COGNITIVE RADIOS:

A CASE FOR ARTIFICIAL COLLECTIVE INTELLIGENCE IN MOBILE COMMUNICATIONS NETWORKS

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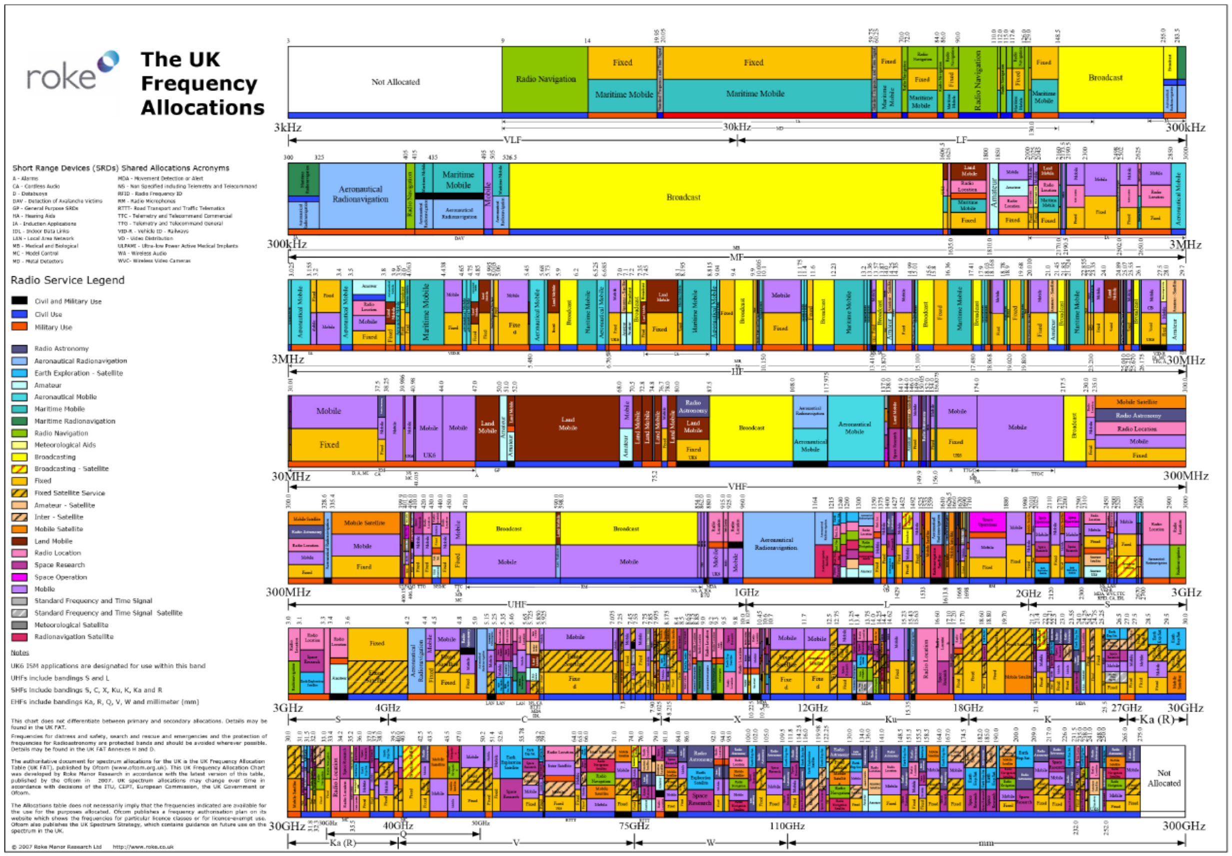
Research Interest

- Cognitive Radios: ACI
- Massive MIMO (EP/M016005/1)
- mmWave Communications
- Full-Duplex Communications (EP/N008219/1)
- Edge Caching & Fog Networking (540864)
- C-RAN, Fly-RAN, WPT, Mobile Computing, V2X, … etc.
- … and more

We will soon be running out of spectrum

- UK Frequency Allocation Table 2007



Source: Roke Manor Research

Use	Percentage of the total	Licence fee per MHz (£,000 per annum)
Aeronautical	25	1
Defence and Emergency Services	28	20
Broadcasting - Radio	1	112
Broadcasting - TV	16	2,000
Fixed Links	5	35
Maritime	5	15
Private Business Radio	4	100
2G Mobile (900+1800MHz)	8	300
3G Mobile (2100MHz)	**7**	**21,000**
Other Mobile	1	257
Total	**100**	

Ofcom raised £22.5bn from the 3G auction in 2000 and £2.34bn from the 4G auction in 2013

- Spectrum: expensive, *limited* and regulated by Ofcom in the UK

Spectrum is underutilised as well

- Rigid and inefficient management (Ofcom's report in 2007)

- The way spectrum is shared is changing worldwide
  - US reclaimed 85 MHz of UHF, authorized the reuse of 500 MHz of spectrum; Germany switched off analogue broadcasting in Berlin, etc.

- **Great opportunity** in the UK:
  - Over 50% of locations have more than 150MHz spectrum
  - Even at 90% of locations have around 100MHz of spectrum
    - Billions of £'s wasted (the entire 3G spectrum only 75MHz!)

- Great interest for licence-exempt cognitive access but
  - Do NOT know how to handle the interference
  - The interference temperature model by FCC abandoned in 2007
  - Current approaches use geolocation databases, IEEE 802.22 in 2011

A definition of cognitive radio

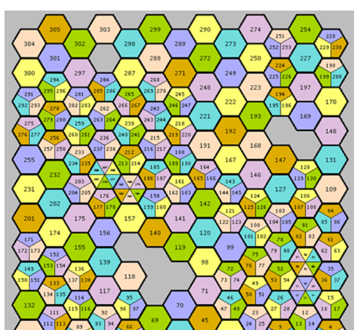
- First proposed by **Joseph Mitola III** in a seminar at KTH in 1998

"The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs."

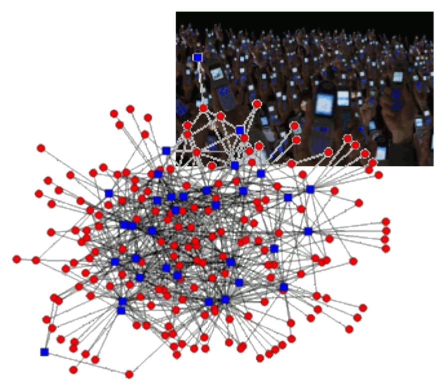
- In engineering terms, it means:

"A cognitive radio (CR) is a radio that can be programmed and configured dynamically to use the best wireless channels in its vicinity to avoid user interference and congestion."

