A Composite Approach to Self-sustainable Transmissions: Rethinking OFDM

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***Abstract*—This paper proposes two novel strategies to extend the battery life of an orthogonal frequency division multiplexing (OFDM) receiver, by exploiting the concept of wireless power transfer (WPT). First a new receiver architecture is devised that does not discard the cyclic prefix (CP), but instead, exploits it to extract power from the received signal, realizing a WPT between the transmitter and the receiver. Subsequently, a flexible composite transmit strategy is designed, in which the OFDM transmitter transmits to the receiver two independent signals coexisting in the same band. It is shown that, by means of this approach, the transmitter can arbitrarily increase the power concentrated within the CP at the OFDM receiver, without increasing the redundancy of the transmission. The feasibility conditions for the self-sustainability of the transmission are derived, in terms of power consumption at the receiver, for both legacy and composite transmission. Numerical findings show that, under reasonable conditions, the amount of power carried in the CP could be made sufficient to decode the information symbols, making the transmission fully self-sustainable. The potential of the proposed approach is confirmed by the encouraging results obtained when the full self-sustainability constraint is relaxed, and partially self-sustainable OFDM transmissions are analyzed.**

***Index Terms*—Energy harvesting, OFDM, self-sustainable, green communications, adaptive transmissions, CIA**

I. Introduction

In mobile wireless systems, the necessary power for the receiver to decode the received information, and perform other system-related operations, is provided by an external power source, e.g., a battery. In practice, the performance of the receiver is usually constrained by the residual battery life, with the latter largely impacting the overall user experience. Increasing the size of the battery to cope with this issue would reduce the portability of the device and possibly its commercial value. This is not always desirable, hence newer techniques to prolong the battery life of the receiver have gained prominence. In this regard, one of the most promising approaches to solve the ever-growing energy scarcity problems in our society[1] is represented by the design and implementation of energy harvesting devices, to scavenge power from human activities or deriving energy from ambient heat, light, vibrations and so on.

This belief is nowadays very popular in wireless communications as well, where energy harvesting techniques have grown from long-established concepts into devices for powering ubiquitously deployed sensor networks and mobile electronics [1]. A possible source of energy comes from ubiquitous radio transmitters, which typically broadcast a significant amount of radio frequency (RF) energy to remote devices. Historically, RF signals in wireless communications have been mainly used as a means for information transmission. However, recent advances in microwave technology and signal processing have unveiled the potential of the so-called wireless power transfer (WPT) from one device to the other [2], [3]. Conceptually, this energy is captured and converted into functional direct current (DC) voltage by means of a specialized circuit directly connected to a receiving antenna [4]. This way, a reduction of the need for local power sources at the remote devices could be achieved by deliberately broadcasting RF energy, for harvesting purposes at the receiver. In this regard, a new research front has been recently envisioned by Varshney [2], who first formalized the idea of transmitting information and energy simultaneously in a wireless communication. The trade-off between energy and information transfer has been investigated in many scenarios, i.e., multi-antenna systems, opportunistic networks, wireless sensor networks and so on [5]–[7]. The performance of these approaches is encouraging. Nevertheless, practical circuits to harvest energy from RF signals are not able to decode the information at the same time. Thus, state-of-the-art contributions on the subject typically propose additional power splitting and/or time switching strategies at the receiver, to perform both these operations [5]–[7], with possible modifications of the structure of the communication w.r.t. the operations in current cellular networks.

In this paper, we target a very popular physical layer technology, namely the orthogonal frequency division multiplexing (OFDM) and propose a novel approach to prolong the battery life of an OFDM receiver by exploiting the concept of WPT. State-of-the-art solutions to realize a WPT

This work was partly supported by the SRG ISTD 2012037, SUTD-MIT International Design Centre under Grant IDSF1200106OH, and the A*STAR SERC Grant 1224104048.

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[1]Note that, the words energy and power are used interchangeably in this paper, for the sake of simplicity, in spite of their conceptual difference.

in OFDM-based systems rely on either power splitting or time switching strategies at the receiver [8]–[12], similar to what is typically proposed in the literature [5], [6]. Accordingly, they propose modifications to the first stage of the RF front-end of the OFDM receiver [8], [10], [12] or to both the protocol/scheduling at the transmitter and the receiver activities depending on the state of the latter (idle/active) [9], [11]. The typical goal of these contributions is to identify both the power loading strategy at the transmitter and the power or time splitting ratio at the receiver that maximizes the amount of energy and/or information that can be transfered to the receiver. In particular, [12] first proposes a comprehensive practical framework for OFDM-based simultaneous wireless information and power transfer. Therein, a multi-antenna transmitter is considered and several power control problems are identified and solved for different practical scenarios, e.g., downlink/uplink transmission, single/multi-user system, variable/constant bit-rate. Herein, we depart from the approaches considered in the prior works, and show how the structure of an OFDM transmission offers an intrinsic way to realize an energy transfer from the transmitter to the receiver and enhance the receiver's battery lifetime, without the need for additional antennas, more complex power allocation algorithms at the transmitter, or time/power splitters at the receiver as in [8]–[12]. We start from the intuition that a significant amount of power is typically wasted in OFDM transmissions due to the presence of the cyclic prefix (CP). This unavoidable redundancy in the transmission has a purely functional role and is introduced to eliminate both inter-carrier and inter-block interference (ICI and IBI, respectively), by means of a simple removal operation after the time-frequency synchronization at the receiver [13]. This results in an inevitable spectral efficiency loss for the transmitter. Accordingly, we first propose a novel OFDM receiver architecture that does not discard the CP, but exploits it to extract power from the received baseband signal, effectively realizing a WPT between the transmitter and the receiver. Subsequently, we increase the flexibility of the proposed solution by designing a composite transmit strategy, in which the signal generated by the OFDM transmitter is obtained as the combination of two independent components: 1) the standard OFDM signal, 2) a signal obtained by means of a cognitive interference alignment (CIA) precoding [14].

The goal of our approach is to transform the aforementioned loss of spectral efficiency at the transmitter to a power saving at the receiver. An appropriate tuning of the transmit parameters could result in an amount of power carried by the CP that could significantly reduce the impact of the OFDM digital signal processing operations on the battery. If this were the case, intuitively the OFDM symbol could provide to the receiver both the information and the power necessary to retrieve it, making the transmission *self-sustainable* in terms of power consumption of the OFDM digital signal processing operations at the receiver. We analytically derive the feasibility conditions to achieve the self-sustainability of the transmission, for both transmit strategies, as a function of an adaptive scaling parameter that models different degrees of self-sustainability. Remarkably, the results of our subsequent numerical analysis show that, under reasonable conditions, the amount of power carried in the CP could be sufficient to achieve a fully self-sustainable OFDM transmission. In particular, the feasibility of the full self-sustainability is substantiated by the consistent performance of the composite strategy for several system configurations. Finally, the potential of both proposed strategies is confirmed by the encouraging results obtained when the full self-sustainability constraint is relaxed, and partially self-sustainable OFDM transmissions are analyzed.

The rest of the paper is organized as follows. In Sec. II, we describe the classic OFDM receiver architecture. In Sec. IV, we describe and analyze both the novel OFDM receiver architecture and the flexible composite transmit strategy to realize the WPT. In Sec. V, we evaluate the performance of the WPT numerically, for both proposed approaches. Finally, conclusions and future research directions are discussed in Sec. VI.

Notations: Lower case bold characters represent vectors and upper case bold characters represent matrices. All vectors are column vectors, unless otherwise stated. We denote the $N \times N$ identity matrix by $\mathbf{I}_N$, the $N \times M$ zeros matrix by $\mathbf{0}_{N \times M}$, the trace of the matrix $\mathbf{A}$ by $\mathrm{tr}[\mathbf{A}]$, its kernel by $\ker(\mathbf{A})$ and its element at the mth row and the nth column by $[\mathbf{A}]_{m,n}$. For a given vector $\mathbf{a} = (a_1, \ldots, a_N)$, we denote as $d(\mathbf{a}) = diag(\mathbf{a})$ a diagonal matrix such that $[d(\mathbf{a})]_{i,i} = a_i$. We denote the expectation of a random variable X by $\mathbb{E}[X]$. The set of all positive real numbers, excluding $\{0\}$, is denoted by $\mathbb{R}_0^+$.

II. Model

Consider the OFDM downlink transmission between an access point (AP) and a single user equipment (UE), both single-antenna devices. We assume a slotted communication, with slot duration such that the channel can be considered time invariant during each scheduling slot. No specific duplexing mode is enforced, i.e., the communication can be either in time or frequency division duplexing mode (TDD or FDD, respectively). Accordingly, in the case of FDD, the downlink channel state information (CSI) can be acquired by the AP from the feedback signal of the the UE. In the TDD case, the CSI can be acquired by exploiting channel reciprocity. Let $\mathbf{h} = [h_0, \ldots, h_l] \sim \mathcal{CN}(0, \mathbf{I}_{l+1}/(l+1))$ be the Rayleigh fading channel vector, composed by $l+1$ independent and identically distributed taps, representing the frequency-selective channel between the AP and the UE. As usually done in similar contributions on the subject, we assume that the AP has perfect channel state information of the downlink channel vector $\mathbf{h}$ [8]–[12].

We start by briefly reviewing some basics of OFDM. A typical OFDM signal is composed by two components, i.e., a portion of the signal carrying the information sent to the receiver and a redundancy called CP. The purpose of the CP is twofold [13]. On the one hand, it is prepended to the information symbols by the transmitter to accommodate the multi-path channel impulse response. On the other hand, its presence allows to eliminate both the IBI between two adjacent OFDM blocks and the ICI between the sub-carriers, resulting

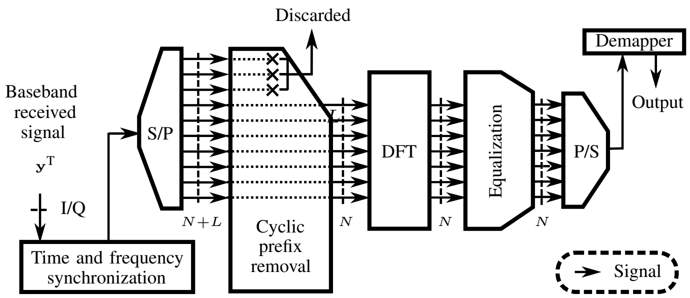

Fig. 1. Classic OFDM receiver architecture.

