Citation for published version:
Ahmed Bannour, Claudio Sacchi, and Yichuang Sun, 'MIMO-OFDM Based Energy Harvesting Cooperative Communications Using Coalitional Game Algorithm', *IEEE Transactions on Vehicular Technology*, Vol. 66 (12): 11166-11179, December 2017.

DOI:
https://doi.org/10.1109/TVT.2017.2768622

Document Version:
This is the Accepted Manuscript version.
The version in the University of Hertfordshire Research Archive may differ from the final published version.

MIMO-OFDM Based Energy Harvesting Cooperative Communications Using Coalitional Game Algorithm

Ahmed Bannour, Claudio Sacchi, *Senior Member, IEEE,* and Yichuang Sun, *Senior Member, IEEE*

***Abstract*—In this paper, we consider the problem of cooperative communication between relays and base station in an advanced MIMO-OFDM framework, under the assumption that the relays are supplied by electric power drawn from energy harvesting (EH) sources. In particular, we focus on the relay selection, with the goal to guarantee the required performance in terms of capacity. In order to maximize the data throughput under the EH constraint, we model the transmission scheme as a non-transferable coalition formation game, with characteristic function based on an approximated capacity expression. Then, we introduce a powerful mathematical tool inherent to coalitional game theory, namely: the Shapley value (Sv) to provide a reliable solution concept to the game. The selected relays will form a virtual dynamically-configured MIMO network that is able to transmit data to destination using efficient space-time coding techniques. Numerical results, obtained by simulating the EH-powered cooperative MIMO-OFDM transmission with Algebraic Space-Time Coding (ASTC), prove that the proposed coalitional game-based relay selection allows to achieve performance very close to that obtained by the same system operated by guaranteed power supply. The proposed methodology is finally compared with some recent related state-of-the-art techniques showing clear advantages in terms of link performance and goodput.**

***Index Terms*—MIMO, OFDM, Cooperative Communications, Energy Harvesting, Game Theory.**

I. Introduction

As stated in [1], Energy Harvesting (EH) could represent an interesting and innovative approach to build long-term and self-sustainable wireless networks, such as wireless sensor networks (WSNs) in remote human-unfriendly environments, mobile network infrastructures deployed in areas not reached by stable power sources (this is of particular interest in the framework of the reduction of the *Digital Divide* in developing countries) and, last but not the least, environmental-friendly networking installations, capable of saving carbon-based power through the exploitation of renewable sources.

In Fig. 1, the Bits-per-Joule energy efficiency vs. transmit rate is shown for the case of bursty data transmission, given a constant power supply. As demonstrated in [2], this curve is typically quasi-concave. Therefore, the data rate (expressed in b/s/Hz) that maximizes the number of bits to be transmitted using a Joule of energy, denoted by r_{ee}, can be efficiently obtained by a simple bi-sectional search [1]. Similar considerations can be done also for the EH case. The key difference is that, in presence of EH, the transmission rate depends *also* on the availability of the energy harvested from external unstable sources. When the energy source is stable, the transmission system switches from “off” to “on” status (and vice-versa) simply on the basis of the energy efficiency requirements and the optimum data rate r_{ee} is computed. When the energy is harvested from unstable sources, the switching is activated by specific events related to the harvesting [1]. In such a framework, QoS optimization should satisfy some specific energy efficiency constraints involved not only by the natural necessity of saving power but also by the randomness of the harvesting process [1], [3], [4].

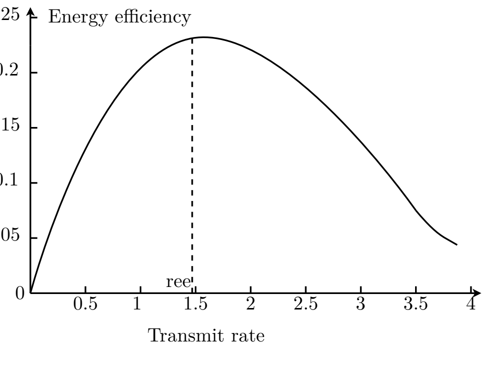

Figure 1. Bits-per-Joule energy efficiency versus transmission rate r in the case of stable power supply [1].

In this paper, we face the problem of QoS provisioning in a cooperative MIMO-OFDM transmission system based on small self-sustainable relay nodes, powered by energy harvesting. MIMO-OFDM provides a powerful, integrated signal-processing tool, capable of exploiting diversity in different domains: space, time and frequency, with augmented efficiency and flexibility [5], [6]. Recent trends of LTE-A design are considering short-range low-power and low-cost base stations to provide ubiquitous services [7]. In a recent paper, Zaidi *et. al* [8] investigated the

A. Bannour is with the University at Carthage, Innov′Com Laboratory, Higher School of Communications of Tunis, Sup′Com, Cité Technologique des Communications Route de Raoued Km 3,5 2083 El Ghazala Ariana Tunisie Tunis, (Tunisia), e-mail: bannour.ahmed@gmail.com.

C. Sacchi is with the University of Trento, Department of Information Engineering and Computer Science (DISI), Trento, (Italy), e-mail: claudio.sacchi@unitn.it.

Y. Sun is with the University of Hertfordshire, School of Engineering and Technology Hatfield, Herts, AL10 9AB, (UK), e-mail: y.sun@herts.ac.uk

Paper submitted on: Oct. 3, 2016, revised on: Apr. 5, 2017, Jul. 25, 2017, and Sept. 29, 2017. Accepted on: Oct. 28, 2017.

performance of a metro-cellular network made of small cells empowered by solar energy harvesting. Our work that considers the cooperation of energy-harvesting powered relay nodes perfectly fits with the aforesaid topics.

The proposed solution is based on a coalitional game approach [9]. In particular, the cooperative MIMO-OFDM network with energy harvesting at relay nodes is modeled as a Class II non-transferable utility coalition formation game with characteristic function based on an approximated capacity expression and Shapley value (Sv) solution concept. The players of the game are actually the relay nodes and their related radio resources (i.e. OFDM subcarriers). They decide to be part of the coalition and, therefore, to cooperate with the base station on the basis of the actual level of harvested energy. The virtual MIMO network that transmit information to the destination nodes is then configured at each epoch by the relays that belong to the coalition. A robust space-time encoder based on Algebraic Space-Time Coding (ASTC) has been introduced in order to improve the link performance of the cooperative MIMO transmission. The proposed coalitional game-based approach is characterized by computational sustainability, efficiency and flexibility and outperforms the related state-of-the-art solutions in terms of achievable goodput and energy efficiency, yielding to performance very close to that obtained with guaranteed power supply.

The rest of the paper is structured as follows: Section II will discuss the novel contribution of the present work as compared to the state-of-the-art background. Section III describes the MIMO-OFDM relay system and discusses EH strategy and power consumption model. Coalitional game formulation and Shapley value expression are shown in Section IV. Simulation results, comparison with related state-of-the-art techniques and computational complexity are discussed in Section V. Finally, conclusions are drawn in Section VI.

Notice: in the following, symbols $(.)^{\dagger}$, $(.)^{H}$, $\|.\|$ and $(.)^{*}$ stand for the pseudo inverse, Hermitian transpose, Frobenius norm of a matrix, and conjugate, respectively.

II. Background and Innovation

A. State-of-the-art review

MIMO-OFDM techniques are robust and spectrally efficient. However, it is not clear whether they are also energy-efficient [10]. MIMO can support higher data rates under the same power budget than Single-Input Single-Output (SISO) systems, but it consumes more circuit power as multiple RF stages are jointly operated. Moreover, in MIMO-OFDM systems, space-time coding and other baseband processing tasks are carried out at subcarrier level and thus the circuit power consumption increases with the number of subcarriers. Long-range communication systems powered by stable energy sources typically target the minimization of the RF transmitted power only. But, when short range applications are considered, using wireless sensors or, as in our case, small relay nodes powered by unstable energy sources, the circuit energy consumption may become a serious issue [11]. An added challenge in the above considerations is that mobile terminals and base stations do not have access to perfect channel state information (CSI). Imperfect CSI knowledge may severely impair power and rate allocation to subcarriers. Indeed stochastic fluctuations of CSI and observation noise make optimization techniques that rely on a greedy “one-off” calculation of optimal transmit characteristics (such as waterfilling) to fail in providing optimal radio resource distribution, with a consequential waste of power and bandwidth [12].

Cooperative MIMO techniques and relaying are regarded by the current literature as viable solutions to the critical tradeoff between energy efficiency and quality-of-service in mobile communication systems operated by non-durable and/or unstable power sources. In [13], the selection of the best transmitter subset minimizing power consumption in cooperative MIMO WSNs is implemented, considering different network configurations (intracluster node-to-node multihop and cluster-to-cluster multihop) and using different algorithms (maximum spanning tree searching and singular-value decomposition). Another paper facing the issues of energy efficiency in WSNs is [14], where data aggregation and cooperative MIMO techniques are adopted in order to control the energy consumption per bit. In [15], the tradeoff between energy and information transfer in a relay-based MIMO-OFDM two-hop wireless network with energy harvesting is investigated. Joint optimal source and relay frequency precoders are designed to efficiently balance the above mentioned tradeoff. In [16], authors investigated how the QoS requirements can be guaranteed in RF energy-harvested cognitive OFDM relay systems. Efficient strategies for power splitting and radio resource allocation have been proposed in [16] to satisfy the QoS requirements in the presence of limited energy and spectrum shortage. The simultaneous wireless information and energy transfer for non-regenerative MIMO-OFDM relaying systems has been considered in [17]. In this work, two relaying protocols have been proposed, namely: Time Switching-based Relaying (TSR) and Power-Splitting-based Relaying (PSR) with optimization of end-to-end information rate for both, under the assumption of ideal CSI knowledge. The optimal broadcast scheduling for energy-harvesting powered transmitter with non-ideal circuit power consumption has been dealt in [18]; in particular low complexity policies to maximize the weighted sum-throughput for MIMO broadcast channels have been formally derived. In [19], the authors proposed an optimal resource allocation strategy for MIMO relay system with energy harvesting in simultaneous wireless information and energy transfer networks. Closed-form solutions for time and power allocation have been derived and tested in [19].

In some recent works, theoretical game-based approaches have been considered to face the problem of QoS provisioning in cooperative relaying systems with energy harvesting. Game theory [20] provides a highly sophisticate mathematical tool, which has been widely used in many fields of economics, social science, physical sciences and engineering to solve NP-complete optimization problems with affordable computational complexity. Several game models have been proposed, which are classified into non-cooperative and cooperative. Non-cooperative game theory models the actions of agents maximizing their utility in a defined procedure, relaying on a detailed description of the moves and information available to each agent [21]. Cooperative game theory models how agents compete and cooperate as coalitions in unstructured interactions to create and capture value. For this reason, cooperative games are called *coalitional*, while non cooperative games are called *procedural* [21].

