Self-Configurable Physical Layer for UWA Communications: from Single to Multi-User Optimization

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Why?

Channel fluctuations
Time/frequency/space at various scales

Operational needs

Interfering sources

[DGA experiment]

[Qarabaqi et al., IEEE OCEANS 2011]

[Qarabaqi et al., IEEE OCEANS 2011]

Other examples of interference: [Wang et al., IEEE TSP 2012], [McGee et al., IEEE OCEANS 2014]

[Qarabaqi et al., IEEE OCEANS 2011]

[Dol et al., IEEE JOE 2017]
Multiple links

- Noncooperative communications
- Decentralized networks (self-organized)
How?

Ingredients

1. **Utility function (performance metric) to optimize**
   Spectral efficiency, power/energy, outage probability (BER, SINR, ...)

2. **Strategy set**
   Power, modulation order, coding schemes, frequency selection, spreading factor ...

3. **Knowledge of the environment**
   Learned through a feedback link
   Round-trip time > Channel coherence time
   Limited bandwidth
## Single user examples

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- **Gain (mostly) provided by adaptation to large scale fluctuations (in time and frequency)**
- **Gain depends on the accuracy of the relationship between the channel knowledge (feature vector)+actions and the modem performance**

Other examples: [Tomasi et al., IEEE OCEANS 2010], [Qarabaqi et al., IEEE OCEANS 2011], [Radosevic et al., IEEE JOE 2014]
From single to multiple links

Formulation

- $M$ Tx-Rx links choices in a private set of strategies
- Goal: maximize their utility

The utility function of each link depends on the choices of the others:

$$\max_{x_i \in \mathcal{X}_i} u_i(x_i, x_{-i}) \quad \forall i \in \{1, \ldots, M\}$$

$\mathcal{X}_i$: set of strategies of the link $i$

$x_i$: strategy chosen by $i$

$x_{-i} = [x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_M]$ strategies of its opponents

$u_i: \mathcal{X}_1 \times \cdots \times \mathcal{X}_M \to \mathbb{R}$ utility function of the player $i$.

Solution concepts

Multi-objective optimization + variables cannot be controlled jointly

$\Rightarrow$ Optimality = ?

Equilibrium (Nash): $u_i(x^*_i, x^*_{-i}) \geq u_i(x_i, x^*_{-i}), \forall i \in \{1, \ldots, M\}, \forall x_i \in \mathcal{X}_i$

No link can do better by unilaterally changing its strategy

May be not (pareto) optimal (due to absence of cooperation)
Multiple links

Example: spectrum sharing for noncooperative com.

[Pottier et al., IEEE JOE 2017]
Joint work with A. Pottier and C. Laot

- **Utility**: information rate
- **Strategy set**: power allocation across frequencies (OFDM)
- **Knowledge**: statistical CSI for each (block) of subcarriers

Equilibrium is learned with iterative algorithms

Channel model

\[ h_{i,j}(t, \tau) = \sum_{l=0}^{L_{i,j}-1} c_{i,j}^l(t) \delta(\tau - \tau_{i,j}^l(t)) \otimes \chi_{i,j}^l(\tau) \]

Ray tracing

Composite lognormal-Rice fading

Frequency-dependent attenuation

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Multiple links

Example (video)
Satisfaction vs Maximization: less can be more

Example: Satisfaction if utility = 1bit/s/Hz, knowledge = statistical CSI

(Txs and Rxs randomly located inside a 1.5 km radius circle)
Satisfaction games: other features

[Pottier et al., IEEE Access 2018]  Joint work with A. Pottier and C. Laot

- Adaptation made possible with minimal knowledge: 1-bit feedback

- Has been applied to heterogeneous systems (eg., DSSS vs OFDM)
Future works

1. Modem(s) used
   \[ f(.) = ? \]
   - Offline learning with past experiments and/or channel models [Pelekanakis et al., Ucomms, 2016]
   - Online detection/learning of novelty needed for UWA communications

2. From noncooperative communications to decentralized optimization of self-organized networks
References

Additional slides
Why?

Channel fluctuations

Fluctuations in time/frequency/space

Various scales

Brest Harbor

Kauai

Marta’s Vineyard

[Socleu et al., IEEE OCEANS, 2015]

[van Walree et al., IEEE JOE, 2017]

[Qarabaqi et al., IEEE OCEANS 2011]
Channel model

Example

\[
 h_{i,j}(t, \tau) = \sum_{l=0}^{L_{i,j}-1} c_{i,j}^l(t) \delta(\tau - \tau_{i,j}^l(t)) \otimes \chi_{i,j}^l(\tau)
\]

Ray tracing

Frequency-dependent attenuation

Composite lognormal-Rice fading

\( H_{11} \)

\( H_{21} \)

\( H_{12} \)

\( H_{22} \)
Channel model

Example

\[
    h_{i,j}(t, \tau) = \sum_{l=0}^{L_{i,j}-1} c_{i,j}^l(t) \delta(\tau - \tau_{i,j}^l(t)) \otimes \chi_{i,j}^l(\tau)
\]

Ray tracing

Frequency-dependent attenuation

Composite lognormal-Rice fading

\[
    h_{11}(t) \quad h_{12}(t) \quad h_{21}(t) \quad h_{22}(t)
\]