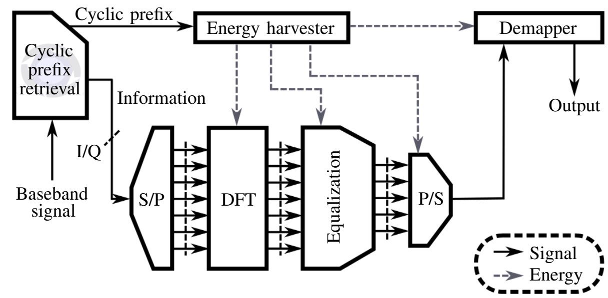

Fig. 2. Energy harvesting OFDM receiver.

in simpler signal equalization procedures. Let us assume that the OFDM transmission is performed over N sub-carriers. Additionally, let L be the size of the CP. As a consequence, each OFDM symbol spans $N+L$ samples in the time domain. Let $\mathbf{s}_{\mathrm{o}} = [s_{\mathrm{o},1}, \dots, s_{\mathrm{o},N}]^{\mathrm{T}} \sim \mathcal{CN}(0, \mathbf{P})$ be the input symbol vector at the AP of size N, with covariance matrix $\mathbf{P} = \mathrm{d}(\mathbf{p}) = \mathbb{E}[\mathbf{s}_{\mathrm{o}}\mathbf{s}_{\mathrm{o}}^{\mathrm{H}}] \in \mathbb{R}^{N\times N}$, where $\mathbf{p} = [p_1, \dots, p_N]^{\mathrm{T}}$ is an N-sized vector carrying the power associated with each of its symbols, and $p_i = s_{\mathrm{o},i}s_{\mathrm{o},i}^{*} \in \mathbb{R}_0^{+}$. If we define $\mathbf{F} \in \mathbb{C}^{N\times N}$ as a unitary discrete Fourier transform (DFT) matrix with $[\mathbf{F}]_{(k+1,l+1)} = \frac{1}{\sqrt{N}} e^{-i2\pi\frac{kl}{N}}$ for $k, l = \{0, \dots, N-1\}$, and

$$\mathbf{A} = \begin{bmatrix} \mathbf{0}_{L,N-L} & \mathbf{I}_L \\ \multicolumn{2}{c}{\mathbf{I}_N} \end{bmatrix} \in \mathbb{R}^{(N+L)\times N}$$

as a CP insertion matrix, then the transmit signal at the AP's antenna reads

$$\mathbf{x}_{\mathrm{o}} = [x_{\mathrm{o},1}, \dots, x_{\mathrm{o},(N+L)}]^{\mathrm{T}} = \mathbf{A}\mathbf{F}^{-1}\mathbf{s}_{\mathrm{o}} \in \mathbb{C}^{N+L}.$$

We can model the convolution of the signal with the channel from the AP to the UE, i.e., $\mathbf{h}$, with $\mathbf{x}_{\mathrm{o}}$, by means of the Toeplitz matrix $\mathbf{H} \in \mathbb{C}^{(N+L)\times(N+L)}$, given by

$$\mathbf{H} = \begin{bmatrix} h_0 & 0 & \cdots & 0 & h_l & \cdots & h_1 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & h_l \\ h_l & \cdots & \cdots & h_0 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & 0 \\ 0 & \ddots & 0 & h_l & \cdots & \cdots & h_0 \end{bmatrix}.$$

Thus, the received signal at the UE's antenna can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{x}_{\mathrm{o}} + \mathbf{n} \in \mathbb{C}^{N+L}, \tag{1}$$

where $\mathbf{n} = [n_1, \dots, n_{N+L}]^{\mathrm{T}} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_{N+L})$ is an additive white Gaussian noise (AWGN) vector, with $\mathbb{E}[n_i n_i^{*}] = \sigma^2$.

Consider the row vector representation of the received signal at the UE, i.e., $\mathbf{y}^{\mathrm{T}}$. At this stage, we assume that the UE is implemented according to the classic OFDM receiver architecture, whose schematic representation is given in Fig. 1.

After the synchronization process, a serial-to-parallel element prepares the signal to be fed to the CP removal block that discards the first L input samples, to remove the ICI and IBI[2].

[2]Note that, herein we are assuming perfect time and frequency synchronization and no RF impairments, as a first approximation.

The resulting N-sized vector $\mathbf{r} \in \mathbb{C}^N$ reads

$$\mathbf{r} = \mathbf{B}\mathbf{y} = \overline{\mathbf{H}}\mathbf{A}\mathbf{F}^{-1}\mathbf{s}_{\mathrm{o}} + \bar{\mathbf{n}}, \tag{2}$$

with $\mathbf{B} = [\mathbf{0}_{N\times L} \quad \mathbf{I}_N] \in \mathbb{R}^{N\times(N+L)}$ matrix representing the CP removal operation. Note that, in (2) the matrix $\overline{\mathbf{H}} \in \mathbb{C}^{N\times(N+L)}$ and the vector $\bar{\mathbf{n}} \in \mathbb{C}^N$ are obtained by removing the first L rows from $\mathbf{H}$ and the first L elements from $\mathbf{n}$, respectively. The subsequent DFT yields

$$\mathbf{r}_{\mathrm{F}} = \mathbf{F}\mathbf{r} = \mathbf{F}\overline{\mathbf{H}}\mathbf{A}\mathbf{F}^{-1}\mathbf{s}_{\mathrm{o}} + \mathbf{F}\bar{\mathbf{n}} \in \mathbb{C}^N,$$

N-sized frequency domain representation of the received information symbols, ready for the subsequent one-tap equalization and decoding operations, i.e., a parallel-to-serial element and a constellation demapper. In particular, we recall that any linear transformation of a Gaussian vector preserves the Gaussian property of the latter, hence $\mathbf{F}\bar{\mathbf{n}}$ has the same statistics as $\mathbf{n}$ and no particular filtering is required before the demapper.

III. Novel OFDM receiver architecture

The main purpose of the CP in each transmitted OFDM block is to provide a means for the receiver to effectively eliminate IBI and ICI from the received signal. This can be achieved by the receiver, without any loss to the information carried by the block, by simply discarding the CP of each OFDM block which consists of redundant data. Naturally, this induces a cost for the OFDM system. First, the presence of the CP in the OFDM block results in an unavoidable spectral efficiency reduction of $\frac{L}{N+L}$, i.e., $N+L$ symbols are used to transmit N information symbols. Subsequently, if we focus on the CP removal operation, we see that the power associated with sending the CP (i.e., up to 20% of the transmit power in long term evolution (LTE) [15]) is completely wasted by the UE, in order to obtain a signal free from IBI and ICI. However, the intrinsic structure of the OFDM transmission offers an opportunity that can be exploited to transform these losses into a power saving for the receiver. The core novelty of the proposed approach is represented by the idea of exploiting the CP for WPT purposes from the AP to the UE.

Consider a receiver architecture as depicted in Fig. 2. A key difference between the novel architecture in Fig. 2 and the legacy OFDM receiver in Fig. 1 is that no CP removal element is present in the former. Two novel blocks are introduced, i.e., a CP retrieval element and an energy harvester [16], [17].

A detailed description of the implementation details of the two elements is out of the scope of this paper and deferred to future investigation. Nevertheless, a qualitative description of their functioning is provided, to better characterize the operations performed by this novel receiver. As a first step, no sampling is performed within the RF chain during the RF down-conversion, such that the input signal to the CP retrieval element is still in analog form. The CP retrieval element serves three purposes:

1) Timing synchronization, to identify and retrieve the CP, for feeding it to the energy harvester in analog form. In this regard, we note the CP retrieval operation can be expressed in accordance with the signal model provided in Sec. II, as
$$\mathbf{q} = \mathbf{Q}\mathbf{y} \in \mathbb{C}^{L}, \tag{3}$$
where $\mathbf{Q} = [\mathbf{I}_L \quad \mathbf{0}_{L,N}] \in \mathbb{R}^{L\times N+L}$ is a matrix retrieving $\mathbf{q}$, i.e., the portion of $\mathbf{y}$ corresponding to the CP. We note that (3) does not explicitly model the physical operation performed by the CP retrieval element. Instead, it provides a representation of the CP in terms of equivalent number of samples L, useful for the forthcoming analysis.
2) Sampling of the remaining portion of the signal, after the CP retrieval.
3) Frequency synchronization, to obtain $\mathbf{r}$ as in (2). The latter is then fed as input to the subsequent OFDM signal processing blocks. In this regard, we note that the branches between the CP retrieval and the DFT elements still carry the vector $\mathbf{r}$, unaltered as in the case of the classic OFDM.

Concerning the energy harvester, we note that in contrast with state-of-the-art solutions for WPT, which harvest energy from the signal at the receiver's antenna by means of a radio frequency to direct current (RF-to-DC) conversion [6], [16], herein the power is scavenged from a baseband signal, after the amplification provided by the RF front-end. In practice, this could significantly reduce the impact of path-loss attenuations on the amount of energy that can be scavenged by the received signal w.r.t. to the aforementioned state-of-the-art approaches. Naturally, the conversion to DC in our case could still be performed by means of a diode operating at the appropriate frequency, as for the RF-to-DC operation, given the nature of the signal after the RF amplifier. Accordingly, we can model the efficiency of the harvesting operation by means of a coefficient $\beta \in [0, 1]$, thanks to the law of energy conservation, as typically done in the literature [5], [6]. Several additional differences can be identified between this approach and what is proposed in [6], [11], [12]. The WPT is accomplished with no need to insert an adaptive time/power splitter in the RF front-end at the receiver or to change the protocol at the transmitter, thanks to the inherent structure of the OFDM transmission. In fact, the OFDM transmission already provides a fixed and constant structure, which dictates a constant "splitting" pattern to the receiver. More precisely, each OFDM frame carries several blocks, which in turn are composed of two portions: the CP and the portion carrying the information to the receiver. Accordingly, once the timing synchronization at frame level has been acquired, the receiver deterministically knows the position of the CP of every OFDM block included in the frame, without the need for further synchronizations. This significantly simplifies the requirements in terms of rapidity and responsiveness of the receiver. In fact, the latter does not need to dynamically optimize its time/power splitting ratio depending on its state, its energy requirements or the downlink CSI (as in state-of-the-art contributions). Conversely, it can actually extract deterministic portions of the received signal in fixed positions, determined immediately after the timing synchronization at frame level. Thanks to this approach, the receiver is able to recycle the inherent left-over resources of the OFDM transmission, i.e., the CP, without requiring additional synchronization procedures w.r.t. a legacy OFDM transmission.