Cooperative game theory analyses situations where agents can cooperate to create value by joining coalitions, but also where agents compete to capture value [21]. Its formalism considers a set of agents and a function that returns the values that each subset of agents called *coalition* can create (*characteristic function*). The characteristic function is actually the input to a *solution concept*, which returns the value captured by each agent, called *imputation.* In cooperative games, the bargaining procedure is not structured like in the non-cooperative counterpart; therefore, the solution concept simply models the negotiations occurring among the agents, accounting for the value created by each coalition [21]. The best known solution concept of cooperative games is the *core* [9] [21]. The core is a set of imputations under which no coalition has a value greater than the sum of its member payoffs. The core is not the only possible solution concept of a coalitional game. Other solution concepts are indeed available [9] [21].

Although coalitional games play an important role in economics and political science, they are less popular in the wireless world. When a common resource must be shared among several agents, which is the case with wireless medium, mobile devices and relay nodes, coalitional game solutions can prove their robustness.

The state-of-the art framework related to theoretical game-based capacity optimization of cooperative networks with energy harvesting contains some recent papers that deserve citation. Stupia *et. al.* proposed in [22] a non-cooperative bargaining game to optimize the goodput of OFDM-based relaying networks with energy harvesting. Repeated non-cooperative Bayesian Stackelberg game has been employed in [23] for relay selection in EH relay networks. Stackelberg game is also used in [24] to manage the exchange of transmitted data and harvested energy in two-hop wireless networks where the base stations are able to wirelessly power the relays. In [24], the Stackelberg competition is managed in two ways: first the single relay node is the leader of the competition and then the leader role is assumed by the base station. A non-cooperative game is formulated in [25], where each relay link is modeled as a strategic player, who aims at maximizing its own achievable rate. Canzian, Badia and Zorzi in [26] proposed a 2-stage Stackelberg game to promote the relay cooperation in wireless networks. A network unit plays the role of access coordinator that triggers cooperative behaviors, increasing the access opportunities of users acting as relays.

A repeated cooperative game model (known also as *grim-trigger* strategy) has been employed in [27] in order to improve performance of radio resource allocation in a dual-hop LTE network. In [28], the cooperation among the agents in a cooperative network with energy harvesting powered relays has been modeled as a canonical coalitional game with core solution concept. It is shown in [28] that in the large–SNR regime, the grand coalition is stable and always preferred, which means that users acting in coalition cannot do worse than acting alone. In [29], a two-level game has been proposed for joint relay selection and resource allocation in MIMO-OFDM cooperative cognitive radio networks. The first level of the game of [29] is a non-transferable utility coalition graph game, while the Nash Bargaining approach is the second level. In [30], a hedonic coalitional game has been proposed to maximize the capacity of a cooperative broadcast network with simultaneous wireless information and power transfer. In the hedonic games, players may decide to leave a coalition and to join another coalition only on the basis of their own specific preferences, without taking care about how the remaining players are partitioned. It is worth noting that the hedonic coalitional game proposed in [30] clearly outperforms the non-cooperative schemes.

B. Contribution of the paper

Considering the state-of-the-art background analyzed in the previous subsection, coalitional games can offer feasible and reliable solutions to the problem of QoS provisioning in cooperative MIMO networks with unstable power sources. Approaches based on mere mathematical optimization and a-priori fixed relaying protocols like those of [15], [16] [17], [18], and [19] may lack of flexibility in addressing the QoS fluctuations due to unstable power supply and/or may be computationally expensive. Non-cooperative game solutions of [22], [23] [24], [25], and [26], considering bargaining games or Stackelberg games, are inspired to centralized and strictly normative concepts aimed at disciplining the selfish behavior of agents. Such an approach does not seem the best way to model the distributed cooperation typical of MIMO-based relaying with energy harvesting, where agents should harmonize their behavior in order to exploit at their best the radio resources and the limited energy reserves. In such a perspective, results shown in [28] and [30], obtained by different kinds of coalitional games, are very promizing. However, some key issues should still be solved.

The canonical game with core solution concept adopted in [28] is very appropriate to model competitive interactions, introducing a notion of individual and self-interest. However, canonical coalitional game class (namely: *Class I*) does not take into account some critical factors in cooperative relaying with energy harvesting, basically: the network structure that might change in different transmission epochs, depending on harvesting and channel conditions, and the cost involved for cooperation. Moreover, the core may be empty, too large or the allocation that lies in the core can be unfair for some players of the game [9] [21]. When the core is empty, the related solution concept simply does not exist, revealing the intrinsic instability of the considered interaction. When the core is too large, the selection of a suitable core allocation may be difficult and inefficient [9]. In the last case, some players may be unsatisfied by the payoff allocation of the core and may have the will to leave the coalition. The solution proposed in [29] is interesting from the formal viewpoint, but the proposed two-level cooperative game is computationally expensive and requires the relaxing of some constraints in order to become tractable. The hedonic game solution proposed in [30] is conceptually attractive, but also computationally prohibitive. Indeed, as shown in [31], to decide whether a hedonic game admits a stable core, Nash equilibrium or an individual stable outcome is a NP-complete problem.

In order to overcome the aforesaid issues, we propose a coalition formation game with non transferable utility and Shapley value as solution concept. Different from canonical coalitional games, coalition formation games, known also as *Class II* coalitional games, better model the time varying conditions of power supply and channel propagation. Unfortunately, the core computation for coalition formation games not only suffers from inefficiencies similar to those noticed in canonical coalitional games, but also, is generally characterized by prohibitive computational complexity [9]. On the other hand, the Shapley value, named in honor of Lloyd Shapley who proposed it in 1953, attributes a unique payoff vector to all the agents in coalition by means of an axiomatic approach [9]. Shapley value is unique, much easier to be computed and it emphasizes the fairness of the division of the value among agents [21]. By virtue of its own properties, Sv solution concept well meets the requirements of our cooperative MIMO scenario, characterized by the necessity of efficiently sharing the radio resources (namely: the OFDM subcarriers) to maximize a global utility (i.e.: the network capacity), under the constraint of unstable power supply. From the algorithmic viewpoint, this is the main innovative contribution of our paper; indeed, to the best of our knowledge, coalition formation game with Sv-based solution concept has not yet been applied either in cooperative networking or in energy harvesting management.

Another remarkable difference of the proposed approach from the state-of-the-art contributions is related to the dynamic configuration of the MIMO-OFDM network directly managed by the coalition formation game. Indeed, the coalition is formed, epoch by epoch, promoting the cooperation between the base-station and those relays that can guarantee the best quality-of-service, under the EH power constraint. The relays in coalition then form the virtual MIMO network that transmits the information to the destination. Such a cooperative and dynamic reconfiguration of the virtual MIMO network structure has been considered for WSNs (see e.g. [13]), but is not straightforward in cooperative relaying.

From the viewpoint of mobile communication techniques, a significant contribution of the present work concerns with the adoption of a robust MIMO space-time coding technique, namely the Algebraic Space-Time Coding (ASTC) [32], [33], in order to improve the link performance of the cooperative relaying system. The superiority of ASTC over orthogonal space-time block coding (OSTBC) has been clearly demonstrated in [33], in particular for number of transmit antennas higher than two. To the best of our knowledge, no published contribution deals with the use of ASTC in cooperative MIMO-OFDM networks with energy harvesting. The performance improvement yielded by ASTC will be shown in Section V.

III. System Model

A. ASTC-MIMO-OFDM transmission for cooperative relaying

Let us consider the cooperative communication system model of Fig. 2. The source node (Base station) is equipped with n_t antennas, while the n_r relay nodes have a single antenna. The transmitted binary message sequence s_k is QAM-modulated. The QAM symbols are then ASTC encoded. ASTC coding has been proposed in [32]–[34], which have the structure of full-rate and full diversity 2×2, 3×3, 4×4, and 6×6 space-time codes. These codes are characterized by a constant minimum determinant as the spectral efficiency increases. These features are expected to be helpful to mitigate the link performance degradation involved by energy harvesting.

We denote with $\boldsymbol{v}_k = [s_{4k-3}, s_{4k-2}, s_{4k-1}, s_{4k}]^T$ the ASTC encoder input at the k^{th} signaling interval and $\boldsymbol{C}_{k,G}$ and $\boldsymbol{C}_{k,T}$ the related encoder output for the Golden Codes (GC) and Tast Codes (TC) respectively, as shown in eq. (1) and eq. (2) (see page 5). The ASTC output is then fed to n_t OFDM modulators, each with n_c subcarriers and cyclic prefix (CP) of length n_g. We denote the ASTC codeword sent to the OFDM modulator with $\boldsymbol{x}_k \in \mathcal{C}^{n_c n_t \times 1}$, while $x_{n,k}$ is the MIMO codeword transmitted over the n^{th} subcarrier at the signaling period k. The overall vector of length $n_c + n_g$ is transmitted over a frequency-selective and time-varying MIMO channel. The CP length n_g is assumed to exceed the largest multipath delay spread in order to remove inter-symbol interference. The k^{th} MIMO-OFDM symbol $\boldsymbol{u}_k \in \mathcal{C}^{n_t(n_c+n_g)\times 1}$ is then given by $\boldsymbol{u}_k = \boldsymbol{\xi}_1\sqrt{n_c}(\boldsymbol{F}^{-1}\otimes \boldsymbol{I}_{n_t})\boldsymbol{x}_k$ where $\boldsymbol{F}^{-1}$ is the $\mathcal{C}^{n_c n_c\times 1}$ Fourier matrix, whose $(n,k)^{\text{th}}$ element is $\exp\left(-j2\pi nk/n_c\right)$, $\otimes$ denotes the Kronecker product, $\boldsymbol{I}_{n_t}$ represents the n_t identity matrix, and $\boldsymbol{\xi}_1 \in \mathcal{C}^{n_t(n_c+n_g)\times n_c n_t}$ is the CP adding matrix given by $\boldsymbol{\xi}_1 = \left[\begin{pmatrix} 0 & \boldsymbol{I}_{n_g} \\ & \boldsymbol{I}_{n_c}\end{pmatrix} \otimes \boldsymbol{I}_{n_t}\right]$.

