Outline

- *Introduction;*
- *System model and link performance model;*
- *Power allocation strategy;*
- *Bargaining Game for Relay-Aided BICM-OFDM links;*
- *Numerical results;*
- *Conclusion and future works.*

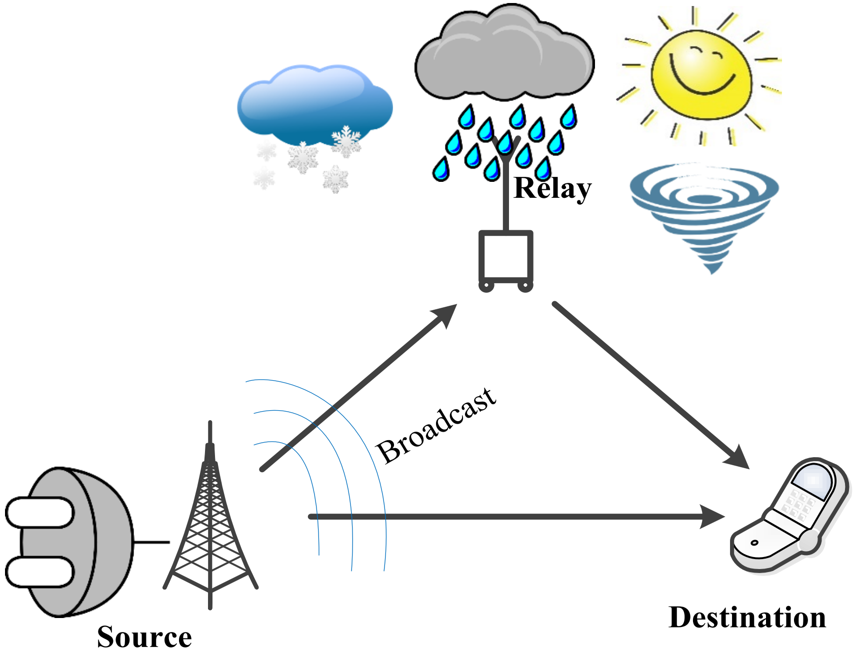
Introduction

- **Green wireless communications and networking**
  - There are many methods suggested to enable green communications:
    - *Energy-efficient power amplifiers;*
    - *Dense deployment of low-power self-organizing small cells;*
    - *Resource allocation methods based on energy saving (e.g. BS switch on/off depending on traffic load);*
    - *Cooperative communications, etc.*
  - A very interesting methodology has been proposed in [HUA13], based on the use of self-sustainable relay nodes that are capable of harvesting energy from green sources like solar or wind energy.

[HUA13] C. Huang, R. Zhang, and S. Cui, "Throughput Maximization for the Gaussian Relay Channel with energy harvesting constraint," *IEEE J. on Selec. Areas in Comm.*, vol.31, no.8, pp. 1469-1479, Aug. 2013.

Introduction

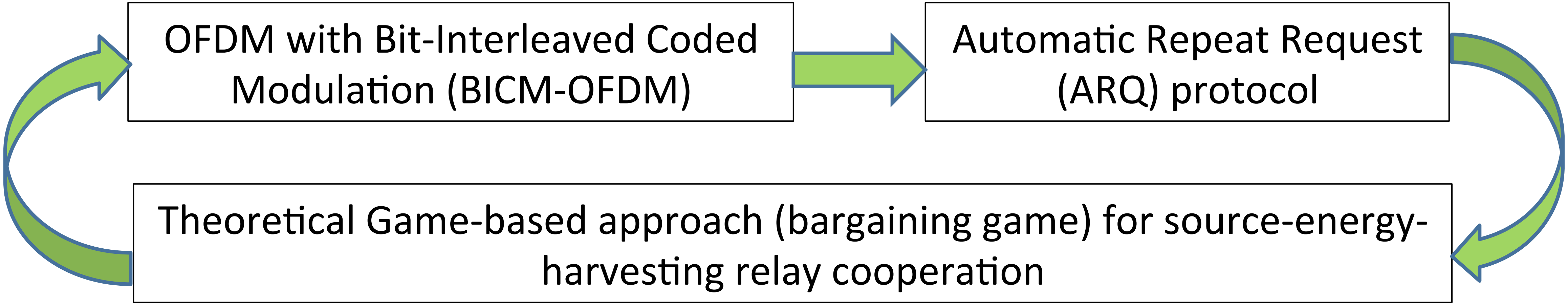
- **Cooperative relaying with energy harvesting**
  - In general, cooperative relaying allows to reduce the effects of pathloss and Rayleigh fading (it is forecasted in latest releases of LTE);
  - However, self-sustainable relay nodes must deal with energy fluctuations caused by time-dependent solar and wind patterns;
  - Hence cooperation can take place conditioned to current energy status of the relay (the energy spent by the relay at any time must be less than the energy harvested at that time).