Now, let us focus back to Fig. 2. Therein, the power extracted by the energy harvester is represented by means of blue lines connecting the harvester to the blocks performing the OFDM digital signal processing. We note that, these lines do not symbolize physical connections between the blocks but rather are an abstraction to represent the additional source of power that the receiver can exploit thanks to the proposed approach, to operate the OFDM digital signal processing blocks. In this sense, our goal is to show how the impact of the power consumption of these operations on the receiver lifetime can be reduced by exploiting the presence of the CP in every OFDM block. As a matter of fact, we do not aim at designing a battery-free receiver as in [18], but rather at characterizing the extent to which the receiver's battery (always considered as the primary source of power) could be relieved of the energy expenditure due to the OFDM digital signal processing, thanks to the proposed approach and receiver design. A detailed discussion on the practical implementation of this process is out of the scope of this work. Accordingly, we defer this aspect to future investigations.

IV. Self-sustainable transmission

Due to the proposed architectural change, the AP could set the CP size such that the latter can be exploited by the UE to extract power from the received baseband signal that would be otherwise wasted in the classical OFDM reception. Such an approach significantly modifies the role of the CP in the transmission, transforming a spectral efficiency loss for the AP into a tunable energy saving for the UE. Ideally, if the transmit parameters were appropriately tuned, the AP could be able to transfer sufficient power to the UE to process all the information symbols, zeroing the impact of the OFDM digital signal processing on the UE's battery life, yielding a *self-sustainable* OFDM transmission.

Now, let P_{M} be the total power radiated by the considered AP. Typically the values for P_{M} in real system implementations range from hundreds of milliwatts to a few watts [19]. Furthermore, let $P_{\mathrm{d}} \in \mathbb{R}_0^+$ be the power consumption at the receiver for the digital signal processing of an OFDM block carrying N information symbols, without loss of generality[3]. We note that P_{d} can be in the order of few hundreds of mW in practical implementations, depending on the adopted hardware [20], [21]. Comparing the typical values of P_{M} and P_{d}, we can safely assume that the energy scavenged from the CP and net of the effect of β could have the same orders of magnitude as P_d. This could be sufficient to mitigate the impact of P_d on the UEs' battery life. As a consequence, partial or full self-sustainability of the OFDM transmission in terms of power consumption of the OFDM digital signal processing at the receiver could be achieved. Interestingly, the applicability of this approach is not limited to a specific scenario. Ideally, any OFDM transmission could become self-sustainable if appropriate feasibility conditions were met.

1) Feasibility conditions: As previously said, the goal of the introduction of the novel receiver architecture is to provide a means for the UE to reuse the inherent redundant portion of the received OFDM signal as a source of useful energy that can be used to reduce the impact of the digital signal processing operations on the battery. However, the main purpose of the transmission does not change w.r.t. a legacy OFDM transmission, from the point of view of both AP and the UE. The primary goal of the AP is to maximize the rate of the downlink transmission. Thus, let us consider the classical rate maximization problem for OFDM transmissions (i.e., without WPT), expressed in its general form as

$$\begin{aligned} \max_{\mathrm{d}(\mathbf{p})} \quad & \frac{1}{(N+L)} \log_2 \left| \mathbf{I}_N + \mathbf{FBHAF}^{\mathrm{H}}\mathbf{PFA}^{\mathrm{H}}\mathbf{H}^{\mathrm{H}}\mathbf{B}^{\mathrm{H}}\mathbf{F}^{\mathrm{H}} \right| \\ \text{s.t.} \quad & \tfrac{1}{\Gamma}\operatorname{tr}[\mathbf{P}] \leq P_{\mathrm{M}} \\ & p_i \geq 0, \end{aligned} \tag{4}$$

$\forall i \in [1, N]$, with $\Gamma = \frac{N}{N+L}$. The solution to (4) is given by a water-filling (WF) power loading strategy [13], yielding an optimal power allocation vector, hereafter denoted by $\mathbf{p}_{\mathrm{W}} \in \mathbb{R}_0^{N+}$. We remark that, if perfect CSI is available at the AP, as assumed in Sec. II, (4) can always be solved. Now, without loss of generality, let us assume N fixed by a certain standard, such as the long term evolution (LTE) [15].

The choice of the CP size affects many aspects of the transmission, thus it is less straightforward and subject to some well defined criteria. In practice, if a WF power loading is performed by the AP, then the downlink rate is maximized if L is minimized [22]–[26]. However, in practical OFDM transmissions, the CP size cannot be smaller than the delay spread of the channel, i.e., $L \geq l$ regardless of the performed optimization, to ensure the absence of ICI and IBI at the receiver. Furthermore, if we consider the novel WPT approach proposed in this work, the CP size may also impact the amount of power that can be scavenged at the OFDM receiver. In fact, the smallest possible L might not be optimal in terms of self-sustainability of the transmission. Thus, an additional constraint relating the harvested power from the CP to the total consumed power for the decoding operations at the receiver must be considered. According to all these considerations, the rate maximization problem in (4) can be cast into a new problem, that is

$$\begin{aligned} \min_{L\in\mathbb{N}} \quad & L \\ \text{s.t.} \quad & \beta \operatorname{tr}\left[\mathbf{QHAF}^{\mathrm{H}}\mathbf{PFA}^{\mathrm{H}}\mathbf{H}^{\mathrm{H}}\mathbf{Q}^{\mathrm{H}}\right] - \delta P_d \geq 0 \qquad \text{(a)} \\ & \tfrac{1}{\Gamma}\operatorname{tr}[\mathbf{P}] - P_{\mathrm{M}} \leq 0 \qquad \text{(b)} \\ & p_i \geq 0 \qquad \text{(c)} \\ & L \geq l, \qquad \text{(d)} \end{aligned} \tag{5}$$

$\forall i \in [1, N]$, with β as in Sec. 2, including all the possible inefficiencies in the energy conversion performed by the energy harvester. We note that, in (5), (a) is the aforementioned self-sustainability constraint, expressed as a function of $\delta \in \mathbb{R}_0^+$, adaptive scaling factor that flexibly models several non-zero levels of energy of interest for the energy-harvesting OFDM receiver, resulting in a full ($\delta \geq 1$) or partial ($\delta < 1$) self-sustainability of the transmission.

Unfortunately, (5) is an integer programming problem, whose solution cannot be found in closed form. In this regard, we note that even if we were to express the CP as a period in time (rather than an integer value), the resulting problem would still have an integer structure. This is due to the fact that the CP length would still have to be chosen from a finite set of values, depending on the sampling period at the receiver. In other words, the only difference with the current form of (5) would be that the CP length would still have to be chosen from a finite set of real values, instead of a finite number of integer values. Furthermore, the presence of $\mathbf{P}$ in (a) and (b) in (5) further enforces the discrete representation of (5), $\mathbf{P}$ being the result of the WF performed by the AP in the digital domain. However, let us focus on the constraints in (5). We define $\mathbf{G} = \mathbf{QHAF}^{\mathrm{H}} = [\mathbf{g}_1, \mathbf{g}_2, \ldots, \mathbf{g}_N] \in \mathbb{C}^{L\times N}$, where for the sake of simplicity in the further derivations, but without loss of generality, we let $||\mathbf{g}_1||^2 \leq ||\mathbf{g}_2||^2 \leq \cdots \leq ||\mathbf{g}_N||^2$. Then, the $N+3$ constraints can be rewritten as

$$\begin{cases} \sum_{i=1}^{N} p_i ||\mathbf{g}_i||^2 - \frac{\delta}{\beta} P_d & \geq \quad 0 \\ -\frac{1}{\Gamma}\sum_{i=1}^{N} p_i + P_{\mathrm{M}} & \geq \quad 0 \\ p_i & \geq \quad 0, \quad \forall i \in [1, N] \\ L - l & \geq \quad 0. \end{cases} \tag{6}$$

We note that, (6) is an overdetermined linear system of inequalities, whose feasibility is fundamental to assess if a solution to (5) can be found, that is to demonstrate the non-emptiness of $\mathcal{P} \subseteq \mathbb{R}^N$, set of power allocation vectors satisfying the constraints in (5). The following result can be stated.