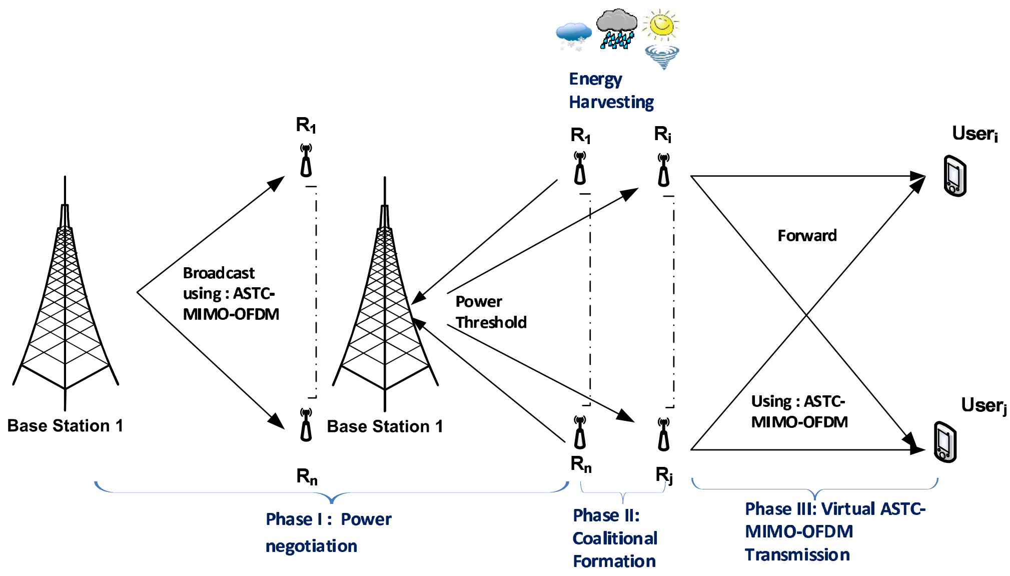

Figure 2. Cooperative MIMO-OFDM communication system with energy harvesting using coalitional game-based transmission strategy.

$$\boldsymbol{C}_{k,G} = \frac{1}{\sqrt{5}} \begin{pmatrix} \alpha\,(\boldsymbol{v}_k[1] + \theta\,\boldsymbol{v}_k[2]) & \alpha\,(\boldsymbol{v}_k[3] + \theta\,\boldsymbol{v}_k[4]) \\ \overline{\alpha}\,(\boldsymbol{v}_k[3] + \overline{\theta}\,\boldsymbol{v}_k[4]) & \overline{\alpha}\,(\boldsymbol{v}_k[1] + \overline{\theta}\,\boldsymbol{v}_k[2]) \end{pmatrix} \tag{1}$$

where:

$$\theta = \frac{1+\sqrt{5}}{2};\ \overline{\theta} = \frac{1-\sqrt{5}}{2};\ \alpha = 1 + i - i\theta;\ \overline{\alpha} = 1 + i - i\overline{\theta}$$

$$\boldsymbol{C}_{k,T} = \frac{1}{\sqrt{2}} \begin{pmatrix} (\boldsymbol{v}_k[1] + \theta\,\boldsymbol{v}_k[2]) & \varphi\,(\boldsymbol{v}_k[3] + \theta\,\boldsymbol{v}_k[4]) \\ \varphi\,(\boldsymbol{v}_k[3] - \theta\,\boldsymbol{v}_k[4]) & (\boldsymbol{v}_k[1] - \theta\,\boldsymbol{v}_k[2]) \end{pmatrix} \tag{2}$$

where:

$$\theta = \exp(i\lambda); \qquad \lambda \in \Re; \qquad \varphi = \theta^2$$

The signal received by the p^{th} receiving antenna during the k^{th} MIMO-OFDM symbol period is expressed as,

$$\boldsymbol{y}_k^p = \sum_{q=1}^{n_t} \sum_{l=0}^{L-1} h_k^{p,q}(l)\boldsymbol{u}_k^q(k-l) + \boldsymbol{w}_k^p \tag{3}$$

where $\boldsymbol{u}_k^q$ is the symbol vector transmitted by the q^{th} antenna and $\boldsymbol{w}_k^p$ is the zero mean white Gaussian complex noise of variance $\frac{N_0}{2}$. Let us define the equivalent channel matrix $\boldsymbol{G}_k \in \mathcal{C}^{n_t(n_c+n_g)\times n_t(n_c+n_g)}$. We can thus express the received MIMO-OFDM signal $\boldsymbol{y}_k \in \mathcal{C}^{n_r(n_c+n_g)\times 1}$ in matrix notation as,

$$\boldsymbol{y}_k = \boldsymbol{G}_k\boldsymbol{u}_k + \boldsymbol{w}_k \tag{4}$$

where $\boldsymbol{w}_k \in \mathcal{C}^{n_r(n_c+n_g)\times 1}$ represents the AWGN noise sample. After CP removal, the received signal is converted to the frequency domain by means of a DFT operation. The signal at the DFT output is then given by $\boldsymbol{z}_k = \frac{1}{\sqrt{n_c}}\left[(\boldsymbol{F}\otimes\boldsymbol{I}_{n_t n_r})\boldsymbol{\xi}_2\right]\boldsymbol{y}_k$, where the CP removal matrix $\boldsymbol{\xi}_2 = [\boldsymbol{0}_{n_c n_g}\boldsymbol{I}_{n_g}]\otimes\boldsymbol{I}_{n_g}$ discards the first $n_g n_r$ elements of $\boldsymbol{y}_k$. Thus, we can reformulate the DFT output signal as

$$\begin{aligned} \boldsymbol{z}_k &= \left[(\boldsymbol{F}\otimes\boldsymbol{I}_{n_t n_r})\boldsymbol{\xi}_3(\boldsymbol{F}^{-1}\otimes\boldsymbol{I}_{n_t n_r})\right]\boldsymbol{x}_k + \boldsymbol{w}_k \\ &= \boldsymbol{H}_k\boldsymbol{x}_k + \boldsymbol{w}_k \end{aligned} \tag{5}$$

where the block circulant matrix $\boldsymbol{\xi}_3 \in \mathcal{C}^{n_t n_c\times n_r n_c}$ is defined as $\boldsymbol{\xi}_3 = \boldsymbol{\xi}_2\boldsymbol{G}_k\boldsymbol{\xi}_1$ and $\boldsymbol{w}_k$ is the frequency domain Gaussian noise with zero mean and variance σ_w^2 and $\boldsymbol{H}_k$ is $\mathcal{C}^{n_t n_c\times n_c n_t}$ frequency domain matrix defined as $\boldsymbol{H}_k = \left[(\boldsymbol{F}\otimes\boldsymbol{I}_{n_t n_r})\boldsymbol{\xi}_3(\boldsymbol{F}^{-1}\otimes\boldsymbol{I}_{n_t n_r})\right]$.

B. Energy harvesting and power consumption model

Renewable energy is harvested from nature and then cumulated in a rechargeable battery. The harvested energy level depends on the occurrence of energy arrivals. The energy state changes when the renewable energy is captured. We assume that the arrival rate of harvested energy is a stochastic process obeying to the Poisson law and thus parameterized by the Poisson frequency λ_e [18].

Between two energy arrivals, the channel state may also change. We suppose that there are $n+1$ channels or energy level modifications times, $0 = t_0 < \ldots < t_n = T$ over the entire transmission interval $[0, T]$. We define an epoch as the interval between two consecutive energy level changing instants whose duration is denoted by $L_i = t_i - t_{i-1}, i = 1, \ldots, n$, with $\sum_{i=1}^{n} L_i = T$. The following set describe the energy arrival process $(a_m, Hr_m, St_m, Us_m, Px_m)$, $m = 0, 1, \ldots, M$, where M denotes the number of energy arrivals, a_m denotes the epoch index of the m^{th} energy arrival time, Hr_m denotes the amount of arriving (harvested) energy, St_m denotes the stored power, and Us_m is the power consumed at time t_{a_m}. The total power transmitted by the relay at time t_{a_m} is given by,

$$Px_m = H_{r_m} + S_{t_m} - U_{s_m} \tag{6}$$

On the basis of the comparison of $Px_m = H_{r_m} + S_{t_m}$ with a fixed threshold ξ, the relay will decide to cooperate with the base station and other relays or to remain in stand-by, i.e.:

$$\begin{cases} Px_m = Hr_m - St_m + Us_m \geq \xi & \text{Tx is On} \\ Px_m = Hr_m - St_m + Us_m < \xi & \text{Tx is Off} \end{cases} \tag{7}$$

The choice of ξ depends on the required energy needed to process the current data. In the threshold-checking selection, the source chooses the relay with the highest harvested energy that is capable to instantiate the real-time instruction in the current epoch. It is demonstrated that threshold-checking selection yields to better performance in terms of achieved capacity, although requiring global channel knowledge during each transmission epoch.

IV. Coalitional Game for Cooperative MIMO-OFDM Transmission Systems with EH

A. Coalitional game theory

Generally speaking, coalitional game theory aims at answering two fundamental questions:

- Which coalition among agents should be formed?
- How should that coalition divide its payoff among its members?

Three formal entities define a coalitional game [9]:

- The set of all the players in the game, denoted by $\mathcal{N}$;
- The characteristic function of the game: $v : 2^{\mathcal{N}} \mapsto \mathbb{R}$;
- The coalition structure defined as: $\mathcal{S} = \{S_1, \ldots S_n\}, \mathcal{S} \subseteq \mathcal{N}$.

Cooperative games are subdivided into two main categories: canonical (Class I) and coalition formation (Class II) games [9]. In canonical games, the formation of large coaltions is always advantageous to any of the involved players. In other words, no group of players will perform worse by cooperating. This property is called *superadditivity*. They key point of canonical game is represented by the *coalition stability*, i.e., no formed coalition should have the convenience to upset the reached agreement. The objectives of the canonical games are: i) to study the stability of the grand coalition $\mathcal{N}$, formed by all the players in the game and ii) to study how the payoff amount received, $v(\mathcal{N})$, should be split among the players (*allocation fairness*). For this reason, canonical coalitional games are defined by the couple $(\mathcal{N}, v)$ [9].

Coalition formation games are suitable for modeling real-world situations where network structure and cost of cooperation play a major role. The coalition formation game is generally not superadditive. Also in coalition formation games, forming a coalition brings gains to its members, but the gains are limited by a cooperation cost (in canonical games, such a cost is negligible). Therefore, the main objective of a Class II coalitional game is to study the coalition structure $\mathcal{S}$, namely: the optimal selection of the players in coalition, the optimal coalition size, etc. The presence of a cost for forming coalitions implies that some negotiation or information exchange is necessary in order to decide how the coalition is structured. Moreover, in Class II games, the coalition structure is imposed by a factor external to the game (*physical restriction* [9]). As a result, we have the coalition structure $\mathcal{S}$, which is not unique, like in the canonical game case. Hence, coalition formation games are defined by the triplet $(\mathcal{N}, v, \mathcal{S})$.

If it exists, the core solution concept $C(v)$ for a coalitional game is the set of imputations $(x_1, x_2, \ldots, x_i, \ldots x_n)$ that satisfies the following condition [9]:

$$C(v) = \left\{ x \in \Re^{\mathcal{N}} : \sum_{i \in \mathcal{N}} x_i = v(\mathcal{N}) ; \sum_{i \in S} x_i \geqslant v(S) \, \forall S \subseteq \mathcal{N} \right\} \tag{8}$$

In other words, the core is the set of imputations where no coalition $\mathcal{S} \subseteq \mathcal{N}$ has an incentive to reject the reached payoff allocation and deviate from the grand coalition. The existence of the core of coalitional games is not always guaranteed [9]. In many games, the core is empty and hence it is not applicable as solution concept. If the core is not empty, it does not necessarily contain a unique imputations vector. This implies that competitive forces alone are not enough to univocally determine agent's captured value [21] and that negotiating capabilities also come into the play. As a consequence, the core generally admits a continuum of solutions. As stated in [9], if the core is not unique and becomes too large, it can be very difficult to select a suitable core allocation. In order to be used as a reliable prediction tool, the core should also verify the stability conditions. The core is stable if two conditions are satisfied: i) no payoff vector is dominated by another vector in the core (*internal stability*), ii) all payoff vectors outside the core are dominated by at least one vector in the core (*external stability*) [9]. It has been demonstrated in [35] that if the core is stable, it is also the unique stable imputations set. But, if the stability property is not verified, the payoff allocation is unfair for some individual players and they may want to leave the grand coalition.