Introduction

- **What is proposed in our paper:**
  - Substantially we are searching for a power-efficient relay-based transmission system that can work when energy harvesting is required to the relay;
  - For this reason we are proposing a "green" synergic approach:

PHY-layer and link-layer robustness against noise, interference and harsh propagation impairments



OFDM with Bit-Interleaved Coded Modulation (BICM-OFDM)

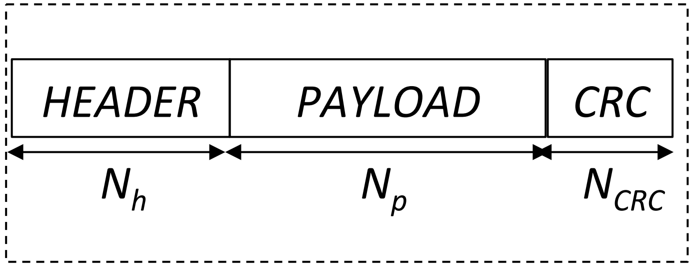
Automatic Repeat Request (ARQ) protocol

Theoretical Game-based approach (bargaining game) for source-energy-harvesting relay cooperation

Efficient management of available power sources

System model and link performance model

- **Cooperative relaying with ARQ: the proposed protocol**



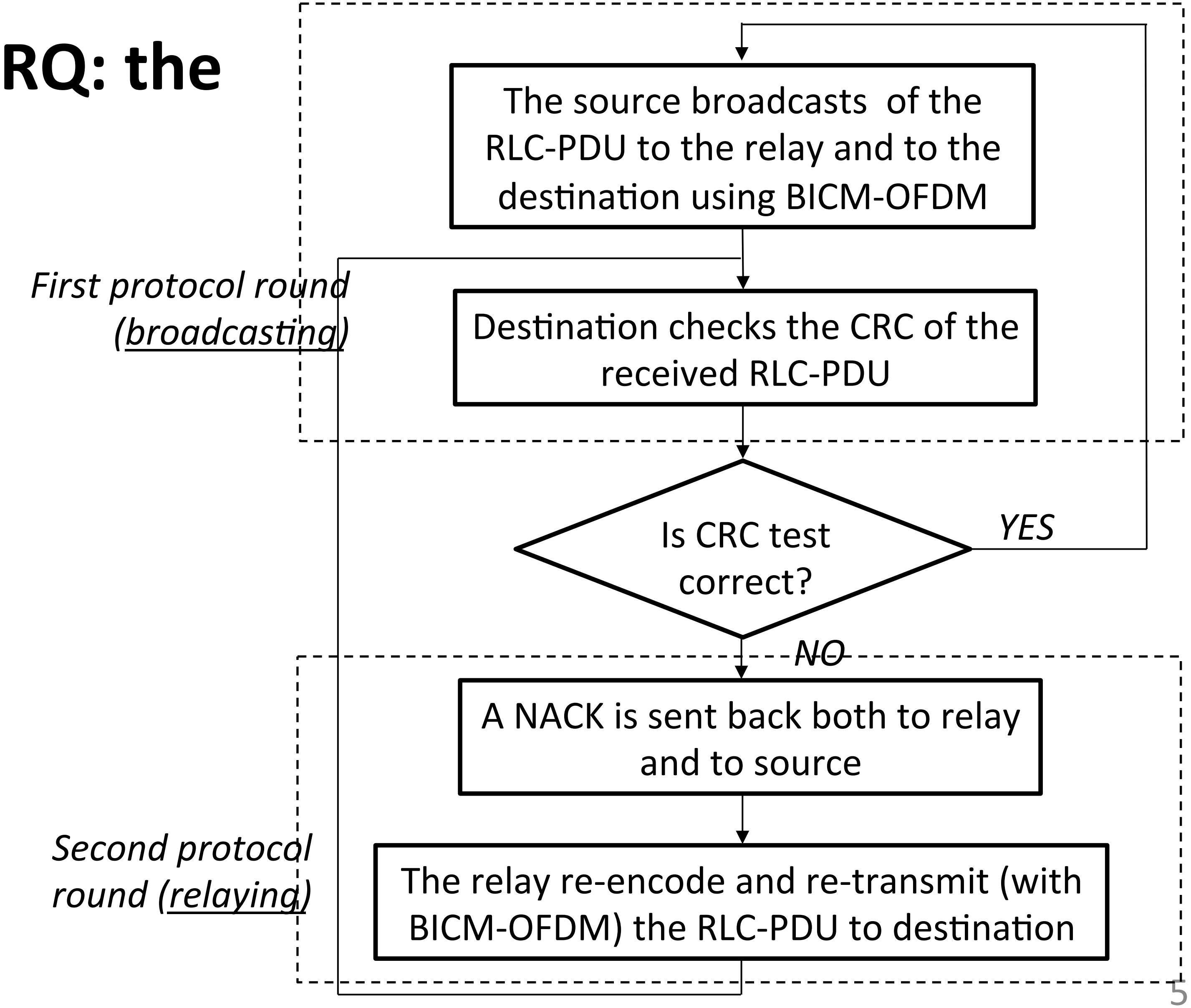
HEADER *PAYLOAD* *CRC*

N_h N_p N_{CRC}

Radio Link Control Packet Data Unit (RLC-PDU)

$N_h+N_p+N_{CRC}=N_s$ *bits*

BTW this kind of source-relay cooperation may be severely impaired by the starvation of the energy-harvesting relay. In such an event, the cooperation should be stopped!



First protocol round (broadcasting)

The source broadcasts of the RLC-PDU to the relay and to the destination using BICM-OFDM

Destination checks the CRC of the received RLC-PDU

Is CRC test correct?

YES

NO

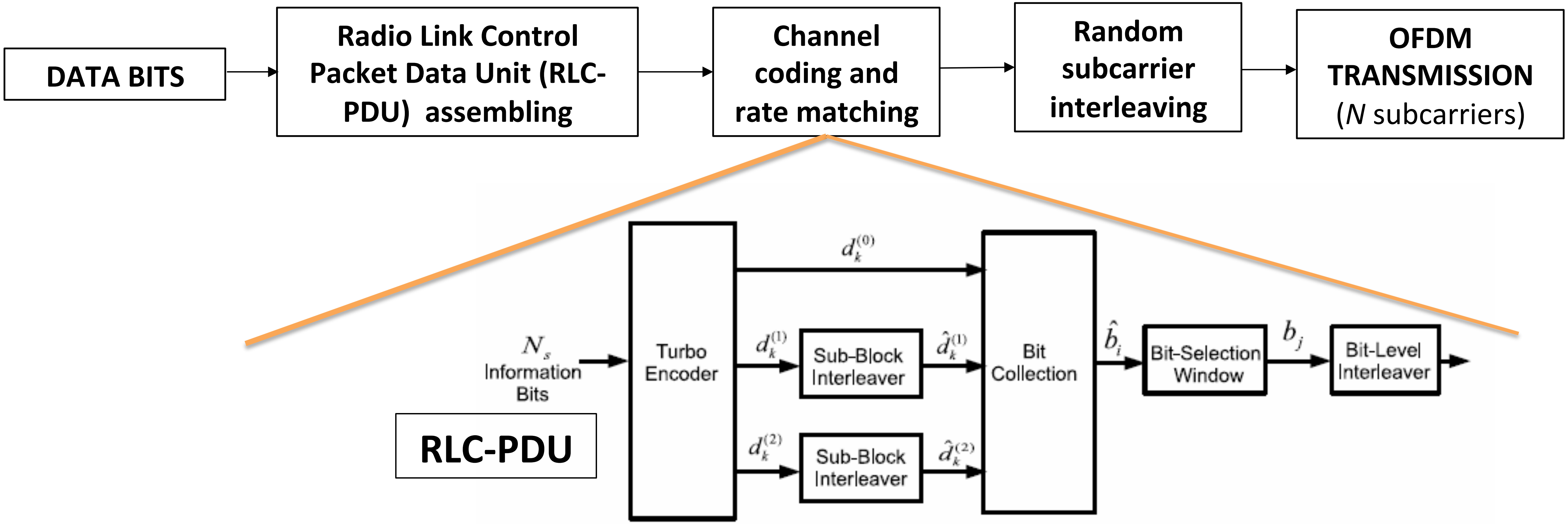
A NACK is sent back both to relay and to source