Gain [dB]

\[
    t [s] \quad f [kHz]
\]

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom
Spectrum sharing games for UWA OFDM

- **Strategies**: Power allocation vectors on $N$ subcarriers under average power constraint
  \[
  \mathcal{X}_i = \{\mathbf{x}_i \in \mathbb{R}_+^N \mid \|\mathbf{x}_i\|_1 \leq P_i\}
  \]

- **Utility function**: related to the information rate [bits/s/Hz]
  \[
  u_i(\mathbf{x}_i, \mathbf{x}_{-i}) = \alpha \sum_{n=1}^{N} \log(1 + \gamma_{i,n}(\mathbf{x}_{-i})x_{i,n})
  \]
  \[\gamma_{i,n}(\mathbf{x}_{-i}) \text{ depends on the channel and interference statistics}\]

- **Nash Equilibrium**: reached with distributed *iterative water-filling* algorithm

Utility function

- Standard figure of merit: \textit{ergodic capacity}

\[
r_i(x_i, X_{-i}) = \frac{1}{N} \sum_{n=1}^{N} \mathbb{E}_{H_{ii}, H_{ji}, X_{j}} \left\{ \log \left( 1 + \frac{|H_{ii,n}|^2 x_{i,n}}{\sigma_{w,i,n}^2 + \sum_{j \neq i} |H_{ji,n}|^2 X_{j,n}} \right) \right\}
\]

Where, the channels $H_{ji,n}$ and the interference powers $X_{j,n}$ are random variables of \textit{unknown distributions}.

\textbf{BUT:} incompatible with the hypothesis made on the UWA communications game (knowledge of the environment)

\textbf{Solution proposed:} \textit{Robust approach}

\[
u_i(x_i, x_{-i}) = \min_{P_{H_{ji}, X_{j}, j \neq i}} r_i(x_i, X_{-i})
\]
Utility function

\[
\begin{align*}
  u_i(x_i, x_{-i}) &= \min_{\mathcal{P}_{H_{ji}, x_{j}, j \neq i}} r_i(x_i, X_{-i}) \\
  &= \frac{1}{N} \sum_{n=1}^{N} \mathbb{E}_{H_{ii}} \left\{ \log \left( 1 + \frac{|H_{ii,n}|^2 x_{i,n}}{\sigma_{w_i,n}^2 + \sum_{j \neq i} \mathbb{E} \left[ |H_{ji,n}|^2 X_{j,n} \right]} \right) \right\} \\
  &\geq \frac{1}{N} \sum_{n=1}^{N} \log \left( 1 + \frac{e^{\mathbb{E} \left[ \log |H_{ii,n}|^2 \right] x_{i,n}}}{\sigma_{w_i,n}^2 + \sum_{j \neq i} \mathbb{E} \left[ |H_{ji,n}|^2 X_{j,n} \right]} \right) \\
&\quad \text{Statistical CSI } \gamma_{i,n}(x_{-i}) \times x_{i,n}
\end{align*}
\]

*Chosen as the objective function to maximize*

Satisfaction games

Formulation

- The channel users are **satisfied** if they achieve a predefined utility
  \[ u_i(x_i, x_{-i}) \geq \Gamma_i \]

- Their knowledge of the environment is reduced to a 1-bit feedback from RX to TX
  - ACK => keep the same strategy for the next round,
  - NACK => try another strategy

- **Satisfaction response** (SR)
  \[ \varphi_i(x_{-i}) = \{ x_i \in X_i \mid u_i(x_i, x_{-i}) \geq \Gamma_i \} \]

- The players are at a **satisfaction equilibrium** when none of them has a profitable deviation:
  \[ \forall i, \text{ either } x_i \in \varphi_i(x_{-i}) \text{ or } \varphi_i(x_{-i}) = \emptyset \]

M;Goonewardena et al., “Generalized Satisfaction Equilibrium: A Model for Service-Level Provisioning in Networks”, IEEE Trans. on Information Theory, June 2017
Satisfaction games

Learning satisfaction equilibria

- Assume that $\mathcal{X}_i$ are **totally ordered** and finite sets
  e.g. increasing transmit powers: $\mathcal{X}_i = \{p_1, p_2, \ldots, p_{N_i}\}$

- $J(x)$: set of **players having a profitable deviation** from the strategy profile $x = [x_1, \ldots, x_M]$
  $$J(x) = \{ i \in \{1, \ldots, M\} \mid x_i \notin \varphi_i(x_{-i}), \varphi_i(x_{-i}) \neq \emptyset \}$$

- $\mathcal{Y}_i(x_i)$: set of strategies of the player $i$ that are greater than the chosen strategy $x_i$
  $$\mathcal{Y}_i(x_i) = \{ x'_i \in \mathcal{X}_i \mid x_i < x'_i \}$$

- **Algorithm**: If a TX has a profitable deviation ($i \in J(x)$)
  - It has received NACKs from RX
  - It chooses randomly a higher strategy (in $\mathcal{Y}_i(x_i)$) for the next round
Satisfaction: possible with minimal knowledge
[Pottier et al., IEEE Access 2018] Joint work with A. Pottier and C. Laot

- **Example:** Satisfaction if utility = 1bit/s/Hz, knowledge = ACK/NACK
  (Txs and Rxs randomly located inside a 1.5 km radius circle)