In order to overcome the core drawbacks, the literature [9] [21] suggests to define a different solution concept which can associate to each coalitional game a unique payoff vector known as *the value* of the game. Such solution concept is known as *Shapley value*. The Shapley value, described in the following subsection, offers an efficient alternative solution to Class I games, avoiding potential deficiencies of core solution and, as demonstrated in [9], it represents a feasible and theoretically meaningful solution also for Class II games, where the use of the core is hindered by the presence of coalition structure and physical restriction.

B. Normative approach: the Shapley value

Shapley addressed the problem of finding a possible solution concept to a coalitional game by means of an axiomatic approach [9]. Shapley assigns to the game a unique vector of payoffs, called the value. Let us consider a vectorial function $\Psi(\bullet)$ that associates for each coalitional game v a payoff vector $\Psi(v) \in \mathbb{R}^n$, where $\Psi_i(v) \in \mathbb{R}$ is the prediction payoff of player i in the game v. The Shapley's axioms are the following:

1) *Symmetry* : For any coalitional game v, any permutation π and any player i, $\Psi_i(\pi(v)) = \Psi_{\pi^{-1}(i)}(v)$.
2) *Dummy* : For any coalitional game v, and any dummy coalition[1], $\boldsymbol{D}$, $\sum_{i\in\mathbb{R}} \Psi_i(v) = v(\boldsymbol{D})$.
3) *Additivity*: For any coalitional game v and w, $\forall p \in [0,1]$ and any player i, $\Psi_i(pv + (1-p)w) = p\Psi_i(v) + (1-p)\Psi_i(w)$.

There is exactly one and only one function Ψ satisfying the axioms of Shapley:

$$\Psi_i(v) = \sum_{\boldsymbol{S}\subset\boldsymbol{N}\setminus\{i\}} \frac{|\boldsymbol{S}|! \times (|\boldsymbol{N}| - |\boldsymbol{S}| - 1)!}{|\boldsymbol{N}|!} \times [v(\boldsymbol{S}\cup\{i\}) - v(\boldsymbol{S})] \tag{9}$$

where $|\boldsymbol{S}|$ is the cardinal of set $\boldsymbol{S}$, $k! = 1 \times 2 \times 3 \ldots \times k$ and $0! = 1$. The Shapley value is not generally related to the core in canonical coalitional games [9]. However, in some applications, it can be demonstrated that the Shapley value lies in the core. This is verified, for instance, for convex games [9]. As far as coalition formation games are concerned, it has been demonstrated in [9] that the Shapley value axioms still hold also in presence of physical restriction and coalition structure $\mathcal{S}$. Therefore, Sv-based concept solution is still applicable to the generated coalition. On the other hand, the canonical definition of the core in Class II games is substantially modified by the presence of the coalition structure and the restriction does not apply to the core [9]. This is motivated by the fact that the core depends on all the possible coalitions of $\mathcal{N}$. This implies that the core depends on the values of the coalitions $S_j \in \mathcal{S}$ as well as on the values of the coalitions $S_j \notin \mathcal{S}$. It is clear that the problem of finding the core of $(\mathcal{N}, v, \mathcal{S})$ is much more complex than computing the Shapley value, in particular for non transferable utility games or dynamic formation games [9]. These motivations, widely discussed in the literature, lead us to consider the Shapley value as the most appropriate solution for our problem.

[1] $v(C \cap \boldsymbol{D}) = v(C)$, if a player is not in $\boldsymbol{D}$, it is useless.

C. Proof of existence of the Nash equilibrium

Fink in [36] generalised the Shapley value concept to n players and he proved that, when the Shapley value solution concept exists, the Nash equilibrium is reached. In Appendix C, the main steps of the proof are summarized.

D. The proposed Class II coalitional game algorithm

The model of the proposed coalitional game will be designed on the basis of the system presented in section III, either for uplink (UL) or downlink (DL) channel. The proposed scheme will be modeled as a $(\mathcal{N}, v, \boldsymbol{S})$ coalition formation game with non transferable utility. We believe that such a theoretical game is the best tool to model the cooperation of base-station and relays in the presence of energy harvesting. Indeed, the relay selection to optimize network capacity depends on the channel and energy harvesting status that may change epoch by epoch. Thus, a dynamic coalition structure, taking into account these time-varying factors, is strongly envisaged.

The base station of the cell must allocate a subcarrier n_i to each relay before transmission. In terms of coalitional game theory, each subcarrier n_i is identified as a player in the game. So the grand coalition will be defined as $\mathcal{N} = \{0, \ldots, N = n_c n_t\}$, while v is the utility function resulting from a coalition $\boldsymbol{S}$, based on the QoS requirement in terms of data rate R_{n_i}, and, finally, $\boldsymbol{S}_l = \{n_1 \ldots, n_l\}$ contains a partition of $\mathcal{N}$. We shall consider in our game the transferable utility assumption for the players of a formed coalition, so that the payoffs attributed to such a coalition may be freely redistributed among its members. However, the payoff of a coalition is not transferred to another coalition successively formed during the game. Moreover, we assume that $v(\emptyset) = 0$; this last assumption is satisfied whenever a universal payoff policy is used in the game and means that a single payoff value can be assigned to each coalition. In the following propositions, we shall demonstrate the existence of the Shapley value for the proposed coalitional game.

Proposition-1: The proposed game has a non-transferable utility and the utilities of all members of $\mathcal{N}$ are the same.

Proof-1:

All the relays belonging to $\mathcal{N}$ will lose communication ability, if there is no harvested power, and the network configuration will no longer be the same. We design the utility function $v(\boldsymbol{S}_l)$ based on transmission process in terms of data rate R_{n_i}; hence the utilities of relays are as [37], [38],

$$R_{n_i}^{S_l} = \log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c n_i P_h^2\right]\right) \forall n_i \in \boldsymbol{S}_l, \forall S_l \in \mathcal{N} \tag{10}$$

where P_h denotes the mean power to each channel coefficient in time domain. The coalition value $v(\boldsymbol{S}_l) \in \mathbb{R}^{|\boldsymbol{S}_l|}$ is given by:

$$v(\boldsymbol{S}_l) = \left\{ R_{n_i}^{\boldsymbol{S}_l} \in \mathbb{R} \mid R_{n_i}^{\boldsymbol{S}_l} = \log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c n_i P_h^2\right]\right)\right\} \tag{11}$$

where $|\boldsymbol{S}_l|$ denote the number of relays in $\boldsymbol{S}_l$. ■

Proposition-2: For the proposed game $(\mathcal{N}, v, \boldsymbol{S})$ with the final coalition $\boldsymbol{S}_l = \{n_1 \dots, n_l\}$, the Shapley axioms are true and the function Ψ exists.

Proof-2:
The three Shapley's axioms should be satisfied by the proposed payoff $v(\boldsymbol{S}_l)$ distribution. The Ψ function in (9) satisfying the axioms of Shapley should verify the following properties:
Symmetry: a permutation π is a bijection $\pi : N \rightarrow N$. Given a permutation π and the presented coalitional game v, πv is the coalitional game obtained swapping the indices of the players n_i. So for any player $n_i \in \boldsymbol{S}_l$, $\pi v(\boldsymbol{S}_l) = v(\pi^{-1}(\boldsymbol{S}_l))$, then we can conclude that $\Psi_i(\pi(v)) = \Psi_{\pi^{-1}(i)}(v)$.
Dummy: given a player $n_j \notin \boldsymbol{C}$, where $\boldsymbol{C}$ is dummy coalition, So $v(\boldsymbol{D} \cap \boldsymbol{C}) = v(\boldsymbol{D})=\{R_{n_i}\}_{\forall i \neq j,(i,j)\in \mathbb{R}^2}$, which is equal to $\sum_{i\in\mathbb{R}} \Psi_i(v)$.
Additivity: for any player n_i and $p \in [0, 1]$, let us consider two coalitional games v_1 and v_2. We have $\Psi_i(pv_1) = K_1 \sum_{z=1}^{i} pv_1^i$, where $K_1 = \sum_{\boldsymbol{S}\subset \boldsymbol{N}\setminus\{i\}} \frac{|\boldsymbol{S}|!\times(|\boldsymbol{N}|-|\boldsymbol{S}|-1)!}{|\boldsymbol{N}|!}$ is an integer constant representing the residual set after adding the player i. $\Psi_i((1-p)v_2) = K_1 \sum_{z=1}^{i}(1-p)v_2^i$, hence $\Psi_i(pv_1) + \Psi_i((1-p)v_2) = K_1(\sum_{z=1}^{i} pv_1^i + \sum_{z=1}^{i}(1-p)v_2^i) = \Psi_i(pv_1 + (1-p)v_2)$. ■

By now, we are sure about the existence of the Shapley value that can be derived as explained in the following paragraph.

Ψ function derivation: Eq.(9) for the Shapley value can be rewritten by noting that the term inside the summation is a beta function,

$$\frac{|\boldsymbol{S}|! \times (|\mathcal{N}| - |\boldsymbol{S}| - 1)!}{|\mathcal{N}|!} = \beta(n_l + 1, n_c n_t - n_l) = \int_0^1 x^{n_l}(1-x)^{n_c n_t - n_l - 1} dx \quad (12)$$

Thus, the Shapley value can be evaluated by integrating $x^{n_l}(1-x)^{n_c n_t - n_l - 1}$; this requires to evaluate a function whose size doubles every time a new player is added. Obviously, this method has exponential complexity. In order to overcome this problem, we should approximate the integrand in some reliable manner. Assuming that each player n_i cooperates with probability x, independently of other players, a random variable v_i^x is defined that counts the number of cooperative players in the game. In large games with many small weights, v_i^x will be almost normally distributed for the central limit theorem, and the desired probability $x^{n_l}(1-x)^{n_c n_t - n_l - 1} = Pr[\xi - w_i \leq v_i^x \leq \xi]$ can be approximately computed by using the Gaussian distribution function. In the aforesaid expression, $w_i \in \mathbb{R}^+$ stands for the weight of the player n_i. Such a weight is equal to one if the player has enough harvested power level ξ, i.e.,

$$w_i = \begin{cases} 1 & P_{x_m}^i \geq \xi \\ 0 & otherwise, \end{cases} \quad (13)$$

where $w(S^l) = \sum_{i=1}^{l} w_i \geq \acute{\xi}$.