Second protocol round (relaying)

The relay re-encode and re-transmit (with BICM-OFDM) the RLC-PDU to destination

System model and link performance model

- **BICM-OFDM system model with ARQ**
  - Block diagram of BICM:



DATA BITS

Radio Link Control Packet Data Unit (RLC-PDU) assembling

Channel coding and rate matching

Random subcarrier interleaving

OFDM TRANSMISSION (*N* subcarriers)

Mother-code rate *r* (*r*=1/3 in the above scheme)

System model and link performance model

- **Energy Harvesting (EH) and Power Consumption Model**
  - We have adopted the deterministic EH model with finite energy storage limit proposed in [HO12];
  - The energy amount and arrival time are assumed to be known prior the transmission:
  - Under such assumptions, the amount of energy stored in the battery at the time slot *k*+1, denoted with B_{k+1}, can be recursively expressed as follows:

$$\begin{cases} B_{k+1} = \min\{B_k - E_k + H_k, B_{\max}\} \\ B_1 \le B_{\max} \quad (known) \end{cases}$$

✓ E_k energy per symbol used by the power amplifier (less or at most equal to B_k)

✓ H_k harvested energy (random variable uniformly distributed in 0, H_{max})

[HO12] C.K. Ho, and R. Zhang, “Optimal energy allocation for wireless communications with energy harvesting constraints,” *IEEE Trans. on Signal Process*, vol.60, no.9, pp. 4808-4818, Sept. 2012.

System model and link performance model

- **Link performance model (1)**
  - In order to enable the bargaining game problem formulation, we need a suitable link performance metric;
  - We selected the **goodput**, i.e.: the number of information bits delivered to destination in error-free packets per time unit;
  - To compute goodput, we have first extended the procedure presented in [FABR08] for estimating the pairwise error probability (PEP) of the turbo decoder by introducing the concept of aggregate effective SNR mapping (A-ESM);
  - Goodput is computed as a function of A-ESM.

[FABR08] A.G. Fabregas, A. Martinez, and G. Caire, "Bit-Interleaved Coded Modulation," *Now Publishers inc.*, 2008.

System model and link performance model

- **Link performance model (2)**
  - Some more details (index *i* denotes the protocol round):

$$PEP^{i} \approx Q\sqrt{2\Gamma^{(i)}} \quad \Gamma^{(i)} = -\log\left(\frac{1}{\sum_{v=1}^{N} m_v} \sum_{n=1}^{N} \Omega_n\left(p_n^{(i)};\gamma_n^{(i)}\right)\right)$$

EFFECTIVE SNR associated to the i^{th} protocol round

Bits/symbol allocated to the v^{th} *subcarrier*

Power allocated on the n-th subcarrier

SNR measured on the n-th subcarrier

$\Omega_n\left(p_n^{(i)};\gamma_n^{(i)}\right)$ **Modulation model** (see eq.17 of the paper) [STU09]

The original link has been modelled as *a BPSK-AWGN channel* with SNR equal to $\Gamma^{(i)}$

[STU09] I. Stupia, F. Giannetti, V. Lottici, and L. Vandendorpe, “A Novel Exponential Link Error Prediction Method for OFDM Systems,” *Proc. of 7th Int. Workshop on Multi-Carrier Systems and Solutions (MC-SS 2009)*, May 2009.

