Dynamic Spectrum Management for the Coexistence of Cognitive Tactical Radio Networks

Vincent Le Nir, Bart Scheers [1]

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[1]Royal Military Academy, Dept. Communication, Information Systems & Sensors (CISS) 30, Avenue de la Renaissance, B-1000 Brussels, BELGIUM

Outline

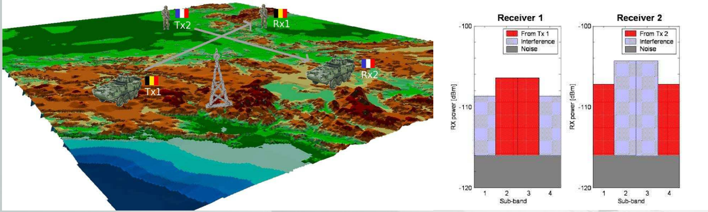
Introduction

Objective : Develop dynamic spectrum management techniques in the military VHF and UHF bands for tactical communications.

What kind of dynamic spectrum management technique are we looking for ?

- Distributed non-cooperative solution : decisions are made locally in an autonomous way.
- Horizontal spectrum sharing model : all nodes have equal rights to access the spectrum.
- Homogeneous networks : PHY layer uses multiple orthogonal sub-carriers (OFDM) or multiple non-overlapping sub-channels.
- Improved performance in throughput, power (longer battery life), delay.
- Robustness with wireless dynamic channels, security.

→ Coexistence of multiple coalition nations in a foreign country with no frequency planning.



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Introduction

Iterative waterfilling algorithm (IWFA) [Yu02] as a potential candidate to meet these requirements.

- IWFA improves the performance in throughput or power.
- IWFA is an autonomous algorithm.
- IWFA solves the distributed power control problem in a frequency selective interference channel.
- For DSL channels, the solution given by IWFA is unique (diagonal dominance of the interference channel).

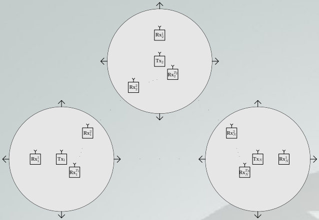
Issues with IWFA

- IWFA is designed for 1 Tx and 1 Rx. For tactical communications (1 Tx and several Rxs), common information should be sent to several receivers.
- Robustness of the IWFA with wireless dynamic channels. Robust versions of the IWFA should be used [Wang08][Scutari08][Setoodeh09][Gohary09][Hong11].
- For wireless channels, IWFA does not converge to a unique solution (multiple Nash equilibria).
- Security with malicious users.

Proposed solutions

- Extend the IWFA to broadcast channels (BC) with only common information [LeNir10].
- Improve the convergence behaviour of the IWFA in wireless channels by an expert rule based on sub-channel selection [LeNir11].

Iterative waterfilling algorithm



- For the theoretical analysis, we assume that the links between the transmitters and the receivers exhibit quasi-static fading, i.e. in which the coherence times of the fading channels are larger than the time necessary to compute the algorithm.
- The received signal $y_{j,it}$ in network j, sub-channel i and receiver t can be modeled as

$$y_{j,it} = h_{jj,it} x_{ij} + \sum_{k \neq j}^{N} h_{jk,it} x_{ik} + n_{j,it}$$

where N_c is the number of sub-channels, N the number of networks, $n_{j,it}$ the complex noise with variance $\sigma^2_{j,it}$ for the receiver t of network j on sub-channel i, x_{ij} the transmitted signal for network j on sub-channel i, and $h_{jk,it}$ the channel from network k to the receiver t of network j on sub-channel i.

