On the Impact of Channel State Information Quantization and Feedback in Practical OFDM Implementation

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***Abstract*— In Orthogonal Frequency Division Multiplexing (OFDM), channel knowledge can be exploited to implement adaptive solutions based on bit-loading to improve the communication performance. Typically, channel estimation is performed at the receiver, with the resulting information being sent back to the transmitter to drive bit-loading. However, feedback information is subject to quantization, with the related errors potentially causing unreliable OFDM adaptation. Therefore, we investigate the impact of information quantization on the transmission efficiency, considering different strategies for feedback signaling. Performance are evaluated by referring to four propagation scenarios, that are radio-frequency, optical, powerline and underwater acoustic channels.**

***Index Terms*— OFDM, bit-loading, channel estimation, channel quantization.**

I. INTRODUCTION

ORTHOGONAL Frequency Division Multiplexing (OFDM) finds use in different technologies and applications, including cellular networks, optical wireless communication (OWC), power line communication (PLC) and underwater acoustic communication (UWAC). Transmission suffers from the impairments introduced by the propagation over time-variable and frequency selective channels. In order to provide link reliability, adaptive OFDM schemes [1] are realized by exploiting channel state information (CSI) available at transmit side. Due to the channel non-reciprocity, estimation is usually performed at the receiver, with the related information being sent back to the transmitter via feedback signaling [2]. Such procedure is time consuming and introduces overhead, lowering the communication performance. Moreover, the fed back CSI may be affected by errors, potentially leading to bad OFDM set up. Very often, the realization of adaptive OFDM is discussed by essentially assuming the channel as ideally known [3], [4]. Hence, the results of performance analysis may be quite unrealistic. Only few studies instead address the challenges of CSI sharing. For instance, the authors in [5] discuss the feasibility of OFDM in UWAC, proposing different strategies for sharing CSI between the communication ends. Deep learning is also considered in [6] for CSI compression and quantization. Anyway, data processing introduces delays that, in the presence of fast time-varying channels and large propagation delay as for instance in UWAC, may severely affect the link performance since the shared CSI may be outdated.

Summarizing, when dealing with OFDM, no sufficient focus is made on the impact of feedback quality, employed to send CSI from the receiver to the transmitter for system adaptation. It is worth highlighting that overhead signaling is represented by data that must be quantized before being transmitted. Therefore, the reliability and amount of feedback information strictly depend on the accuracy of quantization [7]. To the best of our knowledge, the joint impact of channel estimation, quantization and feedback transmission for OFDM set up has been never addressed before in the view of communication efficiency. Moved by this motivation, in this letter we investigate the efficiency of feedback signaling procedure when employed to drive bit-loading in OFDM systems. Specifically, we *(i)* discuss how quantization impacts on the accuracy of feedback, in the cases where channel estimates or power levels are transmitted, and *(ii)* investigate the communication efficiency as a function of the considered overhead signaling strategy. Performance are evaluated for different communication scenarios, that are the RF, OWC, PLC and UWAC.

II. SYSTEM MODEL

Let us refer to a point-to-point link, described in Fig. 1, where OFDM is considered. At transmit side, channel coding and symbol mapping are first applied on the N sub-carriers, with water-filling based bit-loading [8] being performed to maximize the rate under a certain target error rate constraint. Bit-loading allocates power/modulation formats on the sub-channels basing on the estimated signal-to-noise ratio (SNR). Such optimization requires CSI as available at transmit side. Finally, serial-to-parallel conversion, inverse Fast Fourier Transform, parallel-to-serial conversion and cyclic prefix (CP) insertion lead to the resulting OFDM signal.