- In very simple terms, CR is **AI radio**!



Static frequency planning
(e.g. cellular networks)



Autonomous spectrum access
(e.g., M2M networks)

The challenge is ACI

- CR needs to be more than just AI in radio
- The concept of CR seeks to have a paradigm shift from

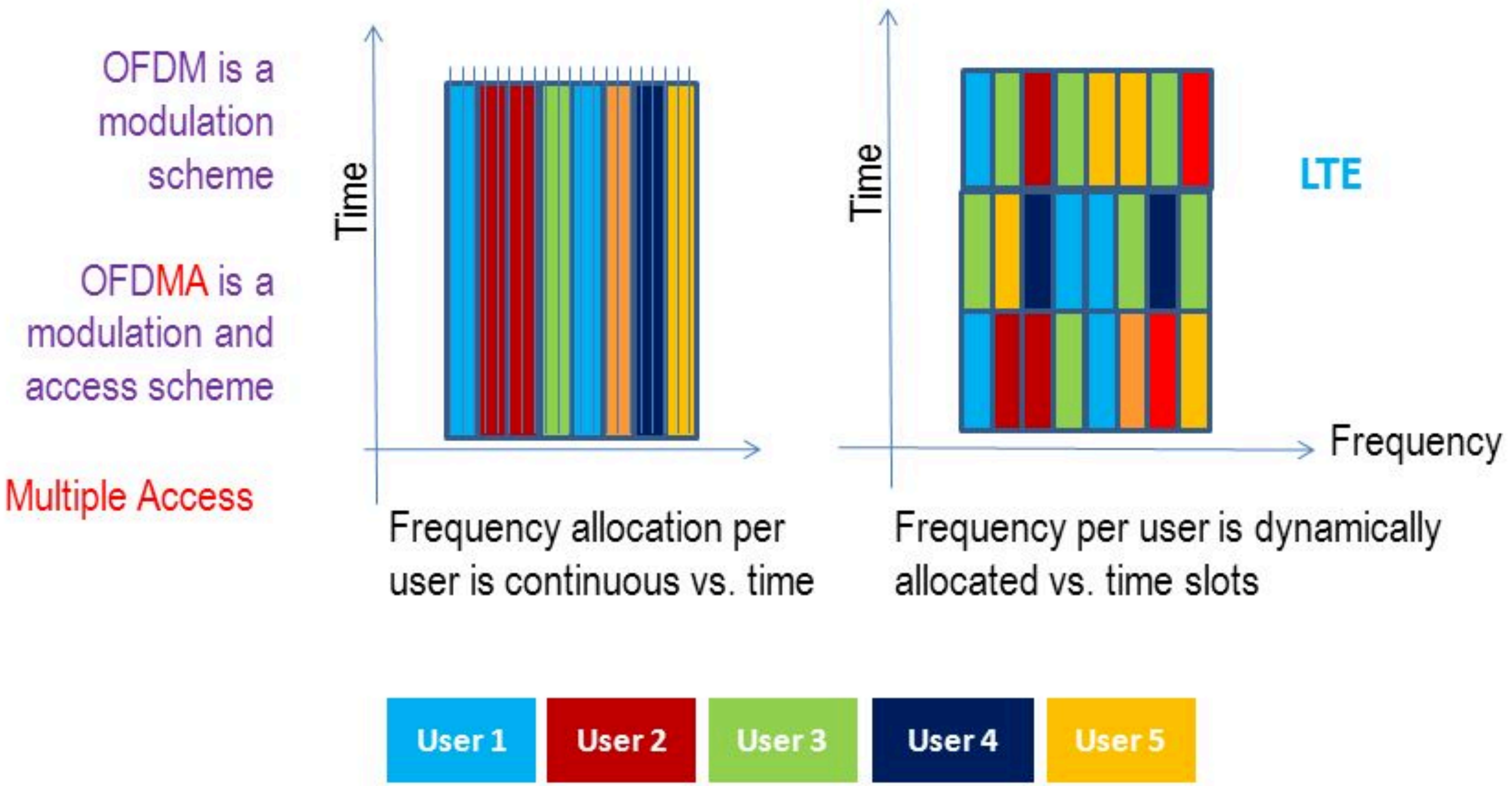
centralised static frequency planning to *a dynamic distributed self-regulating network of competing individuals*

Challenge 1 – AI radio needs to have *global network intelligence* based on *limited local observations*

Challenge 2 – Multiple AI radios compete with each other!

- Ensuring ***Artificial Collective Intelligence*** is the Key!

Spectrum sharing in OFDMA



OFDM = orthogonal frequency division multiplexing
OFDMA = orthogonal frequency division multiple access

- Users occupying the same subcarrier the same time will be avoided

The CR approach: Autonomous OFDMA

- Every user is free to access any of the N subcarriers
- The aim is to decide the power allocation over the subcarriers for all the users in order to maximise the network rate
- The aim of the network is to

$$\boxed{\max_{\{p_k[n]\geq 0, \forall k, n\}} R_1 + R_2 + \cdots + R_k + \cdots + R_K \text{ s.t. } \sum_{n=1}^{N} p_k[n] \leq P_k \ \forall k}$$

- User k's interest will be to solve:

$$\max_{p_k[n]\geq 0, \forall n} \quad R_k = \sum_{n=1}^{N} \log_2 \left(1 + \frac{p_k[n]}{\underbrace{\frac{N_k[n]}{|H_{kk}[n]|^2}}_{\sigma_k[n]} + \underbrace{\sum_{\substack{i=1 \\ i\neq k}}^{K} p_i[n] \frac{|H_{ik}[n]|^2}{|H_{kk}[n]|^2}}_{I_k[n]}} \right)$$

$$\text{s.t.} \quad \sum_{n=1}^{N} p_k[n] \leq P_k$$

$$\boxed{c_k[n] \triangleq \sigma_k[n] + I_k[n]}$$

A quick review of the literature

- **Centralised approaches** – if there is a centralised spectrum manager who knows full network CSI, then

OSB: The optimal solution

- The solution may be found by a nested bisection search in the λ-space
- Computationally highly complex

[A] R. Cendrillon, W. Yu, M. Moonen, J. Verlinden, and T. Bostoen, "**Optimal multiuser spectrum balancing for digital subscriber lines**," *IEEE Trans. Commun.*, vol. 54, no. 5, pp. 922–933, May 2006.

ISB: A near-optimal solution

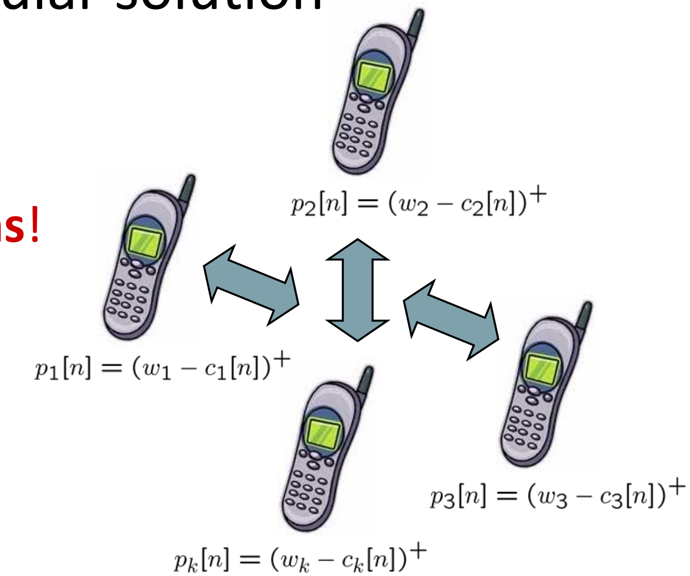
- Can be solved efficiently by decoupling it into N independent problems

$$\sum_{n=1}^{N}\left\{\max_{\{p_k[n]\forall k\}}\left[\sum_{k=1}^{K}\log_2\left(1+\frac{p_k[n]}{c_k[n]}\right)-\sum_{k=1}^{K}\lambda_k p_k[n]\right]\right\}+\sum_{k=1}^{K}\lambda_k P_k$$

[B] W. Yu and R. Lui, "**Dual methods for nonconvex spectrum optimization of multicarrier systems**," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1310–1322, Jul. 2006.

A quick review of the literature

- Game theory is about analysing interactions between individuals
- Simultaneous water-filling (WF) is a popular solution
  - ✅ Each AI radio needs only *local CSI*
  - ❎ CRs selfishly compete → highly inefficient
  - ❎ Leading to **NE = the tragedy of the commons**!



[C] G. Scutari, D. P. Palomar, and S. Barbarossa, “**Competitive design of multiuser MIMO systems based on game theory: A unified view**,” *IEEE J. Select. Areas Commun.: Special Issue Game Theory*, vol. 25, no. 7, pp. 1089–1103, Sep. 2008.

[D] K. Akkarajitsakul, E. Hossain, D. Niyato, and D. Kim, “**Game theoretic approaches for multiple access in wireless networks: A survey**,” *IEEE Commun. Surveys & Tutorials*, Mar. 2011.

[E] O. Popescu, C. Rose and D. C. Popescu, “**Simultaneous water-filling in mutually interfering systems**,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 1102–1113, Mar. 2007.

[F] Z.-Q. Luo and J.-S. Pang, “**Analysis of iterative waterfilling algorithm for multiuser power control in digital subscriber lines**,” *EURASIP J. Applied Sig. Proc.*, May 2006.

[G] K. W. Shum, K.-K. Leung, C. W. Sung, “**Convergence of iterative waterfilling algorithm for Gaussian interference channels**,” *IEEE J. Select. Areas Commun.*, vol. 25, no 6, pp. 1091–1100, Aug. 2007.

[H] G. Scutari, D. P. Palomar, and S. Barbarossa, “**Optimal linear precoding strategies for wideband non-cooperative systems based on game theory— part I & II: Nash equilibria & algorithms**,” *IEEE Trans. Sig. Proc.*, vol. 56, no. 3, pp. 1230–1267, Mar. 2008.

A foresighted CR

- A user can gain more from the game if the user is foresighted
  - Foresightedness = know what is going to happen upon one's action
  - Foresighted if full CSI + the strategies of other users are known
- Described by the Stackelberg Equilibrium (SE)

1. A leader-follower model
2. The leader is foresighted but the followers are myopic
3. The leader directs the game and acts first
4. The leader waits for a steady-state response (an NE of the rest of the users) before it revises its action
5. In so doing, the game will reach the equilibrium that is most beneficial to the leader

- ❎ Full network CSI (✅ can be addressed by conjectures)
- ❎ Bi-level: A strict order of how the game should proceed
- ❎ Can *all* users be foresighted at the same time?

[I] Y. Su and M. Schaar, "**A new perspective on multi-user power control games in interference channels**," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 2910–2919, Jun. 2009.

[J] Y. Su and M. Schaar, "**Conjectural equilibrium in multiuser power control games**," *IEEE Trans. Sig. Proc.*, vol. 57, no. 9, pp. 3638–3650, Sep. 2009.

Our views

- ❎ The idea of leader-follower is impractical
- ✅ Users cannot all be leaders *but* can all be *forward-looking*!
- 📶 *Is it possible to have such ability with local CSI?*

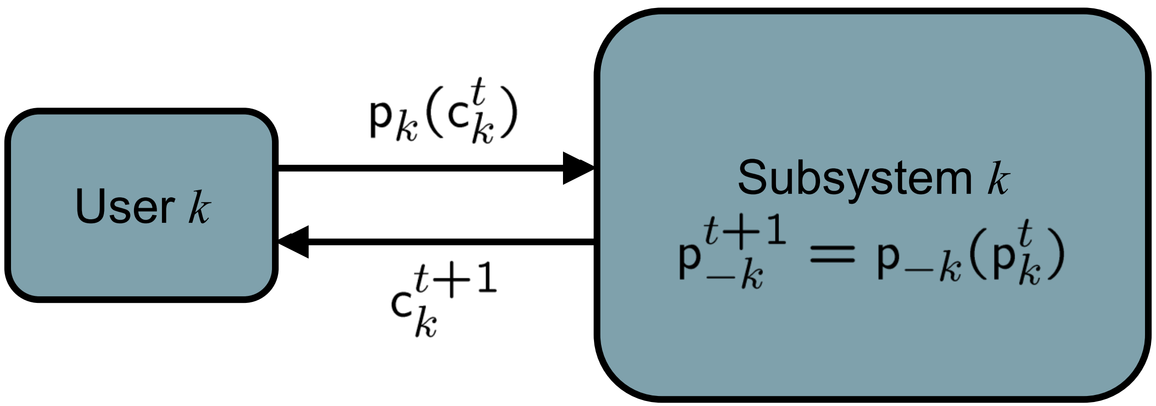
  ACI: Local Observations → Global Forward-Looking-ness?
- 🎉 The good news is: This is indeed possible!

Our approaches

- 📶 To introduce the interactiveness of the game into the optimisation of one's action (via a *belief-directed game*)
- 📶 To study the key properties of NE and SE
  - ▶️ See if forward-looking capability can be realised by local CSI
  - ▶️ To propose a *new* equilibrium (FE via BNE) in which users are all forward-looking using the properties of NE and SE

A subsystem model for the OFDMA game

- For each user we view it as a user (e.g., user k) interacting with an environment (which consists of the rest of the users)
- User k acts by its power allocation strategy $\mathsf{p}_k \triangleq \{p_k[n] \forall n\}$
- The environment reacts with an overall response, a result of the actions by all other users $\mathsf{p}_{-k} \triangleq \{\mathsf{p}_1, \dots, \mathsf{p}_{k-1}, \mathsf{p}_{k+1}, \dots, \mathsf{p}_K\}$



Autonomous OFDMA:
A belief-directed game of forward-looking players

- Environmental function to quantify the influence of other CRs' strategies p_{-k}^t onto CR k's reward $\mathsf{c}_k(\mathsf{p}_{-k}^t)$
- Belief function to reflect a CR's understanding on its environment function about the competition in the game, $\mathsf{c}_k^{\mathsf{B}}(\mathsf{p}_k, \mathsf{p}_{-k}^t)$

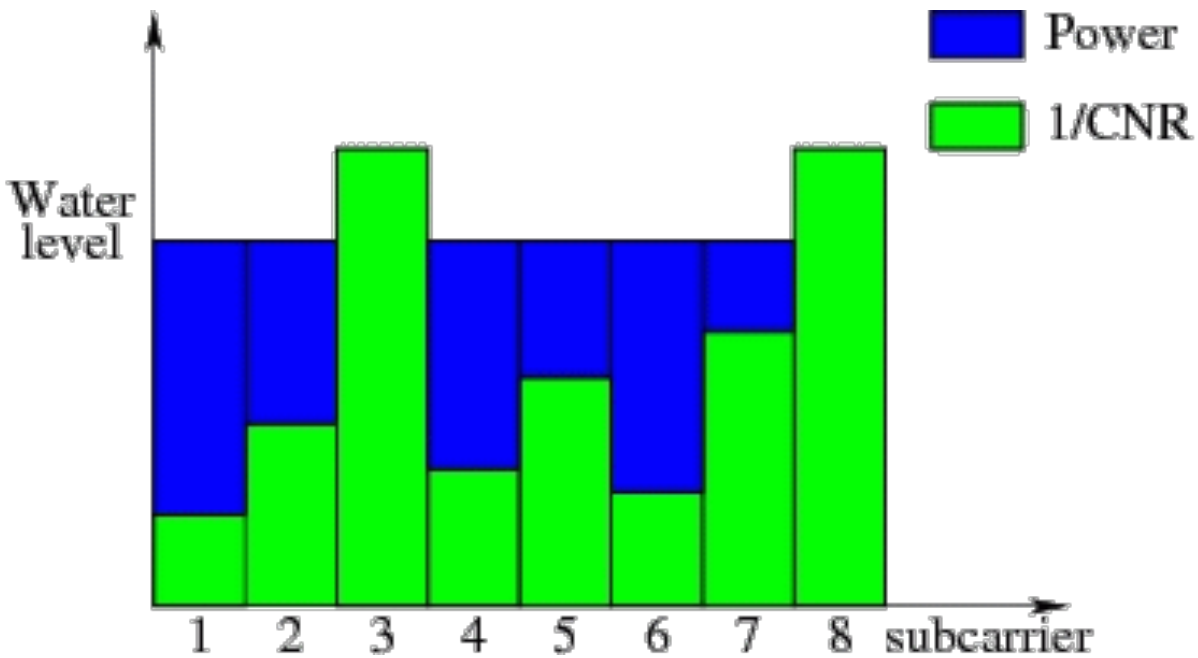
$$c_k^{\mathsf{B}}[n] \triangleq c_k^t[n] + \sum_{\ell=1}^{\infty} {\varphi_k^t}^{(\ell)}[n](p_k[n] - p_k^t[n])^{\ell}$$

where ${\varphi_k^t}^{(\ell)}[n]$ is the ℓ th order derivative of the belief function w.r.t. CR k's strategy at time t, $\mathsf{p}_k^t = \{p_k^t[1], \ldots, p_k^t[N]\}$

- The *forward-looking* reward to reflect a CR's utility

$$f_k(\mathsf{p}_k, \mathsf{c}_k^{\mathsf{B}}(\mathsf{p}_k, \mathsf{p}_{-k}^t)) \triangleq \sum_{n=1}^{N} \log_2\left(1 + \frac{p_k[n]}{c_k^{\mathsf{B}}[n]}\right)$$

Water-filling power allocation



- For a single-user case, it is well known that the optimal power allocation has an interpretation of water filling
- Better subcarriers, more power to obtain higher rate

Forward-looking water-filling (FWF)

- In the belief-directed OFDMA game, at time t, CR k aims to

$$\mathsf{p}_k^{t+1} = \arg \max_{\mathsf{p}_k \in \mathcal{P}_k} f_k(\mathsf{p}_k, \mathsf{c}_k^{\mathsf{B}}(\mathsf{p}_k, \mathsf{p}_{-k}^t))$$

- One can then analyse the game and show that at the forward-looking equilibrium (FE), the optimal strategy is given by

$$p_k^*[n] = \left(\frac{w_k^* c_k^*[n] - (c_k^*[n])^2}{w_k^* \varphi_k^*[n] + c_k^*[n]} \right)^+, \quad \forall k, n$$

- Furthermore, one can maximise the rates at FE by choosing

$$\boxed{\varphi_k[n] = -\sqrt{\frac{c_k[n]}{2c_k[n] + p_k[n]}}, \quad \forall k, n}$$

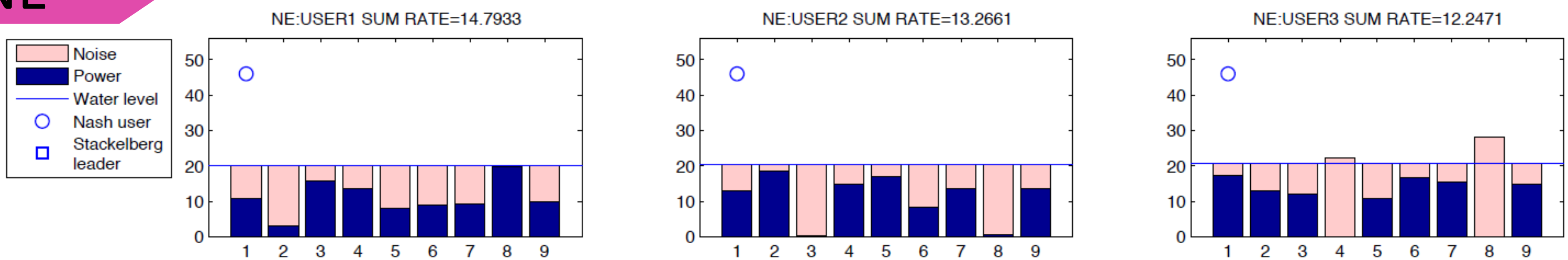
ACI: Autonomous negotiation by FWF

- The harmonisation and negotiation among the CRs are done automatically by competing *calmly* by FWF (with some forward-looking ability introduced by the belief function)

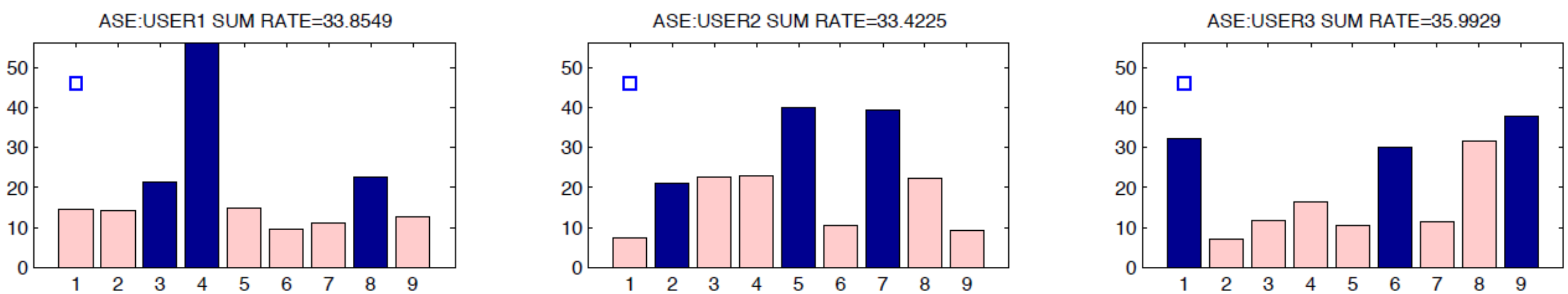
$$
\boxed{\begin{cases} p_k[n] = (w_k - \eta_k[n])^+ \\ \eta_k[n] = \dfrac{c_k^2[n] + \tilde{\varphi}_k[n] p_k^2[n]}{c_k[n] - \tilde{\varphi}_k[n] p_k[n]} \\ \tilde{\varphi}_k[n] = -\sqrt{\dfrac{c_k[n]}{2c_k[n] + p_k[n]}} \end{cases}} \rightarrow \begin{cases} p_k^t + \eta_k^t(\mathsf{p}_k^{t-1}) = w_k^t \\ p_k^{t+1} + \eta_k^t(\mathsf{p}_k^t) = w_k^{t+1} \\ \vdots \\ p_k^* + \eta_k^* = w_k^* \end{cases}
$$

NE (traditional) vs FE (proposed)

NE



FE



- CRs in NE jam each other and suffer from severe interference
- CRs in FE manage to avoid each other and settle on their best subcarrier channels for highest capacities

Results: Convergence

- Illustration of the user strategies

Table 1: Simulation results for the 2-user 2-subcarrier deterministic channel.

Equilibrium	NE		SE		FE	
User k	User 1	User 2	User 1	User 2	User 1	User 2
$p_k[1]$	2.00	8.00	0	9.00	0	9.99
$p_k[2]$	8.00	2.00	9.99	1.00	9.99	0
Rate R_k	2.6439	2.6438	2.9386	3.4739	3.4594	3.4594

- Is convergence an issue?

Table 2: Number of times for divergence in 1000 independent simulations.

(K, N)	$(3, 9)$			$(4, 16)$			$(5, 15)$		
Equilibrium	NE	SE	FE	NE	SE	FE	NE	SE	FE
$x = 5$	0	0	0	5	2	0	9	7	0
$x = 0.8$	78	58	0	310	251	0	386	323	0
$x = 0.5$	23	25	0	115	122	0	200	203	0
$x = 0.2$	0	0	6	0	0	39	0	0	48

Results: Achievable rates

- Average rates for the users

Table 3: Average users' sum-rates for the 3-user 9-subcarrier interference channel.

Sum-rate	User 1	User 2	User 3
NE	13.9944	13.8966	13.8021
SE	16.5275	15.5493	15.4743
FE	32.6641	32.8518	33.0399

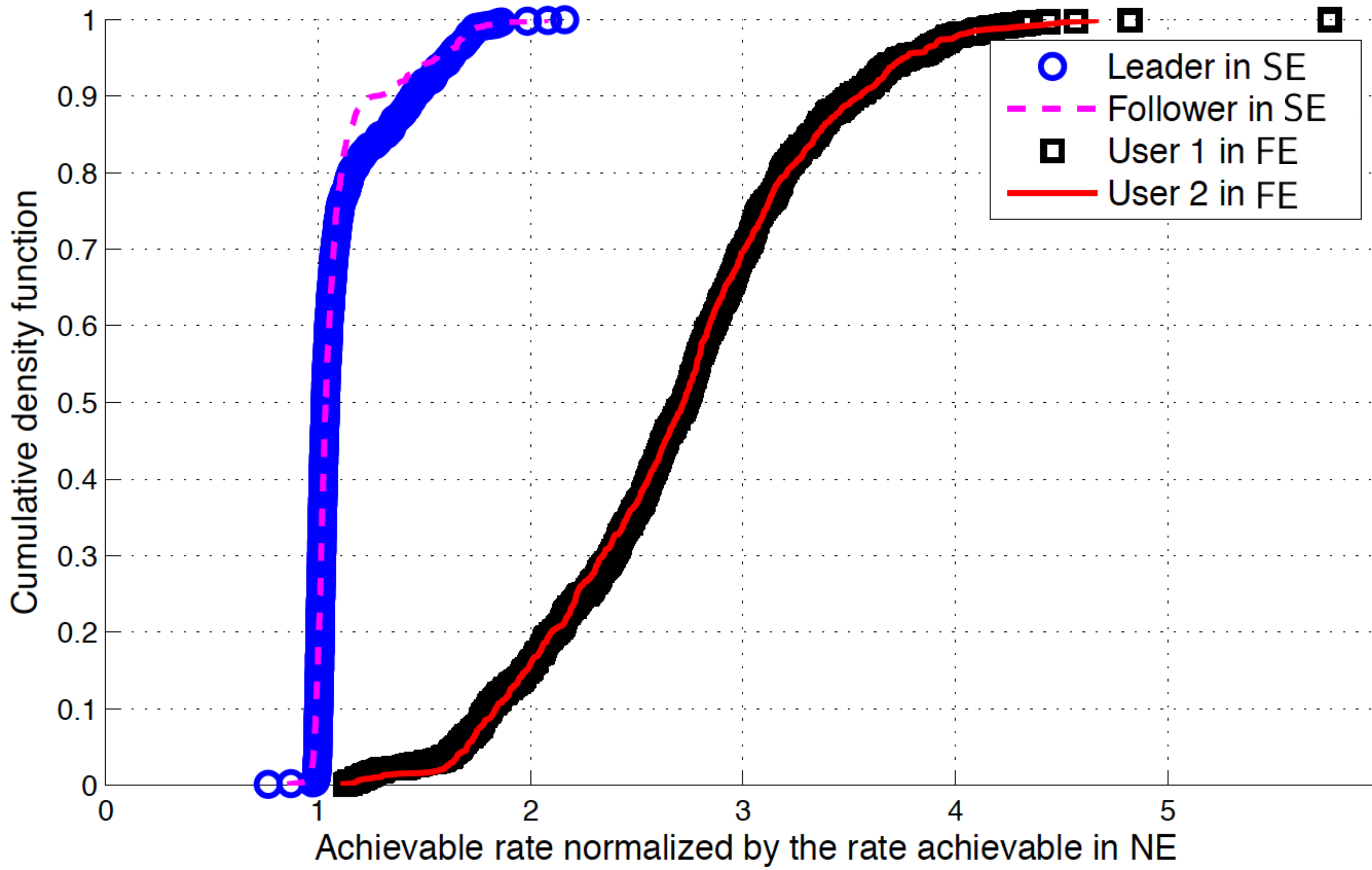
- Comparison with the optimal centralised solution

Table 4: The average per-user sum-rates for FE and ISB.

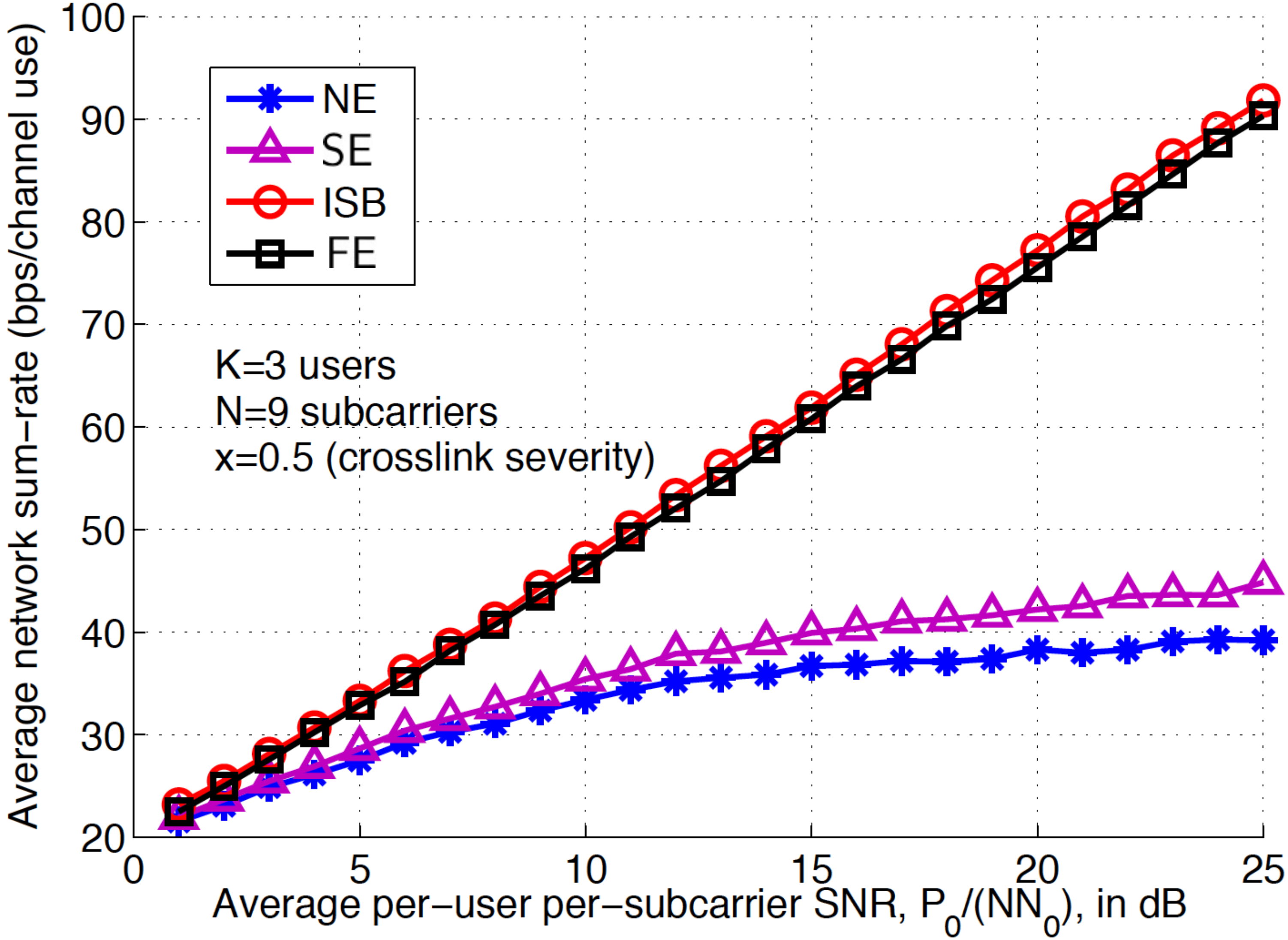
(K, N)	$(3, 9)$	$(6, 18)$	$(12, 36)$
FE	32.8414	32.2201	31.6874
ISB	34.6674	35.5500	35.6335

Results: Rate CDFs

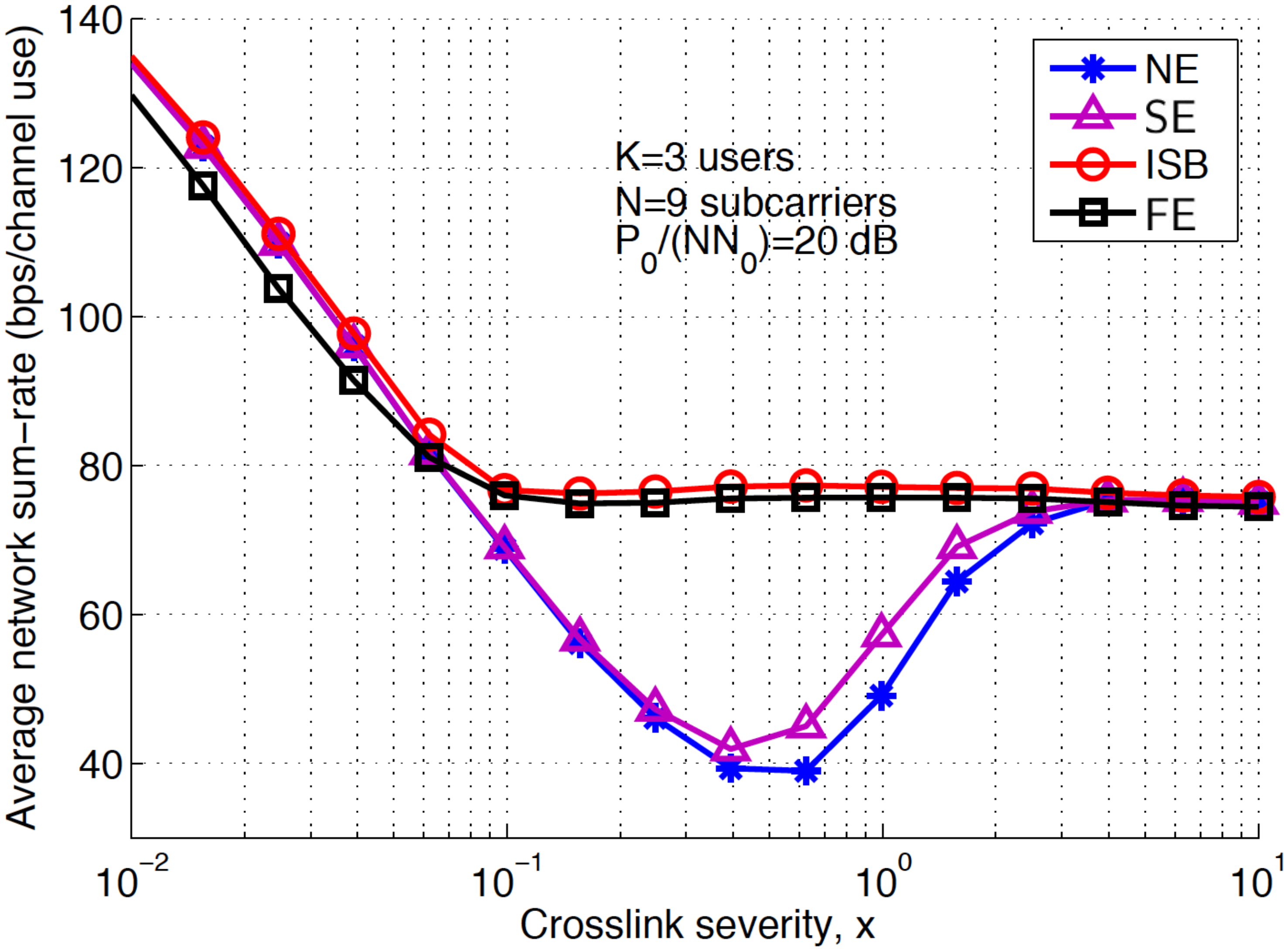
- The CDFs of the rates normalised by those achieved in NE



Results: Rate vs SNR

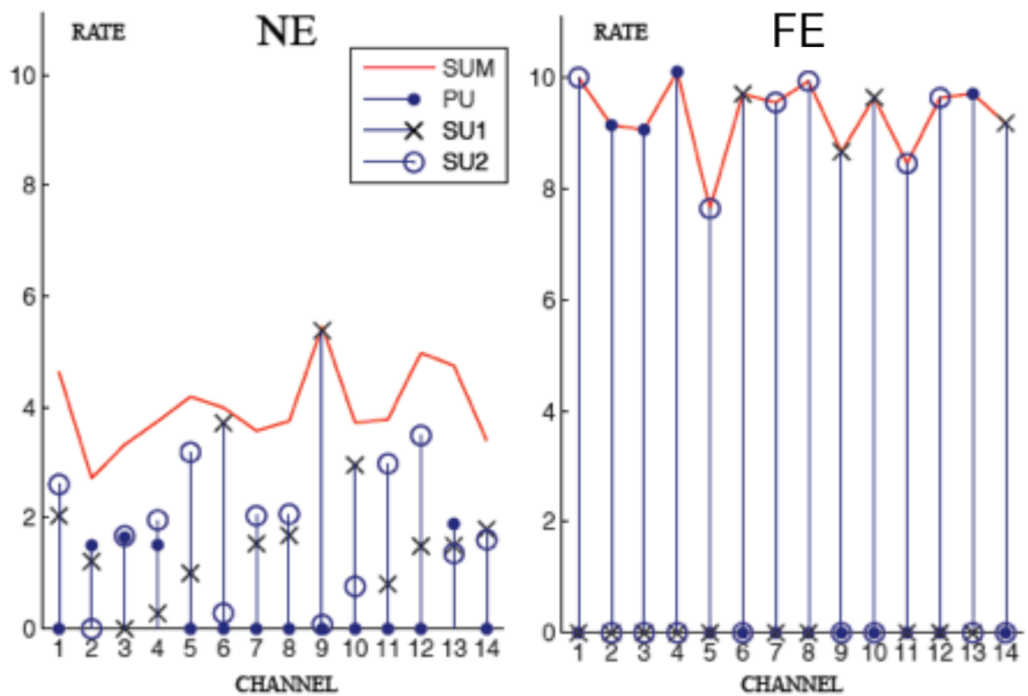


Results: Rate vs x



CRs with primary user protection

- 📶 In the interweave model, CRs are allowed to occupy the spectrum rooms left vacant by the *primary users*
- ✅ Primary users are automatically avoided while secondary users (i.e., the CRs) negotiate with each other for rate maximisation



Results: FE vs NE in the interweave model

❎ NE secondary users harm primary users

✅ FE secondary users do NOT affect primary users

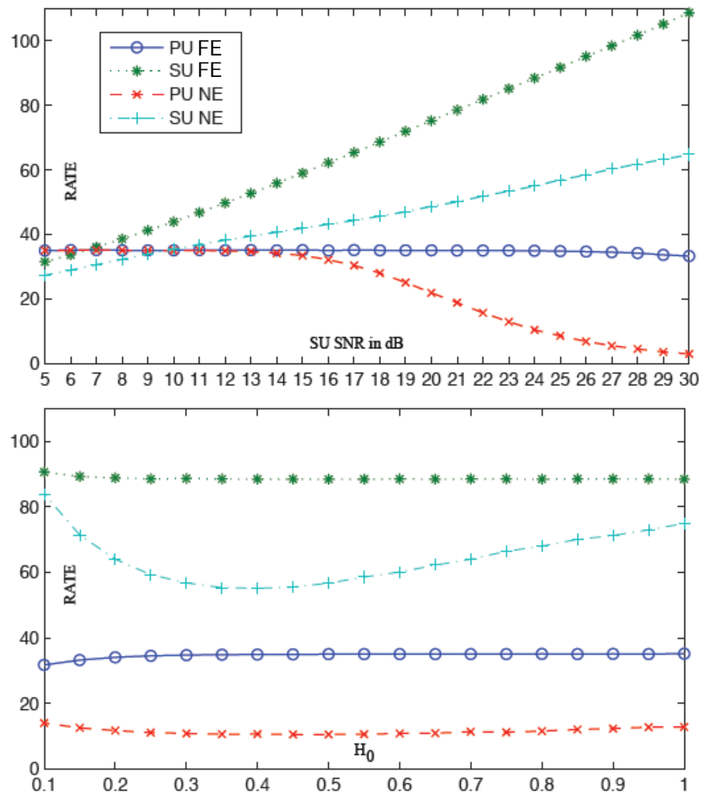


Fig. 2. The average sum-rate results against the SU SNR with $H_0 = 0.4$ (top) and the interference level H_0 with SU SNR = 24 dB (bottom).

Downside?

❎ Interference is present in the negotiation process

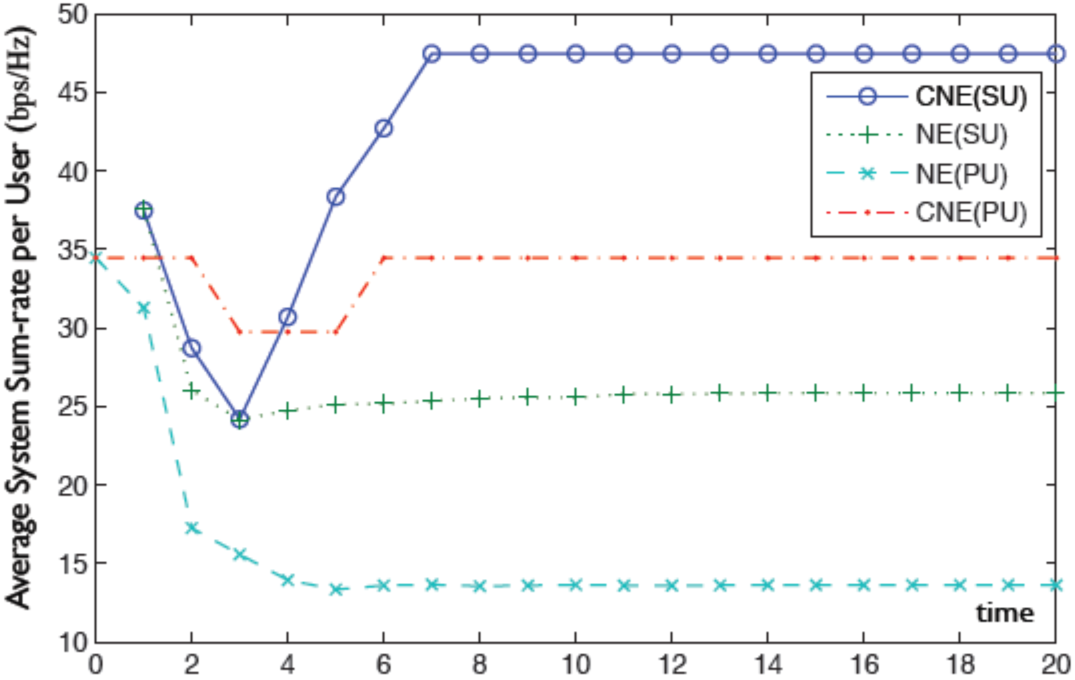


Fig. 3. Sum-rate against the number of interactions for the cognitive Nash game between users with $H_0 = 0.4$, $S = 0.1$ and SNR$= 20$ dB.

Conclusions

What we know

a) Cognition ability can be introduced by belief function
b) Self-optimisation requires global forward-looking capability or ACI
c) Forward looking OFDMA can be gained from local CSI observations
d) FE has a built-in learning ability for protecting primary users
e) OFDMA FE achieves the rate close to that of ISB (centralised)

? A lot remain to be addressed

i. How to speed up the convergence to FE or its variant?
ii. How to control the interference to PUs in the negotiation process?
iii. What if users are heterogeneous, how does that affect their actions?
iv. Can the technique be applied to more complicated networks (e.g., fog network, fly-RAN, NFV, cooperative and relaying networks and etc.)?

If interested

- Parts of the results have appeared in

[1] J. Ren, K. K. Wong, and M. R. A. Khandaker, "**Autonomous spectrum sharing by well-designed games**," in *Handbook of Cognitive Radio*, Editors: Wei Zhang, Springer Singapore, pp. 1-50, 2017.

[2] J. Ren, K. K. Wong, and J. Hou, "**A forward-looking Nash game and its application to achieving Pareto-efficient optimization**," *Applied Mathematics*, vol. 4, no. 12, pp. 1609-1615, December 2013.

– THE END –

Thank you for your attention!