We assume that the channel response remains approximately constant over one ASTC-MIMO-OFDM symbol block. The channel impulse response between the q^{th} transmitting antenna and p^{th} receiving antenna is modeled as a finite-length tapped delay line $\boldsymbol{h}_k^{p,q} = \sum_{l=0}^{L-1} h_k^{p,q}(l)\delta(k-l)$, where $h_k^{p,q}(l)$ is the channel gain related to the l^{th} path from the q^{th} transmit antenna to the p^{th} receive antenna at signaling time k. If Rayleigh fading is considered, the channel tap sequence $\{h_k^{p,q}(l)\}$ is a complex random Gaussian process with zero mean. Then, we can approximate the total power required by the relay as $P_{x_m} = E\left(P_h^2\right) = E\{\boldsymbol{h}_k^{p,q}(l)\left[\boldsymbol{h}_{k-k'}^{m,n}(l')\right]^*\}$. Substituting (12) in (9) gives,

$$\begin{aligned}
\Psi_i(v) &= \sum_{i=1}^{n_l} \int_0^1 x^{n_l}(1-x)^{n_c n_t - n_l - 1} dx \times \quad (14)\\
&\qquad \log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c w_i P_h^2\right]\right)\\
&= \int_0^1 \sum_{i=1}^{n_l} x^{n_l}(1-x)^{n_c n_t - n_l - 1} dx \times\\
&\qquad \log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c w_i P_h^2\right]\right)\\
&\approx \int_0^1 \left(N(\frac{\acute{\xi} - \bar{m}_i^x}{\bar{v}_i^x}) - N(\frac{\acute{\xi} - \bar{m}_i^x - w_i}{\bar{v}_i^x}) \right) d\acute{\xi} \times\\
&\qquad \log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c w_i P_h^2\right]\right)\\
&\approx \log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c w_i P_h^2\right]\right) \frac{w_i(1 - 2\bar{m}_i^x)}{\sqrt{\pi}(\bar{v}_i^x)^2}
\end{aligned}$$

where $\bar{v}_i^x$ and $\bar{m}_i^x$ stand for the variance and the mean v_i^x respectively (see Appendix A for additional details).

E. Game formulation

According to the considered game model, we propose a coalition formation algorithm to implement the cooperative transmission scheme. We assume that each round lasts long enough to enable the coalition formation process and the relays have sufficient processing capabilities to support the game. We suppose also by default that all relays belong to the grand coalition $\mathcal{N}$.

Remark 1: Under the quasi-static assumption made about the channel, since the relay and the base station are fixed and located in the same cell, it is possible to consider the channel matrix $\boldsymbol{H}_k$ as a constant diagonal matrix.

The proposed cooperative game-based approach, hereinafter named: Coalitional ASTC-MIMO-OFDM (CAMO) algorithm, is articulated in three phases, described as follows,

1) *Phase I:* Power negotiation
During Phase I, the proposed algorithm initializes the network on the basis of the power level harvested by each relay ${Px_m}_i^n$. The base station will ask to all the relays present in the grand coalition $\mathcal{N}$ if they have enough harvested power. This is obtained by broadcasting a specific message to the n_r relays,

using ASTC-MIMO-OFDM transmission. If the relay satisfies the threshold condition $Px_m \geq \xi$, it must imperatively send an ACK message to the base station. In fact, the ACK is used just to inform the base station about the current power level measured at each relay. This transmission is processed on the basis of the actual harvested power level. In the case of no information received from one or more relays, the exclusion of such relays from the game is automatically issued. Otherwise, the base station still considers these relay(s) as player(s).

2) *Phase II:* Coalition formation
By sending the ACK, the relay can maintain its position in the grand coalition $\mathcal{N}$, showing its ability to be part of the final coalition $\boldsymbol{S}^l$. Consequently, the base station will allocate the subcarriers n_i to that relay which has enough available power. For any relay, which does not satisfy the threshold condition, its subcarrier n_i will be excluded from the grand coalition $\mathcal{N}$ and the grand coalition $\mathcal{N}$ will be updated as $\mathcal{N} \leftarrow \mathcal{N} \setminus \{n_i\}$ until the formation of the stable coalition $\boldsymbol{S}^l$.

3) *Phase III:* Dynamically-Configured (DC) virtual ASTC-MIMO-OFDM transmission
During this phase, each relay, whose allocated subcarriers are in the final coalition, will form a virtual network with the other relays in coalition and perform an ASTC-MIMO-OFDM data transmission to l mobile terminals, each one provided with a single receive antenna.
During phase III, the relays, which cooperate with the base-station, are not a-priori known. At each epoch i of the transmission process, the set of selected relays may change, so the spatial repartition of the transmitting relays (and their related antennas) will no longer be the same. Under these conditions, we are not dealing anymore with a conventional MIMO-OFDM transmission, where TX/RX antennas are fixed and a-priori known. In our case, the MIMO network configuration can change epoch after epoch depending on the new updated set (relays/users) generated by the coalitional game algorithm on the basis of the time-varying channel conditions and the amount of harvested energy. For this reason, we are speaking about a dynamically-configured (DC) virtual ASTC-MIMO-OFDM transmission. Indeed, the MIMO system is *virtual*, being formed by the selected cooperating single-antenna relays and *dynamically configured*, because the coalition can change during Phase II and the utility of the game is not transferable to the new formed coalition.
The bit-rate offered by the dynamically-configured virtual MIMO network ($R_{offered}$) – resulting from the Sv-based coalitional payoff allocation – is then compared with the bit-rate required to ensure the expected QoS ($R_{demanded}$). If $R_{offered} \geq R_{demanded}$, the ASTC codeword is transmitted in OFDM modality. If the channel conditions change so that $R_{offered} < R_{demanded}$, the game goes back to Phase I and restarts with the power negotiation and the relay selection, issuing a new virtual MIMO configuration. In Fig. 3, the concept of virtual DC ASTC-MIMO-OFDM transmission is pictorially described, showing the dynamic reconfiguration of the virtual MIMO system epoch by epoch. The relay nodes colored in grey are those excluded by the coalition during the Phase II. The EN signal sent to the selected relays indicates that such relays correctly sent the ACK and are then enabled to cooperate with the base station in order to transmit information by means of the established MIMO-OFDM link.

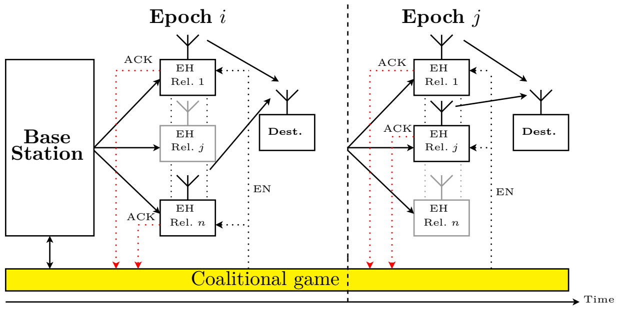

Figure 3. Dynamically Configured (DC) virtual ASTC-MIMO-OFDM transmission: pictorial concept description

The CAMO algorithm can be summarized at a glance by the flow diagram shown in Algorithm 1.

V. Simulation Results and Analysis

A. Performance evaluation methodology

This section will show simulation (*Sim*) and theoretical (*Theore*) results in order to assess the performance of the proposed coalitional game algorithm for cooperative energy-harvested relay networks. Results will be shown for the CAMO algorithm, considering the ASTC MIMO coding, and for CMO (Coalitional MIMO-OFDM) algorithm, not using the ASTC.

We consider a MIMO-OFDM transmission system whose parameters, taken by LTE Release 8, are listed in Table I. We evaluate the performance of the proposed CAMO and CMO algorithms by means of intensive MATLAB simulations. A frequency selective Rayleigh channel is considered during the overall algorithmic phases. To obtain all the numerical results shown in the following of this section, 100000 independent realizations were simulated. Ideal CSI knowledge has been supposed in all our performance evaluation trials.

In order to showcase the robustness of the proposed coalitional game-based algorithm, we introduce in this section the goodput (GP) of the MIMO-OFDM system as reliable performance indicator. When data is transferred over air interfaces, the average transfer speed is often described as throughput. This metric includes all the overhead information, such as packet headers and other data

Algorithm 1 The proposed Coalitional ASTC-MIMO-OFDM (CAMO) algorithm.

Require: $\boldsymbol{N} = n_c n_t, x_l = 0, z = 0, Px_m = 0, R_{offered} = 0$

Phase I: Power negotiation

for $n = 0$ to n_r **do**
  $Px_m^n \leftarrow {Hr_m}^n - {St_m}^n + {Us_m}^n$
  if $(Px_m^n > \xi)$ **then**
    $v \leftarrow [v, n]$
  end if
end for

Phase II: Coalition formation

$(\boldsymbol{S}^l, x_l) \leftarrow (v, length\{\boldsymbol{S}^l\})$ *Set update*
$(n_t, n_r) \leftarrow (x_l, n_t)$
for $n = 0$ to x_l **do**
  $Ack^n \leftarrow \left[(\boldsymbol{F} \otimes \boldsymbol{I}_{n_t n_r})\boldsymbol{\xi}_3(\boldsymbol{F}^{-1} \otimes \boldsymbol{I}_{n_t n_r})\right] \boldsymbol{x}_k + w_k$ *Relays UL Acknowledgement Signal*
end for

Phase III: Virtual ASTC-MIMO-OFDM transmission

$x_l \leftarrow n_l + 1$
for $n = 0$ to x_l **do**
  $\Psi_n \leftarrow \log_2 \left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c n P_h^2 \right] \right)^{\frac{(1-2\bar{m}_n^x)}{\sqrt{\pi}(\bar{v}_n^x)^2}}$
  $R_{offered} \leftarrow \Psi_n + R_{offered}$ *Evaluate the offered rate*
end for
Compare$(R_{offered},\ R_{demanded})$
if $R_{offered} \geq R_{demanded}$ **then**
  Transmission
else
  Goto Phase I
end if

Table I
LTE Rel.8 Downlink Simulation Parameters

System Parameter	**Parameter Value**
Modulation	16-QAM
Bandwidth	20 MHz
Number of subcarriers	$n_c = 128$
Cyclic prefix length	$n_g = \frac{n_c}{4} = 32$
Subcarrier spacing	15 kHz

that are included in the transfer process. It also includes data that are retransmitted because of network conflicts or errors. Goodput only measures the throughput of the useful data and can be calculated by dividing the size of a transmitted packet by the time it takes to be transferred. We adopt in this paper the normalized goodput (GP) metric as defined in [39],

$$GP = GP_{max}(1 - BER) \tag{15}$$

where the maximum normalized goodput, GP_{max}, corresponds to the number of data bits sent per subcarrier. For a MIMO-OFDM system with n_c subcarriers, cyclic prefix of n_g symbols and 8 CRC bits inserted every 120 data bits, the maximum normalized goodput is given by:

$$GP_{max} = \frac{120}{128} \times \frac{n_c}{n_c + n_g} \times log_2\,(M) \tag{16}$$

where M is the number of symbols of the chosen digital modulation constellation.