Lemma 1: Let $\xi = \frac{P_{\mathrm{M}}}{P_d} \in \mathbb{R}_0^+$ be the ratio between the total transmit power budget at the transmitter and the power consumed by the receiver for the OFDM digital signal processing. Then, (5) admits a solution if and only if

$$l \leq N\left(\max\{||\mathbf{g}_i||^2\}\xi\frac{\beta}{\delta} - 1\right), \tag{7}$$

Proof: See Appendix A. □

Let us focus on the implications of Lemma 1. It is straightforward to see that if we divide both left- and

[3]The actual value of P_{d} in practical implementations depends on the complexity of the operations performed by the receiver for the digital signal processing. Thus, the dependency between the number of information symbols per OFDM block, i.e., N, and P_{d}, cannot be explicitly characterized unless specific architectural assumptions are made.

right-hand side members of (7) by N, the satisfiability of the condition in (7) increases as N grows. Accordingly, for fixed values of δ, ξ and β, an increase in the number of sub-carriers would enhance the feasibility of the self-sustainability of the OFDM transmission. Now, if we consider that $l \geq 0$ by definition, then the condition $l \leq N\left(\max\{||\mathbf{g}_i||^2\}\xi\frac{\beta}{\delta} - 1\right)$ implies that $\max\{||\mathbf{g}_i||^2\}\xi\frac{\beta}{\delta} - 1 \geq 0$, that is $\max\{||\mathbf{g}_i||^2\} \geq \frac{\delta}{\xi\beta}$. In practice, Lemma 1 implicitly identifies a lower bound for the maximum equivalent channel gain, such that a feasible CP length can be found. Interestingly, this exclusively depends on system parameters. In particular, higher the value of δ, the larger the necessary $\max\{||\mathbf{g}_i||^2\}$ in order to find a feasible CP length, whereas an opposite behavior is noticeable w.r.t. β, as expected intuitively. Also, we note that considering $\delta = 0$ is neither interesting nor meaningful, since in this case, any power allocation strategy and CP length would satisfy the constraint (a) in (5), making the problem trivial. In fact, by carefully looking at (5), we notice that if $\delta = 0$, then $\mathcal{P}$ actually coincides with $\mathbb{R}^N$, i.e., $\mathcal{P} \subseteq \mathbb{R}^N$ and $\mathbb{R}^N \subseteq \mathcal{P}$. Furthermore, the right-hand side of the inequality in (7) would be undefined in this case, rendering the result of Lemma 1 rather ambiguous. For these reasons, δ has been defined as belonging to $\mathbb{R}_0^+$, such that it could model only meaningful non-zero levels of self-sustainability.

A. Composite OFDM Transmission

Interestingly, the adaptivity of the approach described so far can be increased if we depart from the purely parametric approach by means of δ and adopt a flexible and modular structure for the OFDM transmission [27]. From a practical point of view, the level of self-sustainability that can be achieved by means of the proposed approach hinges on the amount of power carried by the CP. Nevertheless, in the legacy OFDM transmission, the transmitter does not have the possibility to arbitrarily alter the amount of power that is concentrated in the CP at the receiver, by construction. However, this limitation can be overcome if we design a composite OFDM transmission by means of a precoder-based technique called cognitive interference alignment (CIA) [14], as detailed in the following.

In its first formulation for two-tiered networks, CIA allows a secondary transmitter to transmit a signal that coexists with an OFDM signal, in such a way that the OFDM receiver may experience an interference-free decoding. This is achieved by aligning the subspace of the signal transmitted by a cognitive secondary transmitter to the kernel of the matrix that represents the equivalent OFDM interference channel matrix, obtained after the CP removal at the receiver. In practice, the interference generated at the OFDM receiver by the CIA transmission is always concentrated within the CP, regardless of the channel realization. As a consequence, this interference is obliviously discarded by the OFDM receiver by means of a simple CP removal operation, hence no modification to the classic receiver architecture is necessary. We remark that, the effectiveness of this approach depends both on the precision of the synchronization between the OFDM and CIA signal at the OFDM receiver and on the availability of CSI w.r.t. the equivalent OFDM interference channel at the secondary transmitter. The interested reader may refer to [14], [28] for further details on CIA for both single-user and multi-user scenario.

Now, assume that the AP adopts a composite transmit strategy in which the simultaneous transmission of both an OFDM and a CIA signal is performed. We start by noting that, herein the direct and interference link (from the CIA perspective) to the UE coincide. This would entail that: 1) the OFDM and CIA signal are simultaneously received by the UE, achieving a perfect synchronization between them, 2) CSI w.r.t. the channel needed by CIA to design the linear precoder is available at the AP, the latter already disposing it for resource allocation purposes. Consequently, the two fundamental conditions to ensure the effectiveness of CIA would always be satisfied in this case. Therefore, let $\mathbf{x} \in \mathbb{C}^{N+L}$ be the new signal transmitted by the AP, such that $\mathbf{x} = \mathbf{x}_\mathrm{o} + \mathbf{x}_\mathrm{c}$, with $\mathbf{x}_\mathrm{c} \in \mathbb{C}^{N+L}$ as the new CIA signal, whose construction is detailed in the following[4].

Consider $\mathbf{H}$ and $\overline{\mathbf{H}}$, as introduced in Sec. II. For the rank-nullity theorem we have that

$$\operatorname{rank}(\mathbf{H}) = \operatorname{rank}(\overline{\mathbf{H}}) + \operatorname{rank}(\ker(\overline{\mathbf{H}})), \tag{8}$$

thus, since $\overline{\mathbf{H}}$ has full rank by construction, then $\operatorname{rank}(\ker(\overline{\mathbf{H}})) = L$, $\forall \mathbf{h} \sim \mathcal{CN}(0, \mathbf{I}_{l+1}/(l+1))$. If we let $\mathbf{s}_\mathrm{c} = [s_{\mathrm{c},1}, \ldots, s_{\mathrm{c},L}]^\mathrm{T} \sim \mathcal{CN}(0, \mathbf{\Phi})$ be an input vector with covariance matrix $\mathbf{\Phi} = \mathrm{d}(\boldsymbol{\phi}) = \mathbb{E}[\mathbf{s}_\mathrm{c}\mathbf{s}_\mathrm{c}^\mathrm{H}] \in \mathbb{R}^{L\times L}$, where $\boldsymbol{\phi} = [\phi_1, \ldots, \phi_L]^\mathrm{T}$ is an L-sized vector carrying the power associated with each of its symbols, and $\phi_i = s_{\mathrm{c},i}s_{\mathrm{c},i}^* \in \mathbb{R}_0^+$, then we know from [14] that a semi-unitary precoder $\mathbf{E} \in \mathbb{C}^{(N+L)\times L}$, such that $\mathbf{x}_\mathrm{c} = \mathbf{E}\mathbf{s}_\mathrm{c}$ and

$$\overline{\mathbf{H}}\mathbf{E} = \mathbf{0}_{N\times L}, \tag{9}$$

can always be found. In other words, a CIA precoder which satisfies (9) can precode any input signal $\mathbf{s}_\mathrm{c}$ (i.e., complex-, real-, constant-, random-valued), and align it to the CP of the OFDM block at the receiver. This is guaranteed by the rank-nullity theorem, which ensures that $\dim(\ker(\overline{\mathbf{H}})) = L$, regardless of both the realization of the link between the AP and the UE and the nature of the input signal. Hence, we can proceed to adopt the same strategy to devise the CIA precoder as [14], without impacting the effectiveness of the alignment even though, unlike [14], herein the input signal is not Gaussian. Now, the signal received by the UE reads

$$\mathbf{y} = \mathbf{H}\mathbf{x}_\mathrm{o} + \begin{bmatrix} \mathbf{K} \\ \mathbf{0}_{N\times L} \end{bmatrix}\mathbf{s}_\mathrm{c} + \mathbf{n}, \tag{10}$$

irrespective of $\mathbf{s}_\mathrm{c}$, with $\mathbf{K} \in \mathbb{C}^{L\times L}$ constant-sized matrix $\forall \mathbf{h} \sim \mathcal{CN}(0, \mathbf{I}_{l+1}/(l+1))$.

Let us switch the focus to the CP retrieval element introduced in Sec. IV, whose output is given by the vectors $\mathbf{r}$ and $\mathbf{q}$. If the CIA signal is present these vectors read

$$\mathbf{r} = \overline{\mathbf{H}}\mathbf{A}\mathbf{F}^{-1}\mathbf{s}_\mathrm{o} + \underbrace{\overline{\mathbf{H}}\mathbf{E}\mathbf{s}_\mathrm{c}}_{=0,\ \mathrm{by}(9)} + \bar{\mathbf{n}} \tag{11}$$

[4]In this regard, we note that, the presence of the CIA signal does not increase the bandwidth footprint of the transmission, as compared to the standalone OFDM transmission [29], [30].

and

$$\mathbf{q} = \mathbf{Q}\Bigg(\overline{\mathbf{H}}\mathbf{A}\mathbf{F}^{-1}\mathbf{s}_{\mathrm{o}} + \mathbf{n}\Bigg) + \mathbf{K}\mathbf{s}_{\mathrm{c}}. \tag{12}$$

Consider the vector representing the signal ready for the DFT element. If we compare (2) and (11) we clearly see that no contribution due to the CIA signal is present in the latter. Thus, the UE does not suffer from any undesired interference after the CP retrieval, despite the composite transmit strategy adopted by the AP. On the other hand, if we compare (3) and (12), the impact of the CIA transmission on the portion of the signal corresponding to the CP at the UE is evident, due to the presence of the component $\mathbf{K}\mathbf{s}_{\mathrm{c}}$ in (12).

At this stage, it is worth noting that the signal received within the CP by the UE carries only a portion of the power allocated to the OFDM information symbols at the AP, by construction. Conversely, all the power allocated to the CIA transmission is received within the CP at the UE, regardless of the nature of the channel, thanks to the properties of the CIA precoder $\mathbf{E}$, as in (10). As a consequence, CIA can be seen as a very efficient means to implement the WPT in OFDM transmissions, and a composite OFDM/CIA transmit strategy could increase the self-sustainability of the communication. However, this increase comes at a cost for the AP in terms of achievable downlink information rate. In fact, in this case, the transmit power budget at the AP is shared between the OFDM and the CIA signals, such that $\frac{1}{\Gamma}\operatorname{tr}[\mathbf{P}] + \operatorname{tr}[\mathbf{\Phi}] \leq P_{\mathrm{M}}$. As a matter of fact, an increase in $\operatorname{tr}[\mathbf{\Phi}]$ would reduce the achievable information rate, due the average SNR reduction at the UE resulting from the lower power allocated to the OFDM signal. In this context, a flexible power sharing strategy depending on the requirements of the OFDM transmission, in terms of both downlink rate and self-sustainability, could be adopted by the AP to determine the portion of power budget to devote to the CIA signal. This way, the most suitable power allocation policy could be chosen from a wide spectrum of solutions. A detailed analysis of the impact of different power budget sharing strategies on the performance on both energy and information transfer is provided in Sec. V.