During the communication, pilot symbols are periodically sent to let the receiver acquire CSI and share it back with the transmitter to drive the bit-loading. Regarding feedback, we explore three known strategies referred as case A, B and C, respectively. In the first case A, the receiver sends quantized channel estimates, so that bit-loading is fully managed by the transmitter. In the second case B, the receiver is responsible

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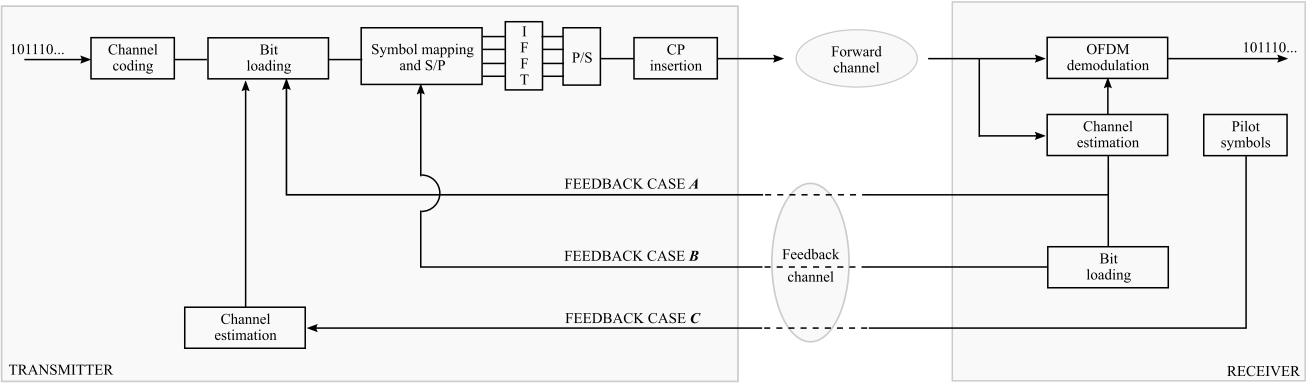

Fig. 1. Block diagram of OFDM transmission and feedback signaling.

for bit-loading processing, with the adapted power levels and modulation constellations related to each sub-carrier being quantized and sent back to the transmitter. So, the feedback information is exploited for symbol mapping, without any additional processing by the transmitter. The last scenario, namely case C, assumes instead channel reciprocity, hence the receiver emits its own pilot symbols that are used at transmit side for channel estimation and OFDM adaptation. So, channel estimation is performed independently at both sides of the communication link, and without any sharing of CSI since feedback signaling is not considered [9].

In general, by referring to case A and B, the feedback channel may be affected by errors compromising the accuracy of the data. Moreover, information about channel estimates, power levels and modulation order necessary to realize bit-loading must be quantized before transmission. Regarding instead case C, if channel reciprocity is not verified, there may be a mismatch between CSI available at transmit and receiver side, and signal demodulation may be subject to errors. The type of feedback signaling and quantization influence both the amount and quality of overhead and, therefore, the link reliability. Now, we investigate the joint impact of quantization and signaling for the considered feedback scenarios.

III. CHANNEL ESTIMATION AND QUANTIZATION

Each of the considered feedback signaling strategies defines the way CSI is acquired and utilized, with the correspondingly generated overhead impacting on the communication performance. First, let us consider the transmission F data bits by assuming the ideal case where CSI is perfectly known at transmit side. The time to deliver data is given as:

$$\Delta_i = \tau + F/R, \tag{1}$$

where $\tau = d/v$ is the propagation delay depending on the link distance d and signal speed v, while R is the transmission rate obtained through ideal bit-loading. Now, we pass to investigate communication time required in real scenarios considering feedback cases A, B and C. Case A is referred as channel quantization (CQ) since feedback concerns channel coefficients, while case B is related to power levels and modulation cardinality quantization (PMQ) as information regards transmission parameters. Finally, we indicate case C as parallel estimation (PE) since relying on channel reciprocity.

A. CQ and PMQ Feedback Cases

In both CQ and PMQ, the transmitter emits pilot symbols known at the receiver, with this latter performing channel estimation according to a maximum-likelihood criterion approach, whose performance depends on the SNR. Then, feedback information must be first represented in a binary form through quantization and then sent back to transmit side. The number of bits q employed for quantization must be compliant with the precision requested for information representation. According to the Lloyd-Max equations [10, Chapt.3], we have that q bits allow $M = 2^q$ quantization levels to be defined. In this regard, given the random variable x characterized by the distribution (probability density function) $f_X(x)$, the ℓ-th quantization level is defined as:

$$\hat{x}_\ell = \frac{\int_{\theta_\ell}^{\theta_{\ell+1}} x f_X(x)dx}{\int_{\theta_\ell}^{\theta_{\ell+1}} f_X(x)dx}, \quad \ell = 0, \dots, M\text{-}1, \tag{2}$$

where the range of integral calculus is given as $\theta_\ell = \frac{1}{2}(\hat{x}_\ell + \hat{x}_{\ell+1})$, representing the decision threshold between two consecutive levels. The number of quantization levels M must be chosen to meet the desired mean square error $E\{(\hat{x}-x)^2\} \leq \mathcal{D}^*$, where $E\{\cdot\}$ is the expected value operator and $\mathcal{D}^*$ is the target constraint. Therefore, q depends on M.

Regarding CQ, the CSI feedback is composed of $2N$ complex channel coefficients (two for each OFDM sub-channel since complex), corresponding to $2Nq_{\text{CQ}}$ bits, with q_{CQ} being the quantization bits employed in CQ. By also including channel coding at rate k/n and the signal rate G on the feedback channel, we have the time needed for sending back CSI given as $T_{\text{CQ}} = 2Nq_{\text{CQ}}n/(kG)$.

Dealing instead with PMQ, the information to be quantized and fed back concerns directly power levels and modulation cardinality (integer number) for the N OFDM sub-channels. Together with q_{PMQ} bits associated to each quantized power level, it is reasonable to assume the use of 3 more bits describing the modulation order (000 triplet for the case of no transmission, up to triplet 111 for 128 symbols constellations). Hence, in PMQ the time needed for transmitting the feedback information is $T_{\text{PMQ}} = N(q_{\text{PMQ}} + 3)n/(kG)$, including the effect of channel coding rate k/n and the data rate on the feedback channel G. It follows that the total time spent for

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transmission in CQ and PMQ is given as:

$$\Delta_{\text{CQ}} = T_p + 2\tau + T_{\text{CQ}} + T_{d,\text{CQ}} + F/R_{\text{CQ}}, \tag{3a}$$

$$\Delta_{\text{PMQ}} = T_p + 2\tau + T_{\text{PMQ}} + T_{d,\text{PMQ}} + F/R_{\text{PMQ}}, \tag{3b}$$

where T_p is the time spent by the transmitter to send pilots, τ is the propagation time, $T_{d,\text{CQ}}$ and $T_{d,\text{PMQ}}$ are the time for feedback decoding, R_{CQ} and R_{PMQ} are the rates obtained by applying bit-loading.

Finally, by recalling (1), we can formally define the transmission efficiency η to measure the efficiency of the considered schemes with respect to the ideal case as:

$$\eta_{\text{CQ}} = \Delta_i/(\Delta_{\text{CQ}} + \tau), \tag{4a}$$

$$\eta_{\text{PMQ}} = \Delta_i/(\Delta_{\text{PMQ}} + \tau), \tag{4b}$$

where τ accounts for the additional delay required, after signaling, to deliver each data packet.

In general, it is expected for the power levels to have a smaller dynamics with respect to the channel coefficients. So, given a target feedback accuracy to be achieved, q_{PMQ} is reasonably lower than q_{CQ}. This impacts on T_{CQ} and T_{PMQ}, resulting different as well. The use of few quantization levels makes large coefficients variations to be poorly described, causing a non-negligible quantization error that leads to a largely sub-optimal bit-loading. So, a proper compression (log-like) can be applied to reduce the range of variations. Additionally, just in case of quasi-flat channel in the frequency domain, it may be possible to reduce the amount of channel coefficients to communicate (that is, by estimating only a sub-set of sub-channels) since interpolation may be computed. Finally, it is worth noting that granting a reliable feedback channel entails a low valued G and k/n, thus increasing T_{CQ} and T_{PMQ}, and so reducing the transmission efficiency.

