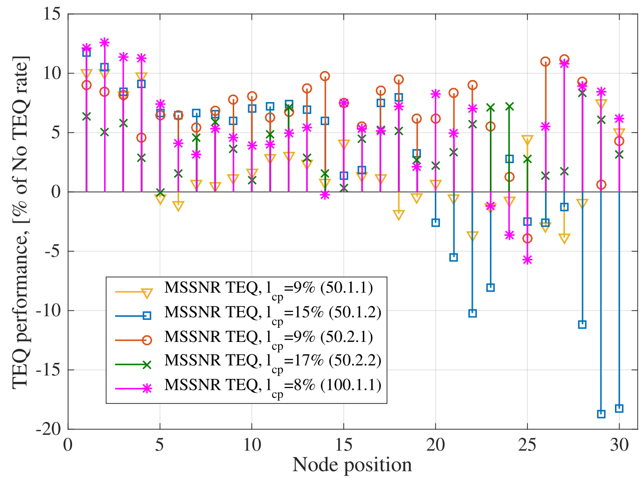

Fig. 9. Data rate gain of MSSNR-TEQ in a 30-nodes bus system with constant CP, with termination, $N = 128$.

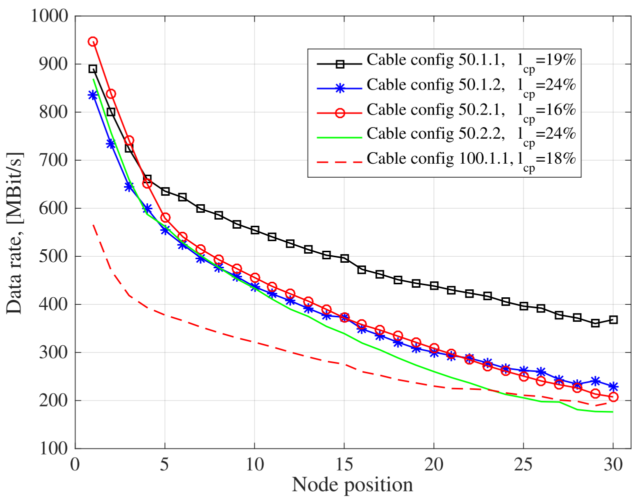

Fig. 8. Data rates in a 30-nodes bus system with constant CP, with termination, No TEQ, $N = 128$.

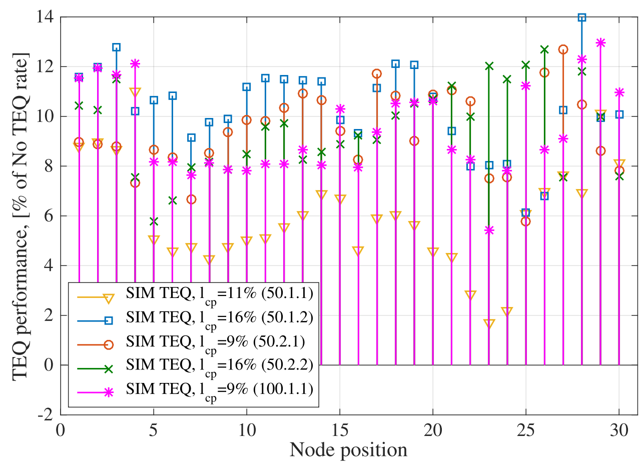

Fig. 10. Data rate gain of SIM-TEQ in a 30-nodes bus system with constant CP, with termination, $N = 128$.

B. Bus Configurations

As far as the cable configuration is concerned, the common recommendation for a bus system is to keep the branches or bridged taps as short as possible. This is confirmed in Fig. 8. Increasing the segment lengths between taps has a negative effect, especially on the far nodes, simply due to the higher attenuation. This also holds for a typically longer receiver cable.