1) Feasibility conditions: To derive the feasibility conditions for the self-sustainability of the composite OFDM transmission we can follow the same approach as in Sec. IV-1. For the sake of compactness, we can directly start from the problem identified in (5) and rewrite it to incorporate the CIA component as

$$\begin{aligned} \min_{L\in\mathbb{N}} \quad & L && (13)\\ \text{s.t.} \quad & \beta \operatorname{tr}\big[\mathbf{QHAF}^{\mathrm{H}}\mathbf{PFA}^{\mathrm{H}}\mathbf{H}^{\mathrm{H}}\mathbf{Q}^{\mathrm{H}} + \\ & \quad +\mathbf{QHE\Phi E}^{\mathrm{H}}\mathbf{H}^{\mathrm{H}}\mathbf{Q}^{\mathrm{H}}\big] - \delta P_d \geq 0 && \text{(a)}\\ & \tfrac{1}{\Gamma}\operatorname{tr}[\mathbf{P}] + \operatorname{tr}[\mathbf{\Phi}] - P_{\mathrm{M}} \leq 0 && \text{(b)}\\ & p_i \geq 0 && \text{(c)}\\ & \phi_j \geq 0, && \text{(d)}\\ & L \geq l, && \text{(e)} \end{aligned}$$

$\forall i \in [1, N]$ and $\forall j \in [1, L]$. As for the case analyzed in Sec. IV-1, (13) is an integer programming problem, whose solution cannot be found in closed form. However, as before, we focus on the constraints in (13) and let $\mathbf{T} = \mathbf{QHE} = [\mathbf{t}_1, \mathbf{t}_2, \ldots, \mathbf{t}_L] \in \mathbb{C}^{L\times L}$. Furthermore we let $||\mathbf{t}_1||^2 \leq ||\mathbf{t}_2||^2 \leq \cdots \leq ||\mathbf{t}_L||^2$ for the sake of simplicity in the further derivations, but without loss of generality. Then, the $N + 4$ constraints can be rewritten as

$$\begin{cases} \sum_{i=1}^{N} p_i||\mathbf{g}_i||^2 + \sum_{j=1}^{L}\phi_j||\mathbf{t}_j||^2 - & & \\ \qquad\qquad -\frac{\delta}{\beta}P_d & \geq & 0\\ -\frac{1}{\Gamma}\sum_{i=1}^{N} p_i - \sum_{j=1}^{L}\phi_j + P_{\mathrm{M}} & \geq & 0\\ p_i & \geq & 0, \quad \forall i \in [1, N]\\ \phi_j & \geq & 0, \quad \forall j \in [1, L]\\ L - l & \geq & 0. \end{cases} \tag{14}$$

The feasibility of (14) is fundamental to assess if a solution to (13) can be found. In this regard, we note that, if $\phi_j = 0,\ \forall j \in [1, L]$, then the composite OFDM transmission would degenerate into the previously discussed case. Similarly to the previous case, (14) is an overdetermined linear system of inequalities, thus the following result holds.

Lemma 2: The minimization problem given by (13) admits a solution if and only if

$$\begin{cases} l \leq N(\mathbf{g}_i^*\frac{\xi\beta}{\delta} - 1), & \text{if} \quad \mathbf{t}_j^* \leq \mathbf{g}_i^*\\ l \geq \frac{N(\frac{\delta}{\beta} - \mathbf{t}_j^*\xi)}{\xi(\mathbf{t}_j^* - \mathbf{g}_i^*) - \frac{\delta}{\beta}}, & \text{if} \quad \mathbf{t}_j^* > \frac{\frac{\delta}{\beta} + \mathbf{g}_i^*\xi}{\xi}\\ l < \frac{N(\frac{\delta}{\beta} - \mathbf{t}_j^*\xi)}{\xi(\mathbf{t}_j^* - \mathbf{g}_i^*) - \frac{\delta}{\beta}}, & \text{otherwise,} \end{cases} \tag{15}$$

with $\mathbf{g}_i^* = \max\{||\mathbf{g}_i||^2\}$ and $\mathbf{t}_j^* = \max\{||\mathbf{t}_j||^2\}$.

Proof: See Appendix B. □

B. Non-emptiness of $\mathcal{P}$

Lemma 1 and 2 guarantee that if (7), or (15), is fulfilled, then $\mathcal{P}$ is non-empty. However, the non-emptiness of $\mathcal{P}$ does not necessarily imply that $\mathbf{p}_{\mathrm{W}} \in \mathcal{P}$. In other words, the full self-sustainability may not always be possible when the AP adopts a WF power loading strategy to maximize the downlink rate.

Nevertheless, if we relax the full self-sustainability constraint, i.e., if we let $\delta < 1$, and look at (a) in (5), or in (13), it is straightforward to see that a suitable value for δ such that $\mathbf{p}_{\mathrm{W}} \in \mathcal{P}$ can always be found, if a non-zero line-of-sight channel path exists. Once the non-emptiness of $\mathcal{P}$ is verified, a suitable value for L can be set by the AP depending on the performance metric of interest. In our case, the choice can be made according to two policies. In case of pure rate maximization approach, we would have $L = l$, ignoring the probability of full self-sustainability of the OFDM transmission and accepting the risk of performance detriment, in case of wrong time synchronization at the receiver. Alternatively, if the AP aims at increasing either the tolerance to synchronization errors or the probability of full self-sustainability (or both), at the expense of the downlink rate, then any L, such that $l \leq L \leq N(\max\{||\mathbf{g}_i||^2\}\xi\frac{\beta}{\delta} - 1)$, could be suitable. In the latter case, an exhaustive search over L to determine optimal CP size would involve a low number of iterations, i.e., upper bounded by $N - l$, due to the structure of the OFDM transmission.

V. Numerical analysis

A set of Monte-Carlo simulations has been performed to assess the merit of the proposed scheme and characterize its performance. The amount of power that can be scavenged on average from the CP by the UEs is computed for several system configurations. For computational tractability, we let $N \in \{128, 256\}$ and $L \in [\frac{9}{128}, \frac{1}{4}]N$, as in the OFDM configuration for the LTE downlink [15]. We assume frequency-selective Rayleigh fading channel vectors of size $l+1$ taps, with uniform power delay profile (PDP), as done for the description of the signal model in Sec. II. Since we consider an AP aiming at a downlink rate maximization (and also due to space limitations), in the following we will restrict our analysis to the case $l = L$, and assume perfect synchronization at the receiver. A WF power loading strategy is performed by the AP to maximize the downlink rate. The efficiency of the energy harvester at the UE is taken to be $\beta = 0.5$, as usually done in the literature [5], [6], and as a realistic first approximation of the performance of state-of-the-art prototypes and products [31]–[37].

In accordance with realistic implementations, practically relevant values are considered for both P_{M} and P_{d}, i.e., $P_{\text{M}} = [3.5, 5]$ W [19] and $P_{\text{d}} = 500$ mW [20], [21]. In this regard, the parameter ξ, as introduced in the enunciate of Lemma 1, provides a compact way to convey the information on both P_{M} and P_{d}. Accordingly, it will be used in the presentation of the obtained results in the remainder of the section, for the sake of compactness, to represent the different considered system configurations. In practice, according to both the aforementioned values of P_{M} and P_{d} and to the definition of this parameter, i.e., of $\xi = \frac{P_{\text{M}}}{P_{\text{d}}}$, in the following we will consider $\xi = [7, 10]$. Finally, we note that with this work we aim at taking a first step towards a complete characterization and realization of self-sustainable OFDM transmissions. Therefore, parameters such as the antenna and RF amplifier gains, distance-dependent path-loss, to name a few, will not be taken into account in the considered scenarios. The relevance of the obtained results could be significantly undermined by an inappropriate choice for these parameters. Nevertheless, the proposed model could be suitably extended to account for a detailed link budget model, owing to the flexibility provided by its parametric description, without modifying the structure of the problem formulation. This will be the subject of a future investigation.

A. Legacy OFDM transmission

Let P_{F} be the probability of full self-sustainability of the OFDM transmission if the feasible set is non-empty, i.e., $P_{\text{F}} = Pr\{\mathbf{p}_{\text{W}} \in \mathcal{P} | \mathcal{P} \neq \emptyset\}$. As a first study, we numerically compute P_{F} for the considered OFDM configurations. Accordingly, we let $\delta = 1$ and depict P_{F} in Fig. 3, as L changes, for $N = 128$. As can be seen from Fig. 3, P_{F} increases with L for all the considered valued of ξ. This is a rather intuitive result. In fact, a larger CP size allows the UE to harvest more energy from the received signal, regardless of the channel realization. In this regard, the impact of the channel on the probability of full self-sustainability can be appreciated if we analyze the impact that different values of ξ have on P_{F}. In order to better characterize this aspect, let us consider the physical meaning of the condition described by Lemma 1,

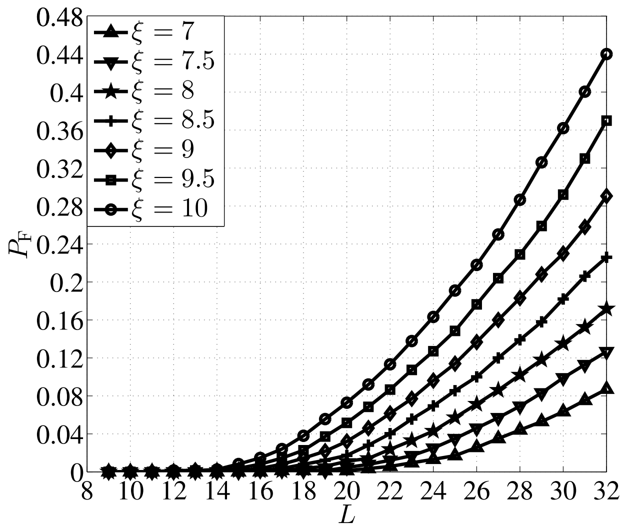

Fig. 3. Probability of full self-sustainability if the feasible set $\mathcal{P}$ is non-empty, as L changes, $N = 128$ sub-carriers.