B. PE Feedback Case

The feedback case C, is based on the assumption of channel reciprocity, that is forward and feedback channels are almost identical, or at least not so different to cause a mismatch leading to inaccurate bit-loading and detection. In PE, channel estimation is performed independently at transmit and receiver side, with pilot symbols sent by both the link parties [9], and *hoping* to achieve the same channel description at transmit and receiver side. However, CSI quantization is still necessary since all the digital devices work with quantized numbers. But differently from CQ and PMQ, pilot symbols transmission suffices to let bit-loading being performed at both sides. Therefore, given the rate R_{PE} on the forward channel obtained through bit-loading, we have that the total communication time is:

$$\Delta_{\text{PE}} = T_p + \tau + F/R_{\text{PE}}, \tag{5}$$

since no feedback is considered. Finally, the transmission efficiency is given as:

$$\eta_{\text{PE}} = \Delta_i/(\Delta_{\text{PE}} + \tau), \tag{6}$$

that essentially depends on data volume F and rate R_{PE} on the forward channel. Anyway, despite performance losses due to feedback signaling are avoided with PE, a bad set up of bit-loading may induce large detection errors due to mismatch in modulation formats between transmit and receive constellations. So, more robust forward channel coding or data retransmission would be necessary with respect to CQ and PMQ cases.

TABLE I

SYSTEMS PARAMETERS FOR SIMULATION

Channel	**PLC**	**RF**	**UWAC**	**OWC**
Transmit power	-35 dBm	1 mW	183 dB @ 8V	10W
Bandwidth (kHz)	20×10^3	20×10^3	8	10×10^3
Number of subcarrier N	128	128	64	128
Distance (m)	20	1500	300	3
Quantization bits (q_{CQ},q_{PMQ})	(16,12)	(16,12)	(16,12)	(16,12)
Rate on feedback channel (G)	5Mb/s	10Mb/s	500 b/s	1Mb/s
Coding rate (k/n)	1/2	1/2	1/2	1/2
Propagation speed (m/s)	1.7×10^8	3×10^8	1.5×10^3	3×10^8

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the three feedback mechanisms under investigation, by considering different channels taken from measurements available in the literature. Channels are related to radio transmission over the air, UWAC, OWC and PLC, respectively. All the simulation parameters are reported in Table I. Although some parameters among channels are very different, they are typical for the specific technology. In order to account for both rate and reliability issues, we consider the bit-loading performed with the SNR-gap approximation [8] so as to achieve a target bit error rate (BER) of 10^{-6}.

First, we show the performance in terms of efficiency η, expressed as a function of the data volume F to be transmitted. In detail, F ranges from few bytes to 80 KB, representing the amount of information that is expected to be transmitted within the channel coherence time. In fact, as the channel changes in time, new re-estimation, feedback signaling and bit-loading are required. Such choice does not represent a limitation to our performance investigation. It guarantees the reliability of the efficiency results since related to that time window where the channel can be assumed as quasi-stationary.

A. RF Channel

Dealing with the RF communication, we consider the 4G measured channel in [11], reporting the efficiency performance in Fig. 2. In general, the PE approach outperforms PMQ and CQ. However, when the file dimension increases, the efficiency of PMQ and CQ approaches the one achieved with PE, with values around 0.8÷0.9. Interestingly, it can be also noted that the performance of PE mechanism are quite insensitive to the data volume to be sent, with efficiency close to 1 since in RF channels the propagation delay is very low and the imperfect channel reciprocity does not cause significant loss in terms of communication reliability. This is also due to the negligible propagation time and to the transmission time that is very short as well. Finally, the last aspect to highlight concerns the comparison between CQ and PMQ. As detailed in the previous section and by referring to (3a) and (3b), the feedback signaling time T_{CQ} is larger than T_{PMQ} since channel

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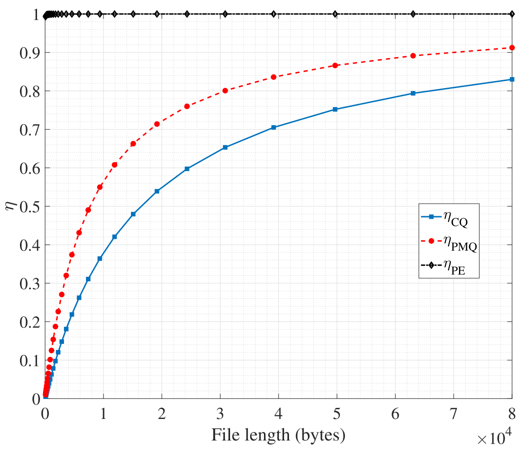

Fig. 2. Efficiency of CQ, PMQ and PE approaches in RF communication.