System model and link performance model

- **Link performance model (3)**
  - From the renewal/reward theorem, we get

Number of information bits

$$\eta\left(\gamma^{(1)},\gamma^{(2)}\right)=\frac{N_p}{W}\frac{1-\upsilon\left(I\right)}{\sum_{i=1}^{2}T_u\left(i\right)\upsilon\left(i-1\right)}$$

Channel gain vectors

Signal bandwidth

Expected goodput (EGP) for a cooperative protocol consisting of *2* rounds

$\upsilon(i)$ **NACK probability at the ith round**

$T_u\left(i\right)$ **OFDM symbol duration at the ith round**

NOTICE: $\upsilon(i)$ is a monotonical decreasing function of the A-SNR value $\Gamma^{(i)}$

Power allocation strategy

The power allocation maximizing the EGP of a BICM-OFDM link must be such that [STU12]

Optimal power allocation on the nth subcarrier

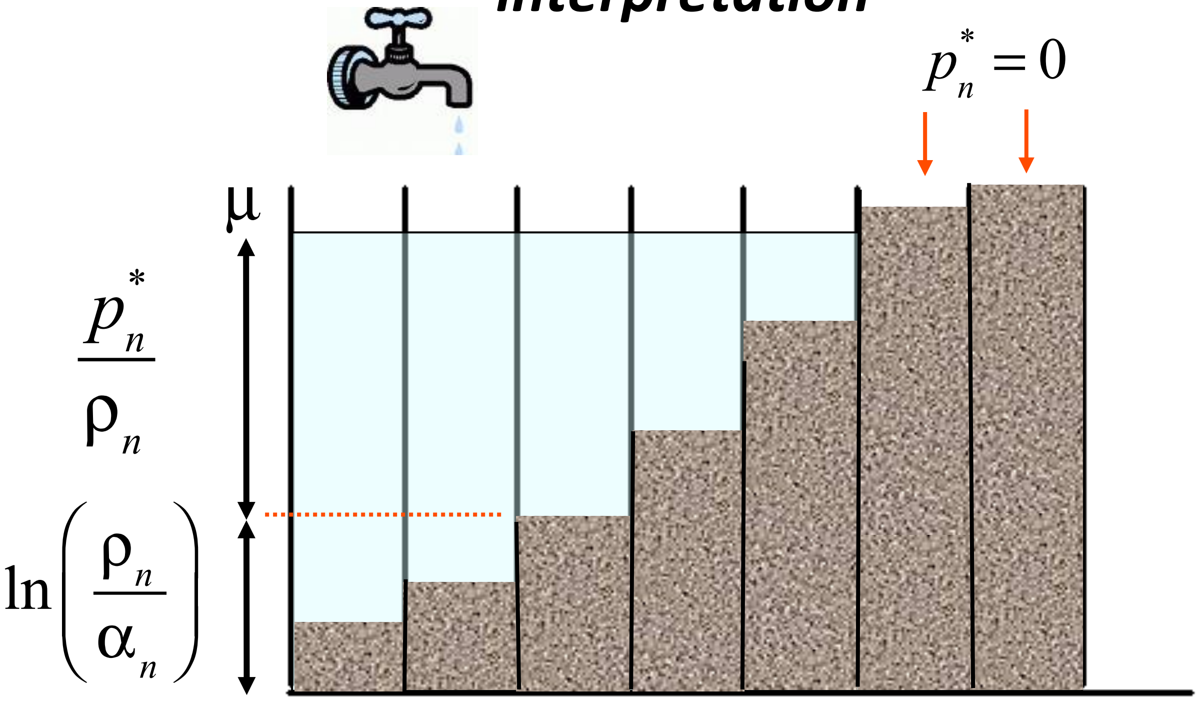
$$\frac{p_n^*}{\rho_n} = \left[\ln\frac{1}{\vartheta} - \log\frac{\rho_n}{\alpha_n}\right]^+$$