i.e., eq. (7). As a matter of fact, the condition in (7) depends on the state of the channel between the AP and the UE. Thus, if we fix β and δ, then (7) is satisfied for low ξ only in the case when $\max\{||\mathbf{g}_i||^2\}$ is high. In other words, the dependency of the amount of power that can be harvested at the receiver from the CP on the power allocation at the transmitter is lower in case of very good channel conditions [13]. Accordingly, the larger ξ the higher P_{F}. On the other hand, if we focus on the quantitative behavior of P_{F}, the impact of the power allocation on the self-sustainability of the transmission is evident $\forall \xi \in [7, 10]$. More precisely, when the WF strategy is adopted at the transmitter and (7) is satisfied, the probability that the full self-sustainability can be achieved is lower than 0.5, irrespective of the value of ξ. This confirms the non-optimality of the classic WF in the considered scenario. However, this does not imply that transmission can only achieve low levels of self-sustainability, as will be shown in the following. Now, we let $N = 256$ and show the corresponding behavior of P_{F} in Fig. 4. We start by noting that the possible values that L can assume are necessarily different in the two cases, by construction. Despite this observation, the difference between the two cases is qualitatively negligible. However, an interesting quantitative difference can be noticed when the number of sub-carriers increases from $N = 128$ to $N = 256$. In practice, P_{F} is higher for $N = 128$, if $\xi \leq 8.5$, whereas it is lower elsewhere. Accordingly, let us study the two regions of ξ, i.e., $\xi \leq 8.5$ and $\xi > 8.5$, separately. To understand the behavior of P_{F} for $\xi \leq 8.5$, we take a step back and focus on the high peak to average power ratio (PAPR) affecting any OFDM block in the time domain. The PAPR causes a very uneven power distribution within the OFDM block, CP included [38]. The number of peaks present inside the CP necessarily depends on L. Therefore, if ξ is not sufficiently high, they may induce a significant non-linear reduction of the average power per

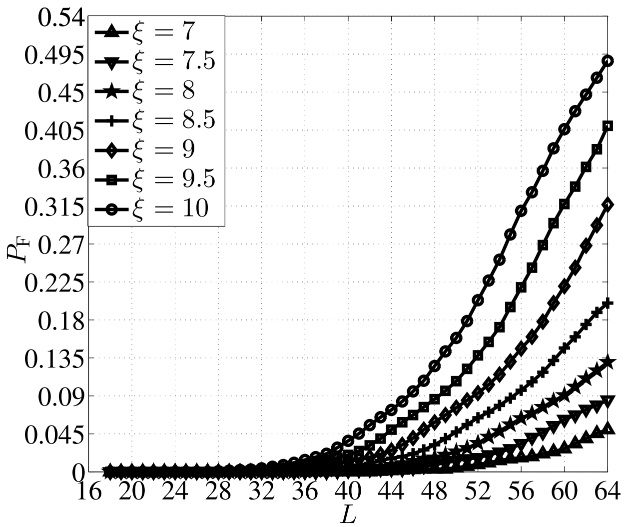

Fig. 4. Probability of full self-sustainability if the feasible set $\mathcal{P}$ is non-empty, as L changes, $N = 256$ sub-carriers.

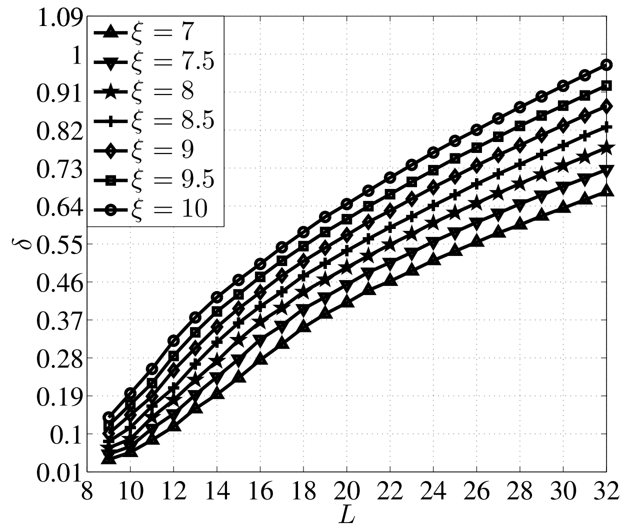

Fig. 5. Average level of self-sustainability δ, as L changes, $N = 128$ sub-carriers.

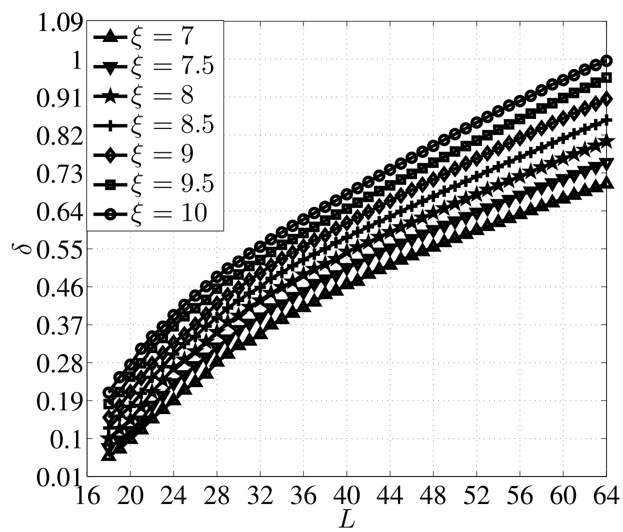

Fig. 6. Average level of self-sustainability δ, as L changes, $N = 256$ sub-carriers.

symbol at the receiver. Thus, the higher N the larger this reduction w.r.t. more uniform power distributions is likely to be. This effect is emphasized by the considered uniform PDP of the channel. Different PDPs may significantly alter the effect of the PAPR on the feasibility of self-sustainability, thus will be matter of future research. We now consider the region $\xi > 8.5$. In this case, ξ is sufficiently high to overcome the aforementioned reduction of average power per symbol, thanks to the higher power carried by the peaks present inside the CP. Accordingly, the probability of finding a sufficiently high $\max\{||\mathbf{g}_i||^2\}$ that satisfies (7) increases, regardless of ξ, due the greater diversity between the different $||\mathbf{g}_i||^2$ as N grows. The previous intuition about the role of $\max\{||\mathbf{g}_i||^2\}$ on the feasibility of the self-sustainability is confirmed.

We switch our focus to the less restrictive adaptive case, i.e., $\delta < 1$, as discussed in Sec. IV. With this second study, we aim at identifying the amount of power that can be scavenged on average from the CP, regardless of P_{F}. Accordingly, we compute δ, for $N = 128$ as L changes, in Figure 5. We start by noting that remarkable levels of partial self-sustainability are obtained throughout the considered range of ξ. More specifically, the maximum supported δ as L changes varies between 0.67 (for $\xi = 7$) and 0.98 (for $\xi = 10$). This result complements and further characterizes the results in Fig. 3. As a matter of fact, this comparison shows that the low achieved values of P_{F} are due to a very large variance of the set of achievable levels of self-sustainability. This confirms the aforementioned impact of the PAPR on the power distribution within the CP, which can induce a large variety of results and, in turn, reduce the probability of full self-sustainability when the WF strategy is adopted. In particular, this impact decreases as ξ and L grow, as shown in Fig. 5. In practice, on one hand both larger transmit power budgets and CP sizes result in higher average levels of self-sustainability. On the other hand, they reduce the variance of the set of higher average levels of self-sustainability, and contribute to achieve a more consistent performance. In this sense, the extent of the non-optimality of the WF strategy strongly depends on the specific scenario. Similar insights can be drawn from the results depicted in Fig. 6, where $N = 256$ and ξ varies within the same range as in the previous test (i.e., P_d is independent of N).

As expected, the full self-sustainability is not guaranteed on average in this case as well, even if a remarkable performance is achieved in this sense. In particular, the maximum δ, obtained for the highest considered ξ, as expected, is around 0.99 if the aforementioned OFDM extended CP mode is adopted, i.e., $L = \frac{N}{4}$. In this regard, the qualitative behavior of δ as L changes is very similar to the previous case. Nevertheless, the obtained values are quantitatively higher than

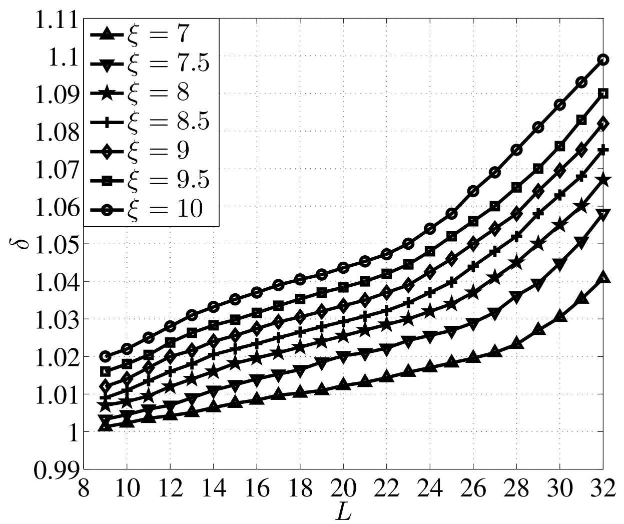

Fig. 7. Maximum average level of self-sustainability δ^* for the composite transmission, as L changes, $N = 128$ sub-carriers.