B. Numerical results

Some preliminary results in terms of bit-error-rate are shown in Fig.4. More precisely, this figure compares the BER performance measured during the three phases (I, II and III) of the proposed cooperative game-based algorithm with and without ASTC, in order to analyze its behavior in the different algorithmic stages. Results look satisfactory mainly when ASTC codes are applied. We can note that, for high and low SNRs, the end-to-end transmission of phase III outperforms in terms of BER phase I and phase II. ASTC coding thus provides better link performance and can significantly contribute to improve the system capacity. In Fig.5, we compare the capacity reached by the proposed MIMO-OFDM system, when the relay energy is harvested and cooperation among the network nodes is enabled and when the energy that empowers the relays is stable and no cooperation is exploited. For sake of clarity and visualization, only the theoretical capacity curve of CMO system has been plotted for the stable energy case. We can note that the capacity offered by the MIMO-OFDM system with stable power supply is only slightly superior to that attained by the same system operating with energy harvesting and cooperation. Moreover, the difference between the simulated capacity results and the corresponding ones computed by means of the analytic equation (14) is not significant. Again, ASTC coding provides an improvement with respect to the uncoded CMO case when energy harvesting is involved. It is clear that the results shown in Fig.5 can provide a first, important, validation to our approach.

Fig. 6 shows the normalized goodput performance vs. average link *SNR*, when our coalitional cooperative game is applied and when the transmission system works with stable energy (in such a case the power level has been fixed to 70 dBmW). For $SNR > 10dB$, the difference between the goodput values reached with or without energy harvesting/cooperation and with 4 or 5 active relays is small. At lower SNRs the goodput loss due to the increased packet error rate mainly occurs when the cooperation between relays increases from 4 to 5 nodes. In any case, fixing the number of active relays, the goodput curves related to stable and harvested energy are very close. This is another evidence of the effectiveness of the proposed theoretical game-based cooperation strategy.

Fig. 7 compare the theoretical goodput with the simulated one for the proposed CAMO algorithm and that achieved by the coalitional game-based transmission strategy for energy harvesting networks presented in [28], which considers canonical Class I game with core solution concept. The coalition is formed by two pairs relays for both the evaluated algorithms. The theoretical goodput has been derived by substituting the simulated BER used in Eq. (15) by the theoretical BER P_e computed in [40],

$$Pe \leq \left(1 + \frac{\sigma_s^2}{4\sigma_n^2} n_t + \sum_{i=1}^{N_i} \lambda_i + (\frac{\sigma_s^2}{4\sigma_n^2})^{N_i N_t} \left(\prod_{i=1}^{N_i} \lambda_i\right)^{n_t}\right)^{-1} \tag{17}$$

where λ_i is the i^{th} eigenvalue of the covariance matrix $\boldsymbol{Q}_y$ of the received vector $\boldsymbol{y}$. It can be seen from Fig.7 that for high SNR, say $SNR > 15dB$, the goodput of the proposed CAMO method is higher than that of the method reported in [28]. For example, at $SNR = 30dB$ the gain is 5.3% and at 40dB the gain becomes larger and reaches 12%. However, for low SNR, say $SNR < 15dB$, the method of [28] performs better. For example, at $SNR = 10dB$, the canonical game of [28] achieves a 6.6% goodput gain with respect to the coalition formation game proposed in this paper. Such a behavior can be explained if we consider the two different theoretical game-based strategies adopted. In our approach, the virtual ASTC-MIMO-OFDM network is dynamically configured by the relays in coalition and the coalition is formed after the negotiation phase. As a result, some relays, along with their subcarriers, may be excluded from the coalition. On the contrary, the Class I game of [28] does not consider any negotiation. The grand coalition is formed by all the relays of the virtual network, independently of their amount of harvested power and their channel status, aiming to seek for a stable core solution concept that is convenient for all the players in the game. At low SNR, the Class I game looks more effective, because system performance is largely constrained by the noise and, therefore, the global sum-rate provided by the larger coalition may become higher. On the other hand, during the negotiation phase, the proposed Class II game may incur misdetection of control packets that contain base station interrogation and/or ACK relay replies, due to the high BER at low SNR. This causes some undue exclusions of players that could actively contribute to increasing the overall system capacity. When SNR increases, the negotiation phase is much less impaired by the control messaging failures and the Class II algorithm dynamically selects, as expected, the players in coalition on the basis of their harvested power amount and their channel conditions. In such a framework, the Sv-based solution concept provides a payoff allocation to the different players, which is adaptive to external network conditions, and thus outperforms the core solution concept of [28]. Indeed, the canonical game of [28] does not consider any change of coalition structure depending on time-varying external factors. The computation of the stable core solution concept, which is capable of guaranteeing fairness to all the individual players in the grand coalition, may, therefore, be hindered by unfavourable changes of channel and/or energy harvesting status that affect one or more players. For the sake of completeness, it should also be noticed that the theoretical and simulated goodput curves attained by the Class I game of [28] tend to approach the corresponding ones of the proposed Class II game for $SNR \geq 45dB$. This is due to the augmented stability of the grand coalition and the core solution concept, which has been proven in [28] to be asymptotically reached for $SNR \to +\infty$. It is worth of highlighting in this series of numerical evaluations the perfect agreement between simulation and theoretical results. This fact can further demonstrate the correctness of our analysis.

In order to highlight the influence on the system performance of harvesting random characterization, Fig. 8 shows the curves of capacity vs. Poisson frequency of the energy harvesting arrivals λ_e, comparing the proposed coalitional game approach with the work of Wang et *al* [18] that is aimed at finding low-complexity near-optimal transmission policies for MIMO broadcast channels. As for Fig.7, CAMO algorithm is implemented for a coalition formed by two pairs relays. It can be seen that CAMO algorithm outperforms the approach proposed in [18] for the overall considered λ_e range. In such a comparison, CAMO demonstrated its superiority in updating in real-time relay configuration and network parameters, as soon as new arrivals of energy available for harvesting occur.

As far as capacity performance vs. harvested power is concerned, in Fig.9, we compare the capacity achieved by the proposed coalitional game strategy with that obtained by the analytical closed-form solution to RRM relay optimization of Yang, Zhou and Xiao [19]. From the curves plotted in Fig.9, we can note a dramatic harvested power gain. For a capacity of 4.5 bits/s/Hz, such a gain is around 50 dB.

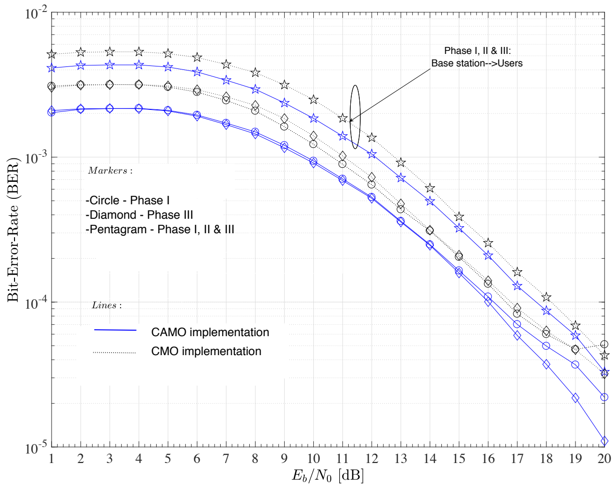

Figure 4. BER performance vs. E_b/N_0 achieved during the different algorithmic phases by the proposed CAMO (blue line) and CMO (black line) coalitional game-based algorithms.

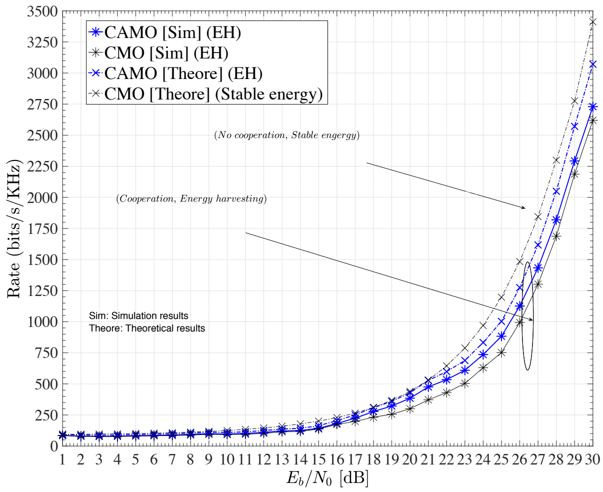

Figure 5. Capacity (in b/s/KHz) vs. E_b/N_0 of CAMO (blue line) and CMO (black line) coalitional game-based algorithms, obtained by Eq. (14) for simulated and theoretical curves: comparison with the stable energy system (no EH).

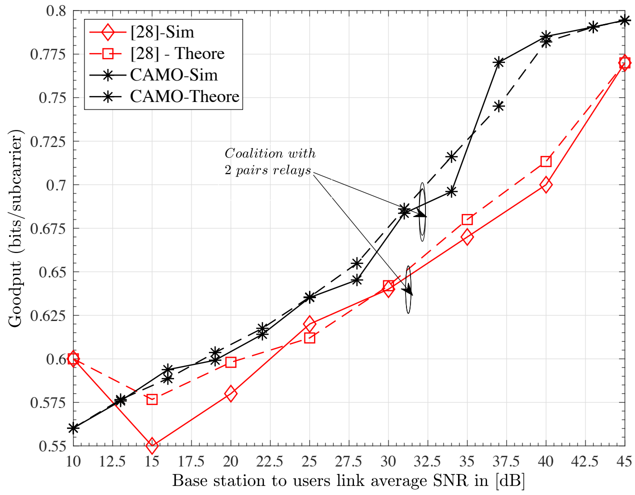

Figure 7. Goodput performance of CAMO algorithm vs. link *SNR* compared with the canonical coalitional game-based approach of Ding and Poor [28].

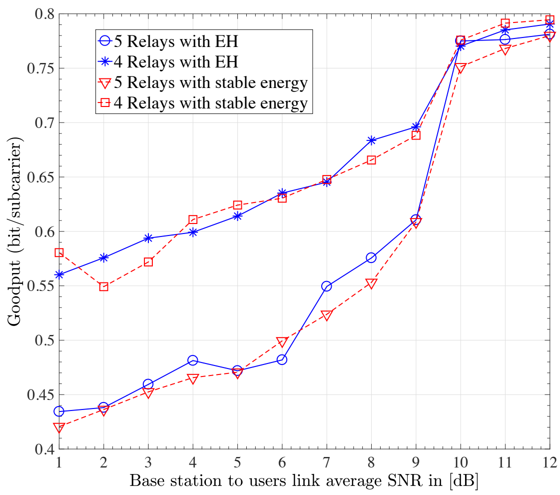

Figure 6. Goodput performance vs. link *SNR* of CAMO algorithm with different numbers of active relays: comparison with the stable energy system (fixed power: 70 dBmW).