Equivalent channel gain

Lagrange multiplier

Adjusting factor (depends on the QAM constellation size)

Intuitive Waterfilling-Like interpretation

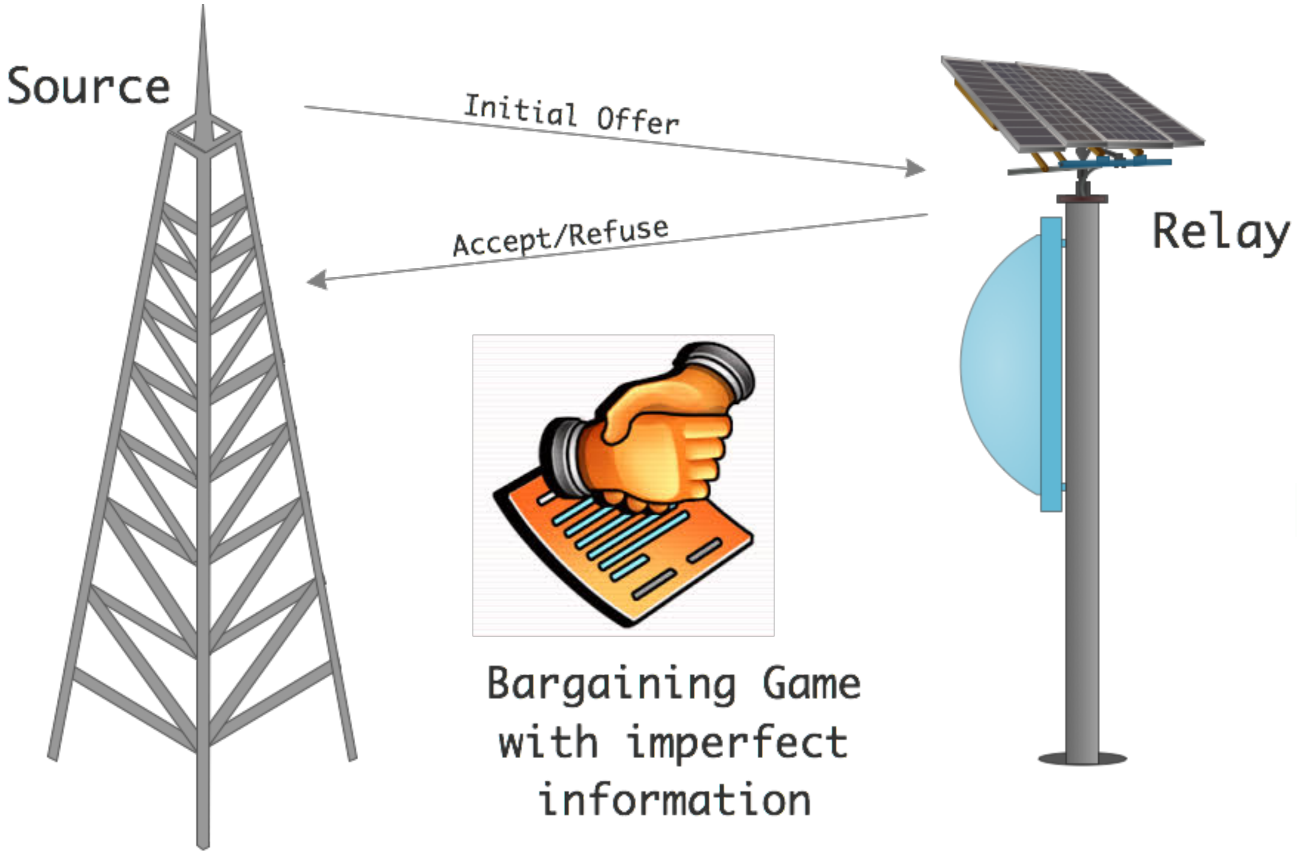


$\mu = \ln\frac{1}{\vartheta}$ plays the role of the water level

[STU12] I. Stupia, V. Lottici, F. Giannetti, and L. Vandendorpe, “Link Resource Adaptation for Multiantenna Bit- Interleaved Coded Multicarrier Systems,” *IEEE Transactions on Signal Processing*, vol. 60, no. 7, pp. 3644–3656, July 2012.