The shortening TEQ has shown mixed results in a multi-path environment (Fig. 9) with a fixed cyclic prefix length on all channels: on the one hand, it boosts the effective data rate of up to 10 % on the channels with shorter impulse response (nodes 1 to 15, closer to receiver); on the other hand, the channels with longer impulse response suffer from data rate degradation with the MSSNR-TEQ. The fixed constant cyclic prefix is the major reason for this behavior. The variance of the node-optimized cyclic prefix length in Fig. 3 compared to the calculated fixed length is getting higher with the distance between the node and base station receiver. The cabling with longer segments between the branches ($l_R.l_M.l_B = 50.2.1$ and $50.2.2$) has a more uniform optimum cyclic prefix distribution, which results in a more consistent TEQ performance over all nodes in a system with a fixed cyclic prefix length. The data rate maximizing SIM-TEQ performs in general much better than the MSSNR-TEQ (Fig. 10). The performance gain of 8-10 % is more evenly distributed over the nodes. Bus systems with less interference due to multipath (50.1.1) and higher data rates without equalization are more challenging for a TEQ. Not surprisingly, the cabling with longer bridge taps (50.1.2) offers more gain potential for the SIM-TEQ. Thus, a TEQ, and especially its data rate maximizing version, provides a way to increase the effective data rate. Another possibility is to utilize a larger number of carriers which results in less overhead due to cyclic prefix but also requires more hardware resources to implement the increased FFT. In a sensor network with a large number of nodes the hardware resources and power consumption of each sensor could be quite limited. Keeping in mind that the FFT is the most demanding part of the digital hardware design, it is very tempting to use a much easier to implement FIR filter for a TEQ to meet the data rate requirements.

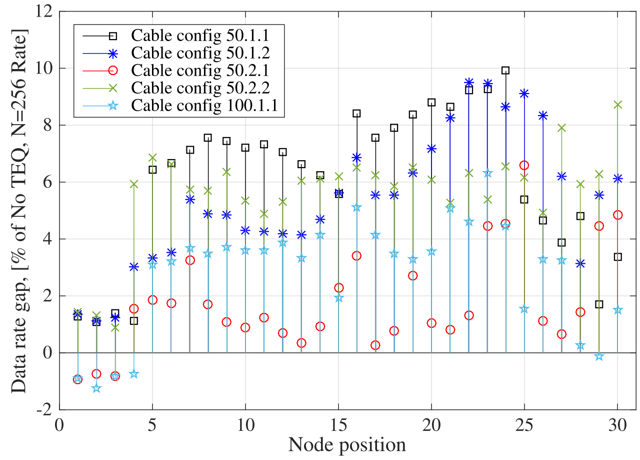

Fig. 11. Data rate gap between SIM-TEQ enabled system, $N = 128$ and a system without TEQ and twice the FFT size (30-nodes bus system with constant CP, with termination).

In Fig. 11, the average gap between the system with smaller FFT with SIM-TEQ and the system with double-sized FFT without TEQ is about 5-6 %. It is smaller for the cabling with longer uniform segments ($l_R.l_M.l_B = 50.2.1$, 100.1.1).

V. Conclusion

Time-domain equalization in multi-carrier systems is a rather simple and effective method of data rate optimization, which can be perfectly used in sensor networks with a bus topology. Different practically relevant scenarios of TEQ usage were investigated, e.g., the influence of the bus termination and the cable configuration on the overall performance (effective data rate) with and without a TEQ.

Choosing a fixed and constant cyclic prefix length, which maximizes the sum data rate of all sensors is easy to implement but not optimum, especially for the shortening-only TEQ, resulting even in a performance degradation, compared to a system without a TEQ. The data rate maximizing TEQ behaves much better in all cases, almost achieving the performance of a system with double-sized FFT.

Depending on the cable configuration, resources availability and data rate requirements, a system with TEQ can be a good alternative to a larger FFT system, which is more resource consuming both at the transmitter (sensor) and the receiver and has a larger latency. However, the complexity of TEQ coefficients calculation at the receiver side in case of the data rate maximizing algorithms has to be taken into account, too. An interesting challenge is the calculation of a general set of coefficients jointly maximizing the data rate of all nodes, thus relaxing receiver resource requirements.

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