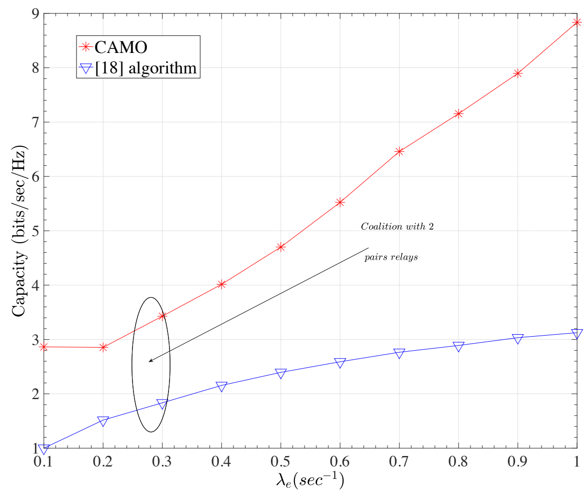

Figure 8. Achievable capacity of CAMO algorithm vs. Poisson frequency of EH arrivals λ_e, compared to that obtained by the approach proposed by Wang *et.al.* [18].

C. Complexity analysis

In this subsection, we compare the complexity of the proposed algorithm to those of the methodologies used for comparison in Fig.7 and 8 (see ref. [18], [28]) and, for sake of completeness, those published in related works: [27] and [29]. From Table II, it can be observed that the order of computational complexity of the proposed algorithm is reduced at least by n_c times with respect to the corresponding order of the algorithm shown in [27], and by n_t times and n_c^2 times respectively as compared to those of [28] [29]. Detailed proof is given in Appendix B. This saving of computational resources becomes significant for large n_c and n_t and further on proves the effectiveness of our coalitional cooperative communication method.

For what concerns the approach shown in [18], the computational burden could be lighter than that of our algorithm and depends on how much time we need to go through the A energy arrivals at relay antenna to identify all the power-changing points.

VI. Conclusion

In this paper, we have proposed a Class II coalitional game-based methodology for cooperative communications

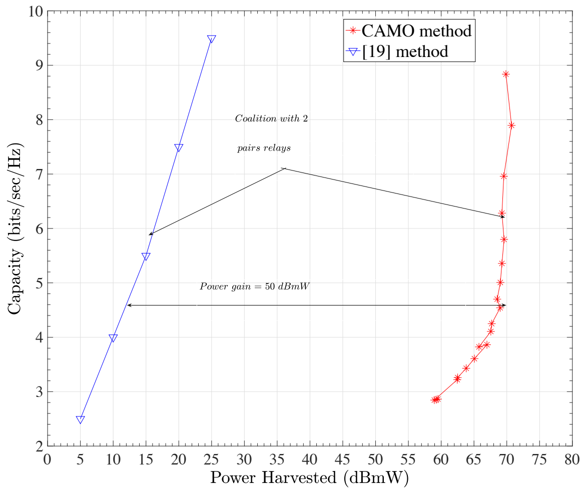

Figure 9. Achievable capacity of CAMO algorithm vs. harvested power, compared to that obtained by Yang's *et.al.* [19] analytical approach.

Table II
COMPLEXITY ANALYSIS

Methods	Complexity
[18]	$\boldsymbol{O}(A)$
[27]	$\boldsymbol{O}\left(n_c^4 n_t^4 + n_t^3\right)$
[28]	$\boldsymbol{O}\left(n_c^3 n_t^3 + 3n_c^2 n_t^2\right)$
[29]	$\boldsymbol{O}\left(n_c^5 n_t^4 + n_t^2\right)$
This Work	$\boldsymbol{O}\left(n_c^3 n_t^2 + n_c n_l^2\right)$

using MIMO-OFDM transmission in a multi-user context with energy harvesting at relay nodes. To maximize the system capacity, we have formulated a non-transferable utility coalition formation game with Shapley value solution concept, in which the players are the EH-powered relay nodes – along with their subcarrier sets – that may cooperate or not with the base-station on the basis of their amount of harvested energy and of the channel conditions. At each transmission epoch, the selected relays in coalition form a dynamically-configured virtual MIMO network that transmits information to destination using robust Algebraic Space-Time Coding (ASTC). The performance of the proposed approach has been evaluated for different MIMO scenarios – employing or not ASTC – and compared both with the empirical bounds and with other three recent related works, namely: [18], [19], and [28]. Simulation results demonstrate that the proposed Sv-based coalition formation game can approach the empirical bounds very closely and outperforms the other considered state-of-the-art techniques, with an affordable computational burden, generally reduced as compared with that of counterpart methodologies.

Future research work may consider the use of the proposed approach in a massive MIMO context. By increasing the number of antennas, the energy harvested from the massive MIMO system could decrease the on-off status of each transmit antenna. This could substantially change the boundary system conditions and will have a significant impact on the overall coalitional game strategy formulation.

APPENDIX A
PAYOFF DERIVATION

Let us start from the following equation:

$$\Psi_i(v) = \sum_{i=1}^{n_l} \int_0^1 x^{n_l}(1-x)^{n_c n_t - n_l - 1} dx \times \tag{18}$$

$$\log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c w_i P_h^2\right]\right) \tag{19}$$

$$\approx \int_0^1 \left(N(\frac{\acute{\xi} - \bar{m}_i^x}{\bar{v}_i^x}) - N(\frac{\acute{\xi} - \bar{m}_i^x - w_i}{\bar{v}_i^x}) \right) d\acute{\xi} \times \tag{20}$$

$$\log_2\left(\left[1 + \frac{1}{\sigma_{w_k}^2} n_c w_i P_h^2\right]\right) \tag{21}$$

We suppose that the total weight satisfies the following condition: $\acute{\xi} \leq \bar{v}_i^x + \bar{m}_i^x + \frac{w_i}{2}$. Then we can use Taylor series of the exponential function to the second order as:

$$\exp(x) \quad \approx \quad 1 + x + O(2) \ when \ x \to 0 \tag{22}$$

With $K = \frac{w_i}{\bar{v}_i^x}$, we derive:

$$\int_0^1 \left(N(\frac{\acute{\xi} - \bar{m}_i^x}{\bar{v}_i^x}) - N(\frac{\acute{\xi} - \bar{m}_i^x - w_i}{\bar{v}_i^x}) \right) d\acute{\xi} \approx \tag{23}$$

$$\frac{2}{\sqrt(\pi)} \int_0^1 \left[K - 2K \frac{\acute{\xi} - \bar{m}_i^x}{\bar{v}_i^x} \right] d\acute{\xi} \approx \tag{24}$$

$$\frac{2}{\sqrt(\pi)} \left[K\acute{\xi} - \frac{2K}{\bar{v}_i^x} (\frac{\acute{\xi}^2}{2} - \bar{m}_i^x \acute{\xi}) \right]_0^1 \approx$$

$$\frac{w_i(1 - 2\bar{m}_i^x)}{\sqrt{\pi}(\bar{v}_i^x)^2} \tag{25}$$

Finally, substituting Eq. (23) into Eq. (18) yields Eq. (14).

APPENDIX B
COMPLEXITY PROOF

Let a coalitional game $G = (V, E)$ be with $V = v_1, \ldots, v_n$ and k be the threshold. We construct a set of agents $A_g = a_1, \ldots, a_n$ and a set of resources $R = r_1, \ldots, r_n$. For each agent a_i, we set $G_i = g_i$. Each goal g_i demands resource, such that:

$$G(g_i, r_j) = \begin{cases} 0 & \text{if i} \neq j \\ k-1 & \text{otherwise} \end{cases} \tag{26}$$

For each pair $(v_i, v_j) \in E$ the construction of the coalitional game G can be completed in $O(|V|^2 \times |E|)$ steps. So the main phase for Algorithm 1 is in Phase II during coalition formation. This leads to $O(ln^2)$, but the complexity of the UL ACK transmission will be dominated by $O(4(n_c^3 n_l^2) + n_c n_l^2)$. ■

Appendix C
Proof of Existence of Nash Equilibrium for Coalitional Games Admitting Shapley Value as Solution Concept

Let us suppose to have a payoff $g^i_\lambda(\omega, x)$ for the benefit of the strategy $x = (x^i)_{i\in N}$. Fink started to prove the unicity of the payoff as in the following proposition:

Proposition–1: $g^i_\lambda(\omega, x)$ is the unique solution for the linear system Ω-equations:

$$g^i_\lambda(\omega, x) = \sum_{a\in A(w)} \left(\prod_{i\in N} x^i(a^i) \right) \left(\begin{array}{c} \lambda g^i(\omega, a) \\ (1-\lambda)\Sigma'_\omega \in \Omega q(\omega, a)(\omega') g^i(\omega', x) \end{array} \right) \quad (27)$$

Fink made the hypothesis that the Shapley value exists for a generic coalitional game. The existence of Shapley value *necessarily* implies that Proposition 1 is true. The verification of Proposition 1 then leads to prove the *continuity* of $(\lambda, x) \mapsto g^i_\lambda(\omega, x)$ function, as stated in the following proposition:

Proposition–2: For any player i and any initial status ω, the function $(\lambda, x) \mapsto g^i_\lambda(\omega, x)$ is continuous and fractional with λ.

At this step Fink used in [36] the continuity to prove the *stationarity* of the game, for which the existence of the Shapley value has been supposed. This allowed him to conclude the existence of the Nash equilibrium by invoking the following theorem:

Theorem (Fink (1964), Takahashi (1965)): Any finite, discounted stochastic game with N players admits an equilibrium in stationary strategies.

The last theorem leads straightforwardly to the proof of the existence of the Nash equilibrium. ■

References

[1] X. Chen, W. Ni, X. Wang, and Y. Sun, "Provisioning quality-of-service to energy harvesting wireless communications," *IEEE Communications Magazine*, vol. 53, pp. 102–109, April 2015.

[2] G. Miao, N. Himayat, and G. Y. Li, "Energy-efficient link adaptation in frequency-selective channels," *IEEE Transactions on Communications*, vol. 58, pp. 545–554, February 2010.

[3] C. Huang, R. Zhang, and S. Cui, "Throughput maximization for the Gaussian relay channel with energy harvesting constraints," *IEEE Journal on Selected Areas in Communications*, vol. 31, pp. 1469–1479, August 2013.

[4] D. Gunduz, K. Stamatiou, N. Michelusi, and M. Zorzi, "Designing intelligent energy harvesting communication systems," *IEEE Communications Magazine*, vol. 52, pp. 210–216, January 2014.

[5] H. Bolcskei, "MIMO-OFDM wireless systems: basics, perspectives, and challenges," *IEEE Wireless Communications*, vol. 13, pp. 31–37, Aug 2006.

[6] M. I. Kadir, S. Sugiura, S. Chen, and L. Hanzo, "Unified MIMO-multicarrier designs: A space-time shift keying approach," *IEEE Communications Surveys Tutorials*, vol. 17, pp. 550–579, Secondquarter 2015.

[7] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A survey on 3GPP heterogeneous networks," *IEEE Wireless Communications*, vol. 18, pp. 10–21, June 2011.