Iterative waterfilling algorithm

We consider the maximization of the aggregate common rate subject to a total power constraint per network

$$\max_{\underline{\underline{\phi}}} \sum_{j=1}^{N} R_{0j}(\underline{\underline{\phi}})$$
$$\text{subject to} \sum_{i=1}^{N_c} \phi_{ij} = P_j^{tot} \ \forall j$$

with

$$R_{0j}(\underline{\underline{\phi}}) = \min_{1\ldots T_j} R_{0jt}(\underline{\underline{\phi}})$$

with

$$R_{0jt}(\underline{\underline{\phi}}) = \Delta f \sum_{i=1}^{N_c} \log_2(1 + \frac{|h_{jj,it}|^2 \phi_{ij}}{\Gamma(\sigma_{j,it}^2 + \sum_{k\neq j} |h_{jk,it}|^2 \phi_{ik})})$$

and $\underline{\underline{\phi}}$ the power allocation among all sub-channels and networks, $\phi_{ij} = E[|x_i|^2]$ the variance of the input signal on sub-channel i for network j, P_j^{tot} the total power constraint for network j, Δf the sub-channel bandwidth, and Γ the SNR gap which measures the loss with respect to theoretically optimum performance [Cioffi91].

Iterative waterfilling algorithm

The distributed algorithm called IWFA iteratively updates the power allocation of each network while considering the interference of all other neworks as noise.

- For $T_j = 1$, the power allocation for interference channels [Yu02] is given by

$$\phi_{ij}^{opt} = \left[\frac{1}{\tilde{\lambda}_j} - \frac{\Gamma\tilde{\sigma}_{j,i1}^2}{|h_{jj,i1}|^2}\right]^+$$

- For $T_j = 2$, the power allocation for parallel Gaussian broadcast channels with only common information [LeNir10] is given by

Find $\underline{\phi}_j^{(w_{j1},w_{j2})^{opt}}$ $\forall j$ given by

$$\phi_{ij}^{(w_{j1},w_{j2})} = \left[\frac{1}{2\tilde{\lambda}} + \sqrt{\frac{1}{4\tilde{\lambda}^2} - \frac{(a_{ij}-b_{ij})(w_{j1}-w_{j2})}{2\tilde{\lambda}} + \frac{(a_{ij}-b_{ij})^2}{4}} - \frac{a_{ij}+b_{ij}}{2}\right]^+$$

with

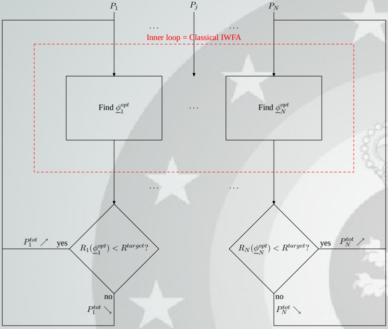
$$(w_{j1}, w_{j2})^{opt} = \min_{w_{j1},w_{j2}} \frac{\sqrt{\frac{1}{T_j}\sum_{t=1}^{T_j}[(R_{0jt}(\underline{\phi}_j^{(w_{j1},w_{j2})}) - \frac{1}{T_j}\sum_{t=1}^{T_j} R_{0jt}(\underline{\phi}_j^{(w_{j1},w_{j2})}))^2]}}{\frac{1}{T_j}\sum_{t=1}^{T_j} R_{0jt}(\underline{\phi}_j^{(w_{j1},w_{j2})})} \quad \forall j$$

in which $\underline{\phi}_j$ the power allocation among all sub-channels for network j,

$$a_{ij} = \frac{\Gamma\tilde{\sigma}_{j,i1}^2}{|h_{jj,i1}|^2} \text{ and } b_{ij} = \frac{\Gamma\tilde{\sigma}_{j,i2}^2}{|h_{jj,i2}|^2}.$$

Iterative waterfilling algorithm

The results from the previous optimization problem are also valid in case of the minimization of the aggregate toal power subject to a common rate constraint per network (distributed power control). An inner loop determines iteratively for each network the power allocation maximizing the common rate and satisfying its total power constraint. Then, an outer loop minimizes the total powers of the different networks individually such that a common rate constraint R^{com} is achieved.



Iterative waterfilling algorithm

Behaviour of the IWFA in a Matlab implementation. Static channels according to the node positions until the algorithm has converged.