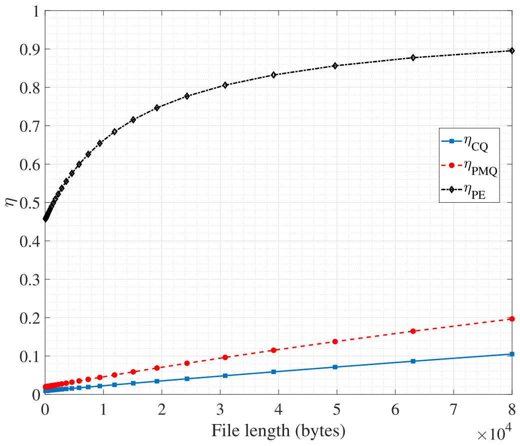

Fig. 3. Efficiency of CQ, PMQ and PE approaches in UWAC.

coefficients quantization requires more bit than power levels quantization. Therefore, the performance of PMQ are slightly higher than CQ.

B. UWAC Channel

The underwater acoustic channel is a really different scenario, where the sound propagation speed is very low and the achievable data rate is limited with respect to conventional RF systems. Even in this case, the considered channel is a measured one [12], leading to the performance reported in Fig. 3. Achieving the maximum efficiency is a very challenging task in this propagation environment due to the very high propagation delay. In fact, with the distance between transmitter and receiver set to 300 meters, the two-ways propagation is 0.4 seconds. This is the reason why the approaches requiring the use of feedback, that are CQ and PMQ, present very low efficiency. As discussed before, the performance difference between CQ and PMQ mainly depends on the feedback signaling time. Regarding instead PE, it can be noted how the efficiency values are lower than in the case of the RF channel. This is due to the relevant non-reciprocity of the underwater acoustic channel, making PE not so reliable as in RF channel scenarios.

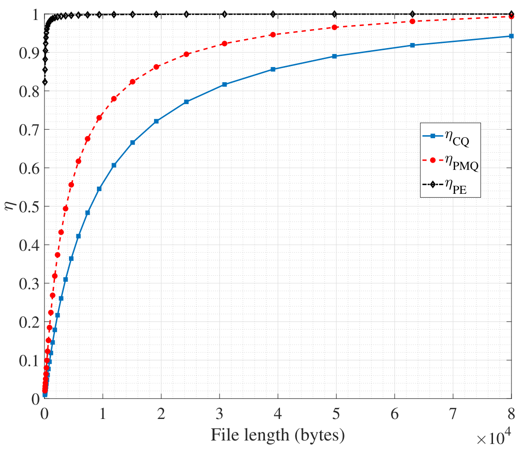

Fig. 4. Efficiency of CQ, PMQ and PE approaches in OWC.

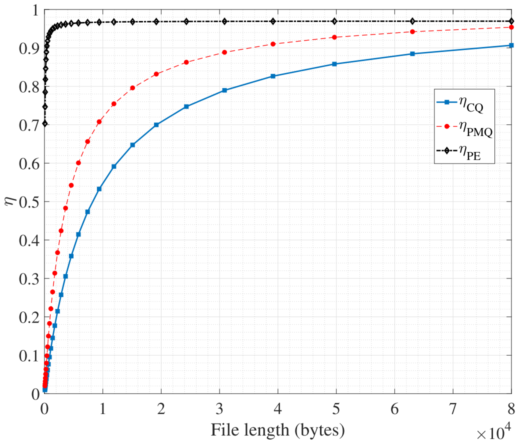

Fig. 5. Efficiency of CQ, PMQ and PE approaches in PLC.

C. OWC Channel

Besides, the case of OWC is different from the above ones since the transmission distance is very short and limited to 3 meters. Hence, the propagation time is very small if compared to the other two scenarios. The channel model has been considered according to [13]. As the dimension of the file to be sent increases, the efficiency value achieved by the three schemes becomes very similar and above 0.9. On the other hand, or very small file dimensions, the efficiency performance of CQ and PMQ are very poor, below 0.2.