[8] S. A. R. Zaidi, M. Ghogho, D. C. McLernon, and A. Swami, "Energy harvesting empowered cognitive metro-cellular networks," in *2014 1st International Workshop on Cognitive Cellular Systems (CCS)*, pp. 1–5, Sept 2014.

[9] W. Saad, Z. Han, M. Debbah, A. Hjorungnes, and T. Basar, "Coalitional game theory for communication networks," *IEEE Signal Processing Magazine*, vol. 26, pp. 77–97, September 2009.

[10] Z. Xu, C. Yang, G. Y. Li, S. Zhang, Y. Chen, and S. Xu, "Energy-efficient configuration of spatial and frequency resources in MIMO-OFDMA systems," in *2012 IEEE International Conference on Communications (ICC)*, pp. 4384–4389, June 2012.

[11] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative mimo techniques in sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, pp. 1089–1098, Aug 2004.

[12] P. Mertikopoulos and E. V. Belmega, "Learning to be green: Robust energy efficiency maximization in dynamic MIMO-OFDM systems," *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 743–757, April 2016.

[13] J. Liang and Q. Liang, "Channel selection in virtual MIMO wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 58, pp. 2249–2257, Jun 2009.

[14] Q. Gao, Y. Zuo, J. Zhang, and X. H. Peng, "Improving energy efficiency in a wireless sensor network by combining cooperative MIMO with data aggregation," *IEEE Transactions on Vehicular Technology*, vol. 59, pp. 3956–3965, Oct 2010.

[15] B. K. Chalise, Y. D. Zhang, and M. G. Amin, "Simultaneous transfer of energy and information for MIMO-OFDM relay system," in *2012 1st IEEE International Conference on Communications in China (ICCC)*, pp. 481–486, Aug 2012.

[16] X. Wang, W. Xu, S. Li, and J. Lin, "Joint power splitting and resource allocation with QoS guarantees in RF-harvesting-powered cognitive OFDM relay systems," in *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 1432–1436, Aug 2015.

[17] K. Xiong, P. Fan, C. Zhang, and K. B. Letaief, "Wireless information and energy transfer for two-hop non-regenerative MIMO-OFDM relay networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, pp. 1595–1611, Aug 2015.

[18] X. Wang, Z. Nan, and T. Chen, "Optimal MIMO broadcasting for energy harvesting transmitter with non-ideal circuit power consumption," *IEEE Transactions on Wireless Communications*, vol. 14, pp. 2500–2512, May 2015.

[19] D. Yang, X. Zhou, and L. Xiao, "An optimal transmission strategy for joint wireless information and energy transfer in MIMO relay channels," *International Journal of Antennas and Propagation*, vol. 2015, no. 5, p. 6, 2015.

[20] D. Fudenberg and J. Tirole, *Game Theory*. Cambridge, MA: MIT Press, 1991. Translated into Chinesse by Renin University Press, Bejing: China.

[21] M. Augier and D. Teece, *The Palgrave Encyclopedia of Strategic Management*. Springer, 2013.

[22] I. Stupia, C. Sacchi, and L. Vandendorpe, "Green BICM-OFDM based cooperative communications using bargaining game algorithm," in *2015 IEEE Aerospace Conference*, pp. 1–9, March 2015.

[23] M. S. Bahbahani and E. Alsusa, "Relay selection for energy harvesting relay networks using a repeated game," in *2016 IEEE Wireless Communications and Networking Conference*, pp. 1–6, April 2016.

[24] B. Varan and A. Yener, "Incentivizing signal and energy cooperation in wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, pp. 2554–2566, Dec 2015.

[25] H. Chen, Y. Li, Y. Jiang, Y. Ma, and B. Vucetic, "Distributed power splitting for SWIPT in relay interference channels using game theory," *IEEE Transactions on Wireless Communications*, vol. 14, pp. 410–420, Jan 2015.

[26] L. Canzian, L. Badia, and M. Zorzi, "Promoting cooperation in wireless relay networks through Stackelberg dynamic scheduling," *IEEE Transactions on Communications*, vol. 61, pp. 700–711, February 2013.

[27] S. Hamouda, I. B. Chaabane, and S. Tabbane, "Cooperative bandwidth sharing for relaying in LTE-Advanced using game theory," *IEEE Transactions on Vehicular Technology*, vol. 64, pp. 2306–2317, June 2015.

[28] Z. Ding and H. V. Poor, "Cooperative energy harvesting networks with spatially random users," *IEEE Signal Processing Letters*, vol. 20, pp. 1211–1214, Dec 2013.
[29] M. G. Adian and H. Aghaeinia, "A two-level cooperative game-based approach for joint relay selection and distributed resource allocation in MIMO-OFDM-based cooperative cognitive radio networks," *Transactions on Emerging Telecommunications Technologies*, vol. 27, no. 1, pp. 34–50, 2016.
[30] W. Chen, M. Xu, Y. Tao, Z. Ding, and Z. Wang, "Distributed coalition formation algorithms for cooperative broadcast networks with SWIPT," in *2014 Sixth International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1–5, Oct 2014.
[31] C. Ballester, "Np-completeness in hedonic games," *Games and Economic Behavior*, vol. 49, no. 1, pp. 1 – 30, 2004.
[32] J. C. Belfiore, G. Rekaya, and E. Viterbo, "The golden code: a 2 x 2 full-rate space-time code with nonvanishing determinants," *IEEE Transactions on Information Theory*, vol. 51, pp. 1432–1436, April 2005.
[33] M. O. Damen, K. Abed-Meraim, and J. C. Belfiore, "Diagonal algebraic space-time block codes," *IEEE Transactions on Information Theory*, vol. 48, pp. 628–636, Mar 2002.
[34] S. Yang, J. C. Belfiore, G. Rekaya, and B. Othman, "Perfect space-time block codes for parallel MIMO channels," in *2006 IEEE International Symposium on Information Theory*, pp. 1949–1953, July 2006.
[35] T. S. Driessen, 'Cooperative games, solutions and applications," Springer Science & Business Media, 2013.
[36] A. M. Fink, "Equilibrium in a stochastic n-person game," *J. Sci. Hiroshima Univ. Ser. A-I Math.*, vol. 28, no. 1, pp. 89–93, 1964.
[37] A. Bannour, Y. Sun, M. L. Ammari, F. Delestre, and R. Bouallegue, "A novel algebraic carrier frequency offset estimator for ASTC-MIMO-OFDM systems over a correlated frequency-selective channel," *IEEE Transactions on Vehicular Technology*, vol. 61, pp. 2468–2475, July 2012.
[38] A. Bannour, M. L. Ammari, Y. Sun, and R. Bouallegue, "The capacity performance of ASTC-MIMO-OFDM system in a correlated Rayleigh frequency-selective channel," *Wireless Personal Communications*, vol. 68, no. 4, pp. 1365–1376, 2013.
[39] W. C. Freitas, F. R. P. Cavalcanti, A. L. F. de Almeida, and R. R. Lopes, "Exploiting dimensions of the MIMO wireless channel: multidimensional link adaptation," in *2005 IEEE 61st Vehicular Technology Conference*, vol. 2, pp. 924–928 Vol. 2, May 2005.
[40] B. Ahmed and M. A. Matin, *Coding for MIMO-OFDM in Future Wireless Systems*. Springer Publishing Company, Incorporated, 2015.

Ahmed Bannour received his Engineering degree, M.Sc in Telecommunications and the PhD from the Ecole Nationale d′Ingénieurs de Tunis, Tunisia, in 2006, 2008 and 2013, respectively. Since 2006 he has been a research associate with Innovation of Communicant and Cooperative Mobiles Laboratory (Innov′Com) at Higher School of Communications of Tunis, Sup′Com, Université de Carthage, Tunisia. He has been an Assistant Professor at the High Institute of Computer Science of Mahdia, Tunisia. Currently he is a project associate with the European Center of Nuclear Research (CERN) of Geneva (CH). His main research interests include MIMO-OFDM systems, system identification, space-time coding, SDR implementations, wireless communications in hostile environment and wireless solutions for industry.

Claudio Sacchi (M′01–SM′07) received the "Laurea" Degree in Electronic Engineering, and the Ph.D. in Space Science and Engineering at the University of Genoa (Italy) in 1992 and 2003, respectively. From 1996 to 2002, he has been research cooperator with the University of Genoa, Dept. of Biophysical and Electronic Engineering (DIBE) and with the National Italian Consortium in Telecommunications (CNIT), managing project activities in the field of multimedia surveillance systems and satellite communications. Since August 2002, Dr. Sacchi is assistant professor at the Department of Information Engineering and Computer Science (DISI) of the University of Trento (Italy). Claudio Sacchi is author and co-author of more than 90 papers published in international journals and conferences. In 2011, he was guest editor of the special issue of PROCEEDINGS OF THE IEEE: "Aerospace Communications: History, Trends and Future." Moreover, in 2015, he was guest editor of the featured–topic special issue of IEEE COMMUNICATIONS MAGAZINE: "Toward the Space 2.0 Era." Dr. Sacchi has been invited lecturer to international PhD Summer schools. He also held seminars and short courses both for MSc and PhD students in recognized EU and North American Universities and research institutions. The research interests of Dr. Sacchi are mainly focused on wideband mobile and satellite transmission systems based on space, time and frequency diversity; MIMO systems; array processing; multi-rate and multi-access wireless communications; EHF broadband aerospace communications; software radio and cognitive radio; radio communications for emergency recovery applications. Claudio Sacchi is a senior member of IEEE and a member of the IEEE ComSoc, IEEE Broadcast and the IEEE AESS society.

Yichuang Sun (M′90–SM′99) received the B.Sc. and M.Sc. degrees from Dalian Maritime University, Dalian, China, and the Ph.D. degree from the University of York, York, U.K., all in communications and electronics engineering, in 1982, 1985, and 1996, respectively. He is currently a Professor with the School of Engineering and Technology, University of Hertfordshire, Hatfield, U.K. His research interests include wireless and mobile communications and RF and analog circuits. He has authored over 280 papers and contributed nine chapters in edited books. He has also authored four text and research books: Continuous-time Active Filter Design (CRC Press, USA), Design of High frequency Integrated Analogue Filters (IEE/IET Press, U.K.), Wireless Communication Circuits and Systems (IET Press), and Test and Diagnosis of Analogue, Mixed-signal and RF Integrated Circuits – The Systems on Chip Approach (IET Press). He was a Series Editor of IEE Circuits, Devices and Systems Book Series. He was an Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS-I from 2010 to 2011 and serves the journal as an Associate Editor again from 2016 to 2017. He is an Editor of ETRI Journal and Journal of Semiconductors. He has been a lead or sole Guest Editor of seven IEEE and IEE/IET journal special issues, which include MIMO Wireless and Mobile Communications published in IEE Proceedings: Communications, 2006, Advanced Signal Processing for Wireless and Mobile Communications in IET Signal Processing, 2009, Cooperative Wireless and Mobile Communications in IET Communications, 2013, and Software-Defined Radio Transceivers and Circuits for 5G Wireless Communications in IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS-II, 2016. He has also been widely involved in various IEEE technical committee and international conference activities.