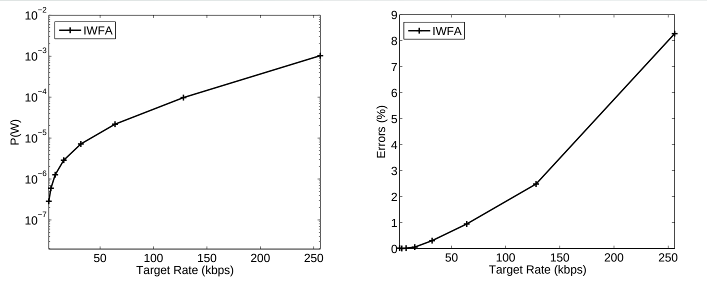
Carrier frequency f_c	80 MHz	Number of networks N	2
SNR gap Γ	9.8 dB	Sub-channel bandwidth	25 kHz
Path loss exponent n	4	Common rate constraint R^{com}	64 kbps

Iterative waterfilling algorithm

Convergence of the IWFA in a Matlab implementation with a jammer. Static channels according to the node positions until the algorithm has converged.

Iterative waterfilling algorithm

Convergence of the IWFA in a Matlab implementation using Monte Carlo Trials.
Static channels according to the node positions until the algorithm has converged.



$\longrightarrow$ Errors of convergence due to multiple Nash equilibrium in the case of strong interference channels. Necessity of another tool to study the the convergence and the effect of dynamic channels.

Expert rule based on sub-channel selection

Additioning an expert rule based on sub-channel selection gives three advantages

- Lower the complexity of the algorithm by allocating power only over a subset of the available sub-channels
- Lower the complexity of the physical layer in the case of a multi-carrier waveform with non-overlapping sub-channels
- Improve the convergence of the algorithm by giving more facility to the networks to avoid each other

At each iteration of the inner loop in the IWFA in parallel Gaussian broadcast channels with only common information, a network can only use L contiguous sub-channels, with $L \in \{1, N_c\}$. In fact, the network j chooses the subset of contiguous sub-channels exhibiting the maximum common rate

$$l_j^{opt} = \underset{l_j}{max} \min_{t=1\dots T_j} \Delta f \sum_{i=l_j}^{l_j+L-1} \log_2(1 + \frac{|h_{i,jj}|^2 P_j^{tot}}{L\Gamma\tilde{\sigma}^2_{j,it}})$$

The optimal subset of sub-channels to be used for the network j is therefore determined by

$$\mathcal{A}_j = \{l_j^{opt}, l_j^{opt} + L - 1\}$$

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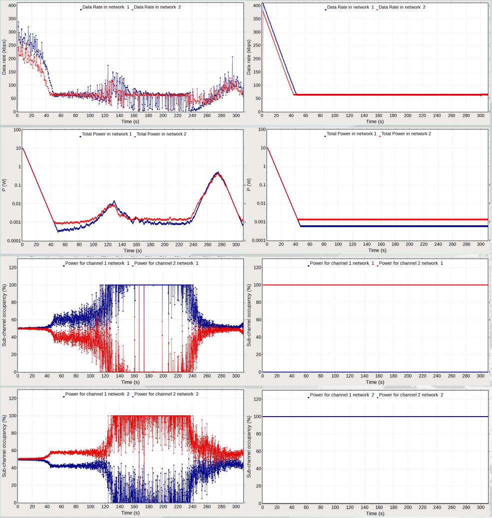
Expert rule based on sub-channel selection

Convergence and robustness of the algorithms in the discrete event simulator OMNeT++/MiXiM. Dynamic channels according to the node positions and relative doppler.