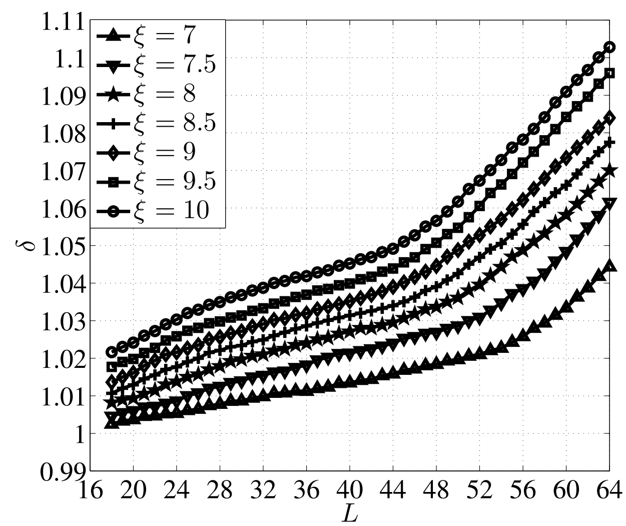

Fig. 8. Maximum average level of self-sustainability δ^* for the composite transmission, as L changes, $N = 256$ sub-carriers.

for $N = 128$. This is due to the twofold positive impact that the number of sub-carriers has in satisfying the result of Lemma 1, given the practically relevant power consumption model considered for the OFDM digital signal processing at the receiver [20], [21]. In fact, on one hand the aforementioned larger diversity of the $||\mathbf{g}_i||^2$, experienced as N grows, renders the condition in (7) easier to satisfy. On the other hand, for any given instance of all the other parameters and variables in (7), we can easily verify that the probability of satisfying Lemma 1 increases with N. We conclude by noting that, as in the previous case, this result complements the results in Fig. 4, for which similar insights can be drawn.

B. Composite OFDM transmission

Consider the case for which the AP can arbitrarily alter the amount of power that is concentrated in the CP at the UE, as described in Sec. IV-A. Let $P_{\mathrm{O}} = \frac{\mathrm{tr}(\mathbf{P})}{\Gamma}$ and $P_{\mathrm{C}} = \mathrm{tr}(\mathbf{\Phi})$ be the power budgets for OFDM and CIA transmissions, respectively, such that $P_{\mathrm{M}} = P_{\mathrm{O}} + P_{\mathrm{C}}$. In particular, since the sole purpose of the CIA signal is the WPT, we assume that all the symbols in $\mathbf{s}_{\mathrm{c}}$ carry the same power, i.e., $\phi_i = \frac{P_{\mathrm{C}}}{L}$, $\forall i \in [1, L]$, for simplicity. We aim at characterizing the enhancement brought by the introduction of the composite scheme over the legacy OFDM model, in terms of self-sustainability of the transmission. Consequently, in the remainder of the section, we will let $P_{\mathrm{O}} \in [0, P_{\mathrm{M}}]$ and numerically evaluate $\delta(P_{\mathrm{O}})$, that is the achievable average power that can be scavenged by the UE from the CP for each of the considered values of P_{O}. Finally, we will identify and discuss both $\delta^* = \max\{\delta(P_{\mathrm{O}})\}$ and the value of P_{O} for which this is achieved, that is P_{O}^*.

Now, similar to what we did for the legacy OFDM case, we start by considering $N = 128$ and depict δ^* as L changes, in Fig. 7. By comparing these results with Fig. 5 (in which $\delta^* = \delta$, since $P_{\mathrm{O}} = P_{\mathrm{M}}$ for the legacy case) we clearly see that the composite scheme brings an advantage in terms of average energy scavenged by the UE, regardless of the CP size. Specifically, values of L for which the full self-sustainability is achieved can be found $\forall \xi \in [7, 10]$, whereas for the legacy OFDM transmission this is never verified. Quantitatively, the maximum supported δ^* varies between 1.04 (for $\xi = 7$) and 1.09 (for $\xi = 10$), confirming the enhancement w.r.t. the previous case. The effectiveness of this approach is more evident for short CP sizes, i.e., in the left part of the plot, where the effect of the CIA component of the signal on the energy that can be scavenged by the UE is significant. However, a more consistent performance w.r.t. the legacy OFDM case is achieved throughout the whole considered range of CP sizes. In particular, we note that δ^* is always larger than 1. In other words, the advantage brought by the composite approach decreases as the CP size increases, even though a better performance w.r.t. the legacy case when $N = 128$ is achieved $\forall L$. In practice, the average energy scavenged by the UE is up to twenty-fold more than the result for the legacy OFDM case for short CP sizes, and is up to 52% larger for extended CP size (when $\xi = 7$). Let us now increase the number of adopted sub-carriers, i.e., $N = 256$, and compute the corresponding δ^* in Fig. 8. The effectiveness of the composite approach is confirmed in this case as well, for which the enhancement in terms of self-sustainability brought over the standard OFDM transmission is very similar to the case $N = 128$. As before, a very consistent performance is achieved throughout the whole considered range of CP sizes, with maximum supported δ^* varying between 1.405 (for $\xi = 7$) and 1.105 (for $\xi = 10$). In particular, the full self-sustainability of the transmission is achieved $\forall \xi \in [7, 10]$.

The nature of these results can be better understood if we study the behavior of P_{O}. Let $\eta = \frac{P_{\mathrm{O}}}{P_{\mathrm{M}}}$ and $\eta^* = \frac{P_{\mathrm{O}}^*}{P_{\mathrm{M}}}$ be the portion of total power budget that is dedicated to the OFDM signal in the composite scheme and its value for which δ^*

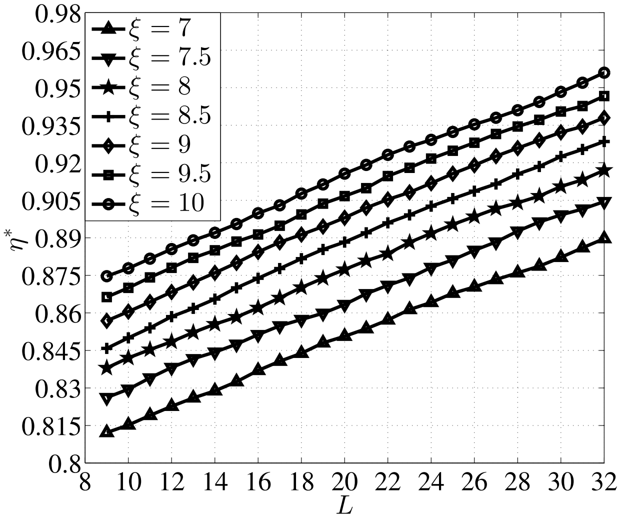

Fig. 9. Portion of the power budget dedicated to the OFDM signal to achieve the maximum average level of self-sustainability δ^*, as L changes, $N = 128$ sub-carriers.

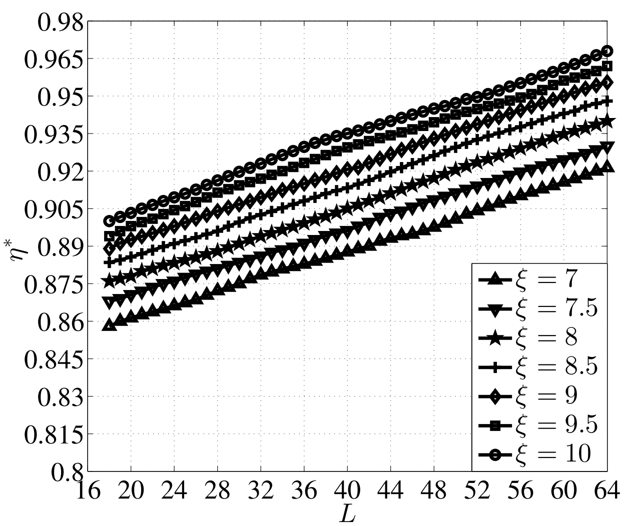

Fig. 10. Portion of the power budget dedicated to the OFDM signal to achieve the maximum average level of self-sustainability δ^*, as L changes, $N = 256$ sub-carriers.

is achieved. Accordingly, we can let L and ξ vary in the ranges so far considered and depict in Fig. 9 and Fig. 10 the values of η^* for which the results shown in Fig. 5 and Fig. 6, respectively, are achieved. Let us start from the case $N = 128$. As it could be expected, P_{O}^* increases with the CP size. In fact, as previously seen, the performance of the legacy OFDM transmission for large L and $N = 128$ is already significant. Specifically, we see that when $L = \frac{N}{4}$, $\eta^* = 0.89$ for $\xi = 7$ and $\eta^* = 0.955$ for $\xi = 10$. If we focus on the left part of the plot, i.e., short CP sizes, we see that the remarkable results shown in the same portion of Fig. 7 are obtained when η^* is between 0.81 and 0.85 when $\xi = 7$ and between 0.875 and 0.915 when $\xi = 10$. The same trend is present when $N = 256$, confirming the previous observations.

At this stage, we note that the adopted value for η, hence the corresponding CP size to achieve the maximum level of self-sustainability, affects not only δ but also the achievable downlink rate for the OFDM transmission, in both the considered cases. On one hand, the CP size reduction, made possible by the presence of the CIA signal in the composite scheme, leads to an increase in the pre-log factor (i.e., the *multiplexing gain*) in (4) due to a lower number of channel uses. On the other hand, a lower available transmit budget for the OFDM signal necessarily reduces the average signal-to-noise ratio (SNR) per symbol at the receiver. A multiplexing gain has a higher impact on the achievable rate of the transmission than a SNR gain/loss at the receiver [13], however assessing the impact of the power penalty potentially experienced by the OFDM signal in the composite case is not straightforward. In this regard, we note that by comparing Fig. 9 and 10, η^* is higher for $N = 256$ than for $N = 128$, irrespective of the CP size. Hence, if the AP aims at achieving the full self-sustainability of the transmission then a larger number of adopted sub-carriers induces a lower power penalty for the OFDM signal. In practice, the impact of the presence of the CIA signal on the downlink rate of the OFDM transmission decreases as N grows, whereas an opposite trend is evident w.r.t. the self-sustainability. However, inferring further conclusions on the achievable rate of the proposed composite scheme is certainly a non-trivial task. As a consequence, an appropriate study on the downlink rate, in light of the introduction of the composite approach, and the design of suitable power allocation policies to achieve either a target rate or a given level of self-sustainability (or a flexible combination of both) for the OFDM transmission, is matter of our future research.