Bargaining Game for Relay-Aided BICM-OFDM links

- **2-players game formulation**



- **Player 1's strategies (source)**
  - Optimize the source-to-destination link.
  - Optimize the source-to-relay link.
- **Player 2's strategies (relay)**
  - Forward the source's signal towards the destination.
  - Do not forward the source's signal.

Bargaining Game for Relay-Aided BICM-OFDM links

- **Source utility function (U_s)**
  - The source targets the maximization of the expected goodput at the destination node.
  - The source has no information about the relay’s battery status (game with incomplete information).
- **Relay utility function (U_r)**
  - The relay’s wants to maximize the expected goodput of the relay-to-destination link minus the cost of cooperation.

$$U_r = \eta_{rd} - C(B_k)E_k$$

Price of cooperation (bit/sec/Joule).

Battery Status

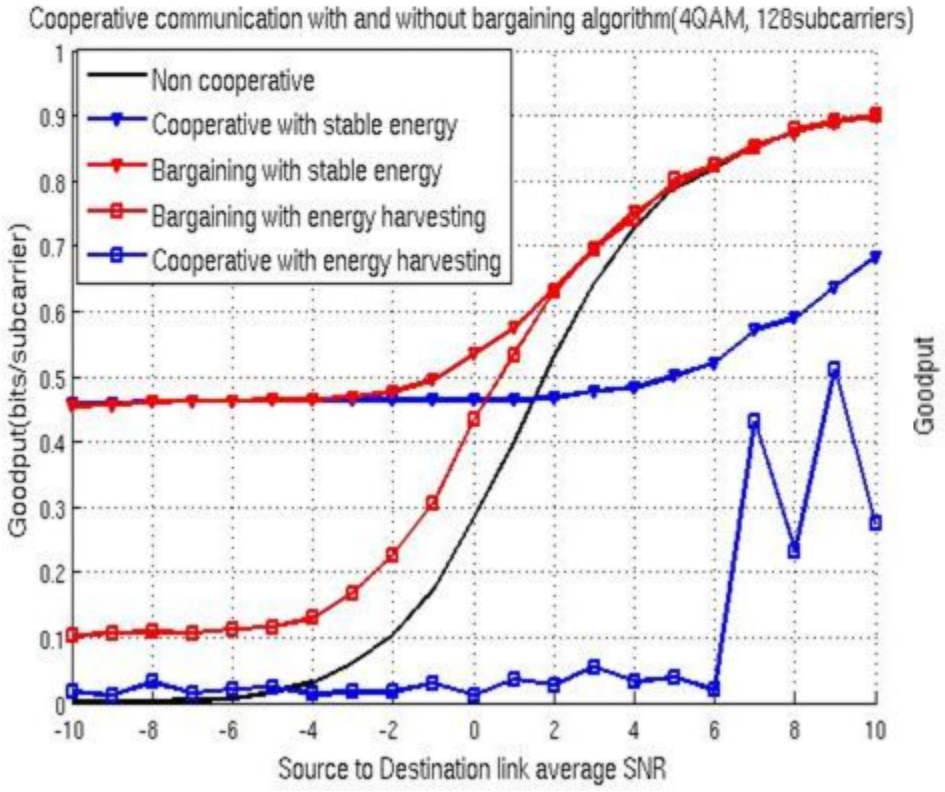
Energy required to forward the signal

Numerical results

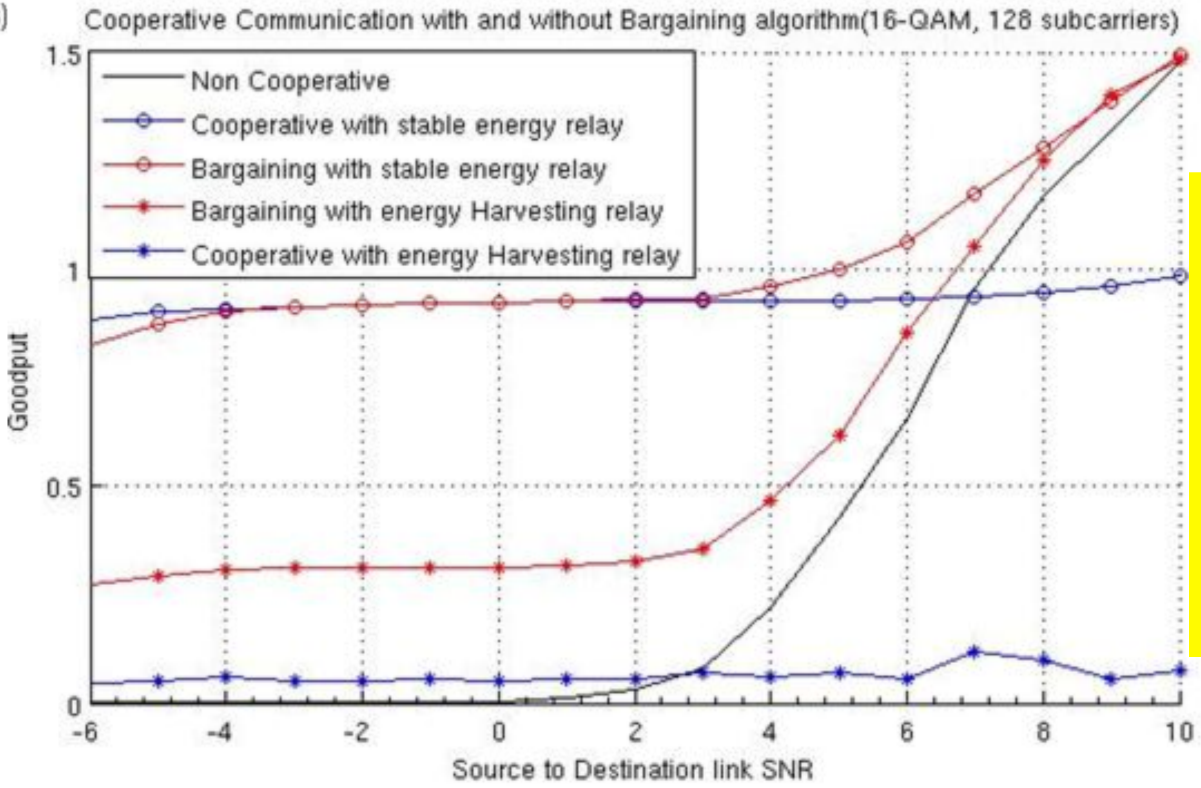
- **Simulation parameters and configurations**
  - Simulations performed in MATLAB environment;
  - Results shown in terms of normalized goodput vs. source-to-destination link average SNR;
  - Coding rate: 1/2;
  - Number of subcarriers: 128 and 512;
  - Modulation format: 4-QAM and 16-QAM;
  - Packet length: 1000 bits;
  - Number of packet sent: 2000;
  - Multipath channel (frequency-selective);
  - Fixed energy and energy-harvesting relay node;
  - *SNR* measured on source-to-relay and relay-to-destination links is, on average, 20dB higher than direct source-to-destination link.

Numerical results

- **Results for *N*=128 subcarriers**



a_{max}=0.01



a_{max}=0. 1

NOTICE: direct link (non cooperative) **always outperforms cooperative link** at high *SNR*, because cooperation **doubles the required time resources**

When we have energy-harvesting relays, <u>bargaining game dramatically improves link performance</u>. Results achieved for 512 subcarriers and 16-QAM modulation (see Fig. 4 of the paper) fully confirm this claim

Conclusion and future works

- A novel "green" methodology based on BICM-OFDM modulation and bargaining game has been proposed for a ARQ-based cooperative link with energy-harvesting relay nodes;
- A non-cooperative bargaining game has been proposed with incomplete information;
- Numerical results showed the effectiveness of the bargaining mechanism in handling time-variant amount of energy harvested by the relay;
- Future works may concern with the analysis of the effects of power back-offs due to non-linear amplifiers on system performance and the extension of theoretical game approach also to power resource allocation.