Carrier frequency f_c	80 MHz	Number of networks N	2
SNR gap Γ	9.8 dB	Time between inner loops	0.1s
Sub-channel bandwidth	25 kHz	Time between outer loops	0.5s
Path loss exponent n	4	Power updates (outer loop)	0.46 dB
Common rate constraint R^{com}	64 kbps	Speed v	90 km/h

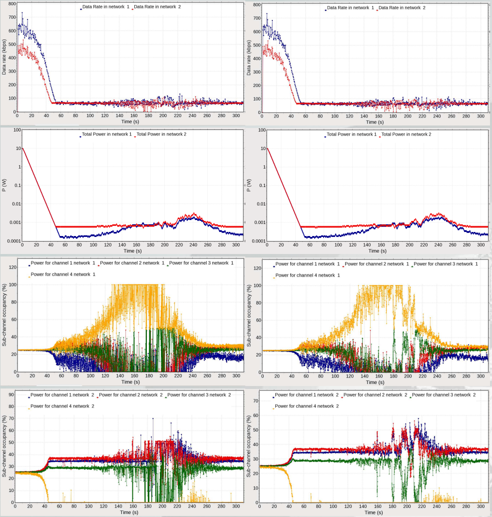
Expert rule based on sub-channel selection

Comparison between classical IWFA (left) and IWFA with sub-channel selection of a single sub-channel (right) ($N_c = 2$ sub-channels)



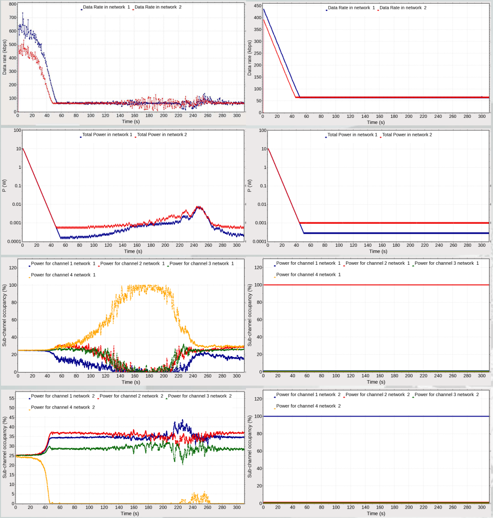
Expert rule based on sub-channel selection

Comparison between classical IWFA (left) and IWFA with averaging [Hong11] (right) ($N_c = 4$ sub-channels)



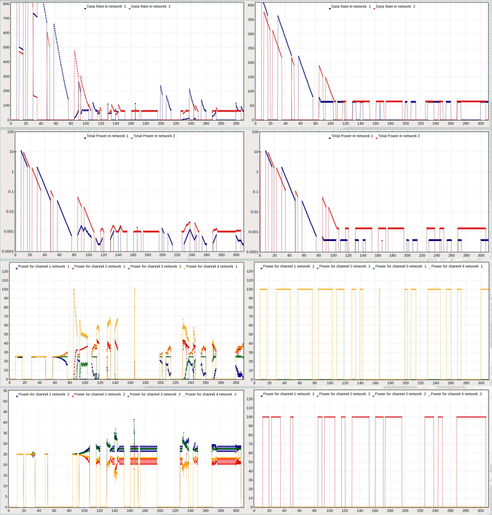
Expert rule based on sub-channel selection

Comparison between IWFA with circular averaging (left) and IWFA with sub-channel selection of a single sub-channel (right) ($N_c = 4$ sub-channels)



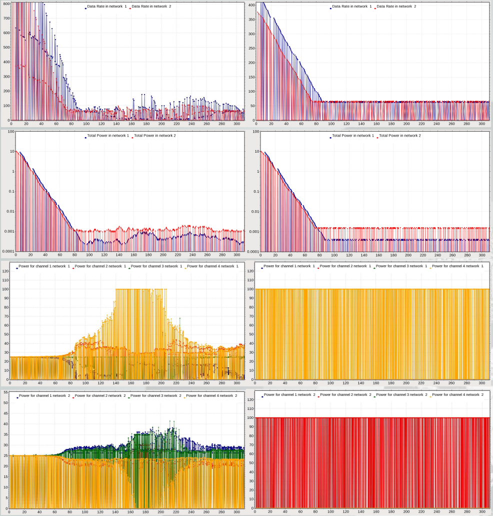
Expert rule based on sub-channel selection