D. PLC Channel

Last, we investigate the power line channel that is a time variant one [14], since the conditions in terms of leads in an electrical network may change. Hence, the impedance varies and so the channel impulse response. Here, we refer to the case of a non-reciprocal channel. In fact, only some topologies (symmetric) are reciprocal when dealing with source-destination and destination-source links. Moreover, in this case channel reciprocity is generally not granted. In our simulations, we consider the topology given by [15, Chapt.2] with a simple bridge-tap inserted in the source-destination path line (Fig. 2.3 of [15]). In Fig. 5, we depict the efficiency introduced in the previous section related to the use of CQ,

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TABLE II

BIT ERROR RATE PERFORMANCE

	RF	**UWAC**	**OWC**	**PLC**
Ideal	10^{-6}	10^{-6}	10^{-6}	10^{-6}
CQ	1.56×10^{-6}	1.89×10^{-5}	1.35×10^{-6}	2.45×10^{-6}
PMQ	1.41×10^{-6}	8.11×10^{-6}	1.16×10^{-6}	1.96×10^{-6}
PE	1.08×10^{-6}	4.3×10^{-6}	10^{-6}	2.12×10^{-5}

PMQ and PE feedback mechanisms, respectively. As general comment, we can observe that the PE approach outperforms PMQ and CQ. However, when the file dimension increases, the PMQ efficiency approaches the one achieved by PE. Interestingly, it can be also noted that the use of PE mechanism does not allow the achievement of the maximum efficiency, since the missing of channel reciprocity leads the detection to suffer from errors.

E. Impact on Error Rate

The last performance comparison involving CQ, PMQ and PE mechanisms is based on the evaluation of BER. It is important to underline that, basing on the only efficiency performance, we can not have a clear view of the reliability achieved by the three mechanisms since the bit-loading procedures are performed under the assumption that the CSI (at the transmitter and/or receiver) is perfect, while this may not be always verified. Hence, we consider the true BER achieved by the three solutions considered in this work. The performance related to the ideal case where CSI is always available both at the transmit and receiver side is taken as benchmark. By looking at the results reported in Table II, it is important to highlight that, with the only exception related to the OWC channel case, PE mechanism is unable to achieve exactly a BER equating 10^{-6}, that is the ideal case performance for all the considered channel scenarios. This is due to the power/modulation allocation mismatch between transmitter and receiver, originating from the missing of channel reciprocity in RF and UWAC cases. On the other hand, in OWC where the link is typically line-of-sight, the channel reciprocity is verified if the pointing between the end devices is sufficiently accurate. However, in general, PE mechanism is the closest one to the ideal case. This is not true for the PLC case since what we obtain is that PE presents the worst performance. This is due to the absence of channel reciprocity that is the basic assumption to let the PE approach work. For what concerns PMQ, the performance by considering all the different channels are in between with respect to PE and CQ. Furthermore, we can appreciate that the performance achieved in UWAC are sufficiently far from the ideal case. This is due to the fact that, despite whatever feedback strategy is considered, underwater acoustic propagation is more challenging than RF and optical cases.

V. CONCLUSION

In this letter, we investigated the joint impact of channel knowledge, quantization and feedback signaling for the implementation of OFDM. Specifically, we considered three mechanisms for acquiring, sharing and using CSI to drive bit-loading at transmit side. In this regard, the impact of quantization is investigated not only in terms of feedback information accuracy, but also regarding the communication efficiency. Simulations related to real channel cases related to RF, OWC, PLC and UWAC links showed that system performance strictly depend on the propagation conditions and the employed technology. Therefore, an optimal strategy to implement the feedback signaling for OFDM setup does not exist as win-win approach, but the solution must be tailored to the considered scenario. In fact, while the PE solution works very well under the hypothesis of reciprocal channels, it is outperformed by CQ and PMQ if that hypothesis does not hold. Among these two, CQ is preferable if the receiver processing may be limited and channel dynamics is small, while if the receiver is equipped with a good processing capability and channel dynamics is large, PMQ can be the most viable solution.

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