VI. Conclusion

In this paper, we proposed a novel approach to prolong the battery life of an OFDM receiver, exploiting the concept of WPT. We first introduced a novel OFDM receiver architecture that does not discard the CP but exploits it to extract power from the received baseband signal, effectively realizing a WPT between the transmitter and the receiver. Subsequently, we increased the flexibility of the proposed solution by designing a composite transmit strategy to provide the transmitter with the capability of altering the amount of power concentrated in the cyclic prefix arbitrarily, thus the amount of energy that can be scavenged from the CP at the receiver. In this scheme, the signal generated by the OFDM transmitter is obtained as the combination of the standard OFDM and a newly generated CIA signal. We have introduced and discussed the concept of self-sustainable OFDM transmission in terms of power consumption of the digital signal processing at the receiver, and analytically derived the feasibility conditions to achieve it for both transmit strategies, as a function of an adaptive scaling parameter that models different degrees of self-sustainability. Our numerical findings show that, under reasonable conditions, the amount of power carried in the CP could be sufficient to achieve remarkable levels of self-sustainability, for both the legacy and composite OFDM transmission. In particular, the feasibility of the full self-sustainability is substantiated by the consistent performance of the composite strategy for several system configurations. A dependence of such performance on several practical aspects is evident, e.g., channel PDP, accuracy of the CSI at the transmitter, considered link budget models, PAPR at the receiver and implementation details of the CP retrieval block. In this regard, in a follow-up of this work we will deal with these aspects ans study their impact on the effectiveness of the proposed approach. Further, future research directions include the analysis of the impact that the introduction of the composite approach has on the OFDM downlink rate, and the design of suitable power allocation strategies to achieve a target performance in terms of both rate and self-sustainability of the transmission.

Appendix A
Proof of Lemma 1

Proof: We can prove the existence of a solution to (6) by means of the Fourier-Motzkin elimination (FME) algorithm [39]. The FME can be iteratively applied to a system of linear inequalities to obtain, at each step, a system of the same kind but without a variable of the original system. This is achieved by pairing the inequalities in which the variable to eliminate appears with opposite sign, such that both systems have the same solutions over the remaining variables. The existence (or nonexistence) of a solution to the system of constant inequalities obtained at the last step of the FME is a sufficient and necessary condition for the existence (or nonexistence) of a solution to the original system.

We write the system obtained at the first step of the algorithm as

$$\begin{cases} \sum_{i=2}^{N} p_i(||\mathbf{g}_i||^2 - ||\mathbf{g}_1||^2) & \geq & -\Gamma||\mathbf{g}_1||^2 P_{\mathrm{M}} + \frac{\delta}{\beta} P_d \\ -\frac{1}{\Gamma}\sum_{i=2}^{N} p_i & \geq & -P_{\mathrm{M}} \\ p_i & \geq & 0, \quad \forall i \in [2, N] \\ L - l & \geq & 0. \end{cases} \tag{16}$$

Subsequently, we can generalize (16) for the jth step of the algorithm as follows. Let $||\mathbf{g}_j||^2$ be the coefficient associated with the variable eliminated by the FME at this step. We define $||\mathbf{g}_0||^2 = 0$ and let $\mathcal{G}_j$ be the set including all the $||\mathbf{g}_i||^2$, such that $(||\mathbf{g}_i||^2 - ||\mathbf{g}_j||^2) \neq 0$. As a consequence, we can express the system obtained at the jth step as

$$\begin{cases} \sum_{i\in\mathcal{G}_j} p_i(||\mathbf{g}_i||^2 - ||\mathbf{g}_j||^2) & \geq & -\Gamma||\mathbf{g}_j||^2 P_{\mathrm{M}} + \frac{\delta}{\beta} P_d \\ -\frac{1}{\Gamma}\sum_{i=j+1}^{N} p_i & \geq & -P_{\mathrm{M}} \\ p_i & \geq & 0, \quad \forall i \in [j+1, N] \\ L - l & \geq & 0. \end{cases} \tag{17}$$

By iterating the FME until the last variable has been eliminated, we obtain the system of constant inequalities

$$\begin{cases} \frac{N}{N+L}||\mathbf{g}_N||^2 P_{\mathrm{M}} - \frac{\delta}{\beta} P_d & \geq & 0 \\ L - l & \geq & 0, \end{cases} \tag{18}$$

regardless of whether $||\mathbf{g}_N||^2 = ||\mathbf{g}_i||^2$, $\forall i \in [1, N]$ or not, as can be trivially verified by looking at (17). Therefore, the necessary and sufficient condition for which (5) admits a solution is given by the condition for which (18) is true, that is $l \leq N(||\mathbf{g}_N||^2 \frac{P_{\mathrm{M}}\beta}{\delta P_d} - 1) = N(||\mathbf{g}_N||^2 \xi \frac{\beta}{\delta} - 1)$, and this concludes the proof. □

Appendix B
Proof of Lemma 2

Proof: As for Lemma 1, we can prove the existence of a solution to (14) by means of the FME algorithm.

We write the system obtained at the first step of the algorithm as

$$\begin{cases} \sum_{i=2}^{N} p_i(||\mathbf{g}_i||^2 - ||\mathbf{g}_1||^2) + & & \\ +\sum_{j=1}^{L} \phi_j(||\mathbf{t}_j||^2 - ||\mathbf{g}_1||^2) & \geq & -\Gamma||\mathbf{g}_1||^2 P_{\mathrm{M}} + \frac{\delta}{\beta} P_d \\ -\frac{1}{\Gamma}\sum_{i=2}^{N} p_i - \sum_{j=1}^{L}\phi_j & \geq & -P_{\mathrm{M}} \\ p_i & \geq & 0, \quad \forall i \in [2, N] \\ \phi_j & \geq & 0, \quad \forall j \in [1, L] \\ L - l & \geq & 0. \end{cases} \tag{19}$$

Profiting from the results in Appendix A, we can write the Nth step as

$$\begin{cases} \sum_{j=1}^{L} \phi_j(||\mathbf{t}_j||^2 - ||\mathbf{g}_N||^2) & \geq & -\Gamma||\mathbf{g}_N||^2 P_{\mathrm{M}} + \frac{\delta}{\beta} P_d \\ -\sum_{j=1}^{L}\phi_j & \geq & -P_{\mathrm{M}} \\ \phi_j & \geq & 0, \quad \forall j \in [1, L] \\ L - l & \geq & 0. \end{cases} \tag{20}$$

At this stage, if $||\mathbf{t}_L||^2 \leq ||\mathbf{g}_N||^2$ then $(||\mathbf{t}_j||^2 - ||\mathbf{g}_N||^2) \leq 0$, $\forall j \in [1, L]$ and each following step of the algorithm will just eliminate the corresponding variable, with no modification to the constant terms of the inequalities. As a consequence, in this case, the necessary and sufficient condition for which (13) admits a solution coincides with the condition provided in Lemma 1, i.e., $l \leq N(||\mathbf{g}_N||^2 \frac{P_{\mathrm{M}}\beta}{\delta P_d} - 1)$.

Now, let us consider the case $||\mathbf{t}_L|^2 > ||\mathbf{g}_N||$ and define $\mathcal{H} = \{\mathbf{g}_N, \mathbf{t}_j \ \ s.t. \ ||\mathbf{t}_j||^2 - ||\mathbf{g}_N||^2 > 0\}$ as the set given by $\mathbf{g}_N$ and all the columns of the matrix $\mathbf{T}$ whose squared norm is larger than the squared norm of $\mathbf{g}_N$. We first note that if $||\mathbf{t}_L||^2 = ||\mathbf{t}_j||^2$, $\forall j \in [1, L]$, then the solution is the same as in the previous step, as can be trivially verified by looking at (20). On the other hand, if there exists a j such that $||\mathbf{t}_L||^2 > ||\mathbf{t}_j||^2$, then we can let $\mathcal{H}^*_{\mathbf{t}_L} = ||\max\{\mathcal{H} \setminus \{\mathbf{t}_L\}\}||^2$ and directly write both the output of the $(N + L - 1)$th step of the algorithm as

$$\begin{cases} \phi_L(||\mathbf{t}_L||^2 - & & \\ -\mathcal{H}^*_{\mathbf{t}_L}) & \geq & -P_{\mathrm{M}}[\mathcal{H}^*_{\mathbf{t}_L} - ||\mathbf{g}_N||^2(1-\Gamma)] + \frac{\delta}{\beta} P_d \\ -\phi_L & \geq & -P_{\mathrm{M}} \\ \phi_L & \geq & 0 \\ L - l & \geq & 0, \end{cases} \tag{21}$$

and the system of constant inequalities obtained at the $(N + L)$th step of the FME as

$$\begin{cases} \xi[||\mathbf{t}_L||^2 - ||\mathbf{g}_N||^2(1-\Gamma)] + \frac{\delta}{\beta} & \geq & 0 \\ L - l & \geq & 0. \end{cases} \tag{22}$$

Therefore, the necessary and sufficient condition for which

(13) admits a solution, if $||\mathbf{t}_L||^2 > ||\mathbf{g}_N||^2$, is given by

$$\begin{cases} l \geq \frac{N(\frac{\delta}{\beta}-||\mathbf{t}_L||^2\xi)}{\xi(||\mathbf{t}_L||^2-||\mathbf{g}_N||^2)-\frac{\delta}{\beta}}, & \text{if} \quad ||\mathbf{t}_L||^2 > \frac{\frac{\delta}{\beta}+||\mathbf{g}_N||^2\xi}{\xi} \\ l < \frac{N(\frac{\delta}{\beta}-||\mathbf{t}_L||^2\xi)}{\xi(||\mathbf{t}_L||^2-||\mathbf{g}_N||^2)-\frac{\delta}{\beta}}, & \text{otherwise,} \end{cases} \tag{23}$$

and this concludes the proof. □

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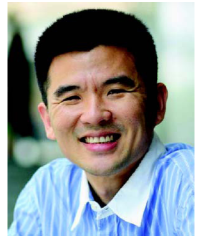

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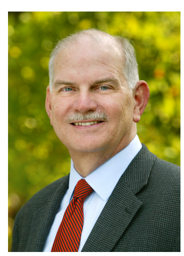

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