Non-continuous transmission for voice (exponential distributions with 10s mean service time and 10s mean idle time)



Expert rule based on sub-channel selection

Non-continuous transmission for data (exponential distributions with 0.1s mean service time and 0.1s mean idle time)

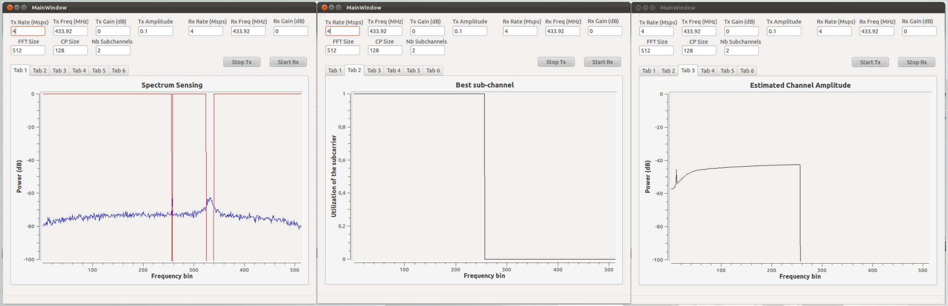


OFDMA PHY/MAC

- Advantages of the proposed OFDMA PHY/MAC
  - Do not require a dedicated control channel (single point of failure)
  - Small delay before establising a connection (contrary to a rendezvous MAC protocol)
  - Allow simultaneous collision-free transmissions
- Characteristics of the proposed OFDMA PHY/MAC
  - Based on the results of IWFA with selection of a single sub-channel by grouping several OFDM sub-carriers to form a sub-channel.
  - Two modes for handshaking (fixed bit-loading and adaptive bit-loading)
  - Robust against multipath due to the insertion of a cyclic prefix
  - Low complexity with a single-tap equalizer per sub-carrier
  - Blind demodulation chain for timing offset, frequency offset, channel estimation.
  - Residual ambiguity solved by transmitting a single sub-carrier pilot or by using differential encoding

OFDMA PHY/MAC

- Implementation of the proposed OFDMA PHY/MAC on USRPs using Qt4/IT++ and the UHD API



OFDMA PHY/MAC

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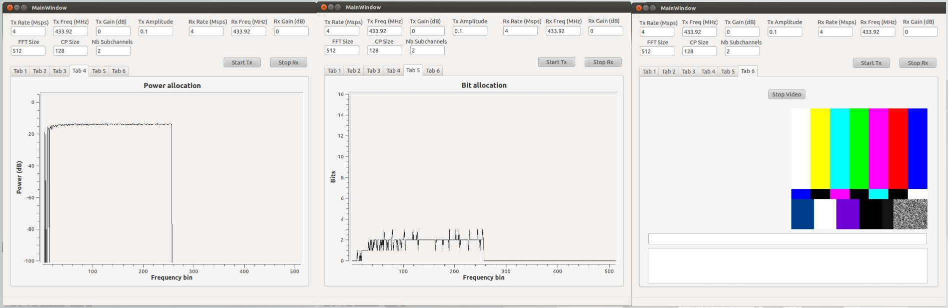

Conclusion

- Expert rule based on sub-channel selection
  - Lowers the complexity of the algorithm by allocating power only over a subset of the available sub-channels
  - Lowers the complexity of the physical layer in the case of a multi-carrier waveform with non-overlapping sub-channels
  - Improves the convergence of the algorithm by giving more facility to the networks to avoid each other
- IWFA with sub-channel selection of a single sub-channel shows no errors of convergence, which could be seen as an enhanced version of a simple "detect and avoid" strategy.
- IWFA with sub-channel selection of a single sub-channel efficient with a non-continuous transmission for voice and data
- OFDMA PHY/MAC to allow simultaneous collision-free transmissions
- Implementation on USRPs using Qt4/IT++ and the UHD API

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