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Cooperative spectrum sensing based on noise power estimation

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Outline

- Introduction
- Cooperative ENP model + validation
- Capacity aware optimization
- Conclusion

Introduction

- Spectrum sensing is a key enabling technology for Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) networks
  - Provides reliable Primary User (PU) detection
  - Aids the decision making process
- Energy detection based spectrum sensing is optimal when *sufficient information on the PU signal is unavailable*
- The alleged SNR wall* (noise uncertainty) limits the performances of the energy detection (+ change of system noise due to temperature variation, initial calibration error, presence of interferers)
- However, the SNR wall is not caused by the presence of noise power uncertainty, but by insufficient information about the noise power estimation
  - Estimated Noise Power (ENP) approach alleviates the SNR wall problem ** by collecting sufficient noise statistics
- This work extends the ENP theory for the Cooperative Spectrum Sensing (CSS) case providing:
  - A practical (experimental) validation of the derived CSS-ENP energy detection analytical models
  - Investigation of the *asymptotic behavior* of the proposed approach
  - A Secondary User (SU) system *capacity aware optimization*

** R. Tandra and A. Sahai, "SNR walls for signal detection," IEEE J. Sel. Topics Signal Process., vol. 2, pp. 4–17, Feb. 2008.*

*** A. Mariani, A. Giorgetti, M. Chiani, "Effects of Noise Power Estimation on Energy Detection for Cognitive Radio Applications," IEEE Trans. Communications, vol. 59, no. 12, pp. 3410-3420, December 2011.*

*** Daniel Denkovski, Vladimir Atanasovski and Liljana Gavrilovska, "HOS based goodness-of-fit testing signal detection," IEEE Communications Letters, Vol. 16, Issue 3, pp. 310-313, March 2012.*

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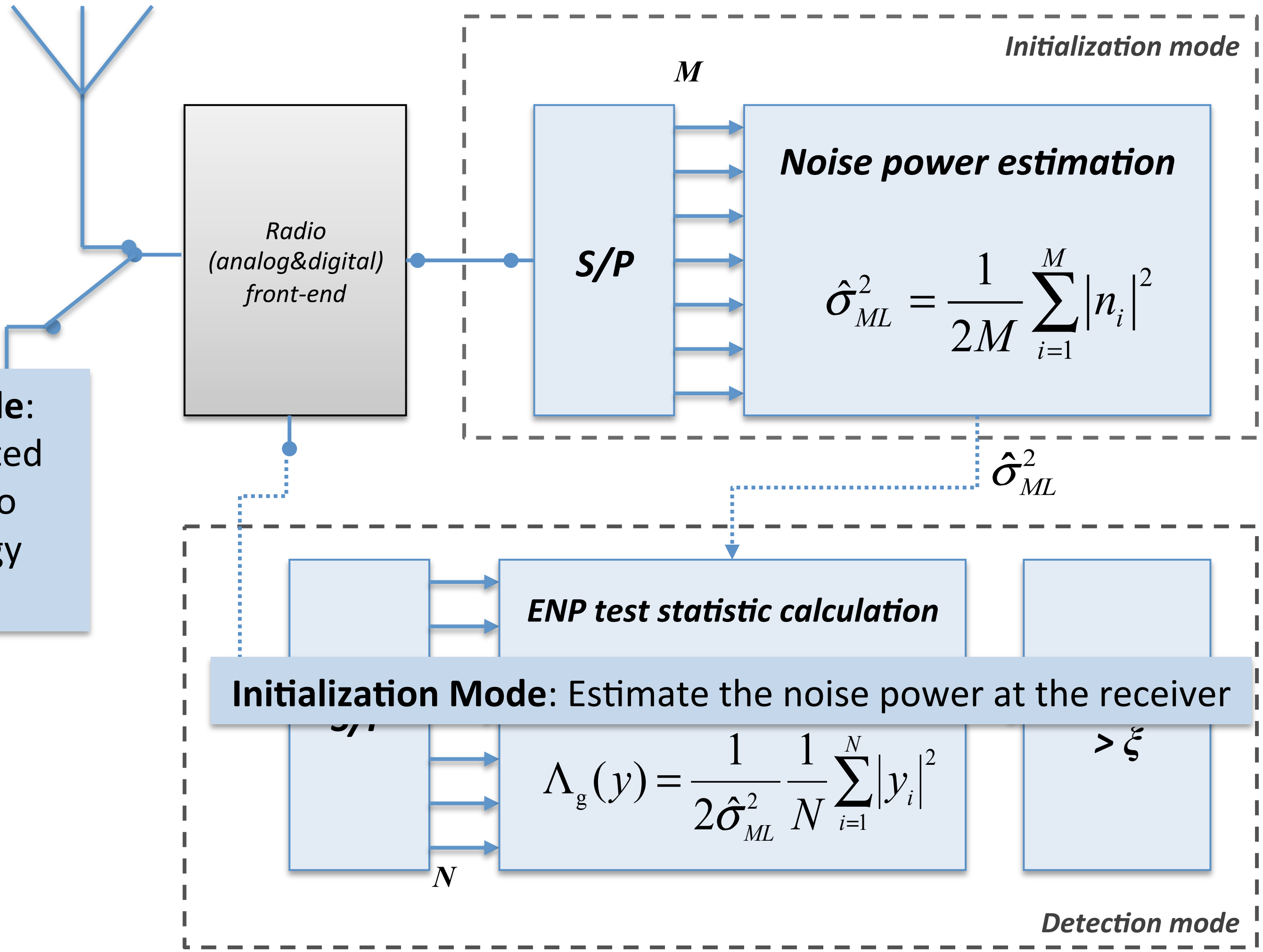
Energy detection based on ENP



Detection Mode: Use the estimated noise power to perform energy detection

Initialization Mode: Estimate the noise power at the receiver

Cooperative ENP*

Equal Gain Combining (EGC) cooperative sensing

- Soft fusion (combining) of *K* user signals
- ML estimation of σ^2 using M noise samples

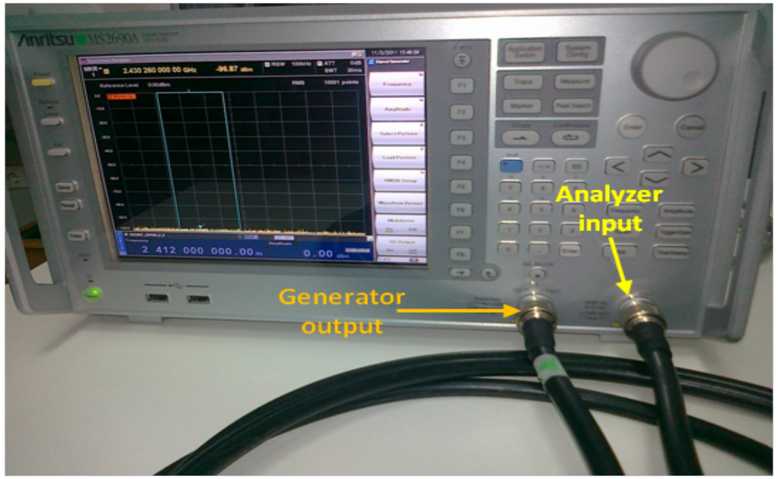
Majority voting (MV) cooperative sensing

- Hard fusion (combining) of *K* user signals – individual signal detection
- Signal is declared present, if at least *K/2 nodes* detect it

** V. Rakovic, V. Pavlovska, V. Atanasovski, L. Gavrilovska, "Cooperative spectrum sensing based on noise power estimation," 2013 International Symposium on Wireless Personal Multimedia Communications, June, 2013, Atlantic City, USA.*

Experimentation validation

- Equipment: Anritsu MS2690A signal analyzer
- Metric of interest: probability of detection (P_d) vs. SNR
- Evaluation parameters:
  - N = 1024-:-65536 sample size, $M = 10^7$ noise samples per scenario
  - K = 1, 2, 5 and 10 cooperative users
  - Decision thresholds for probability of false alarm P_{fa}= 1%

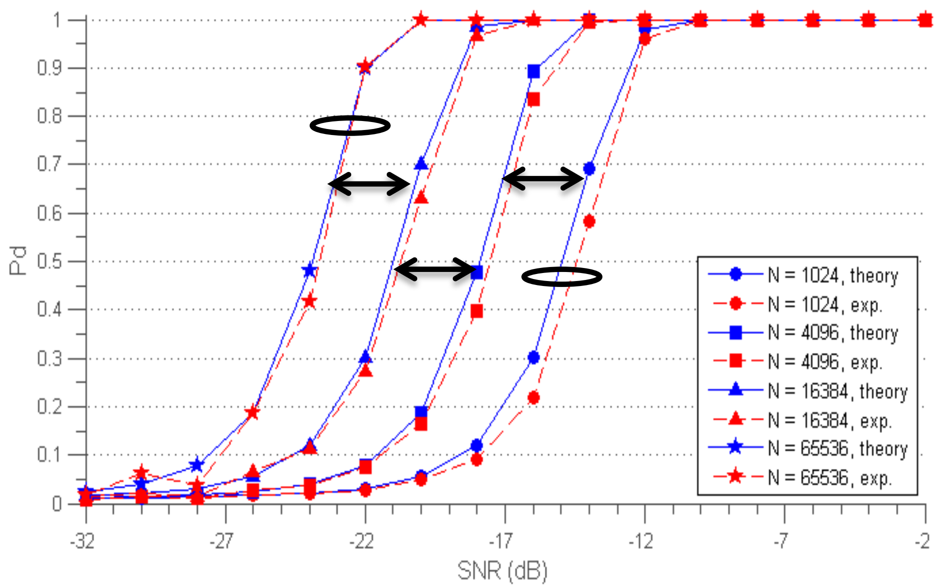


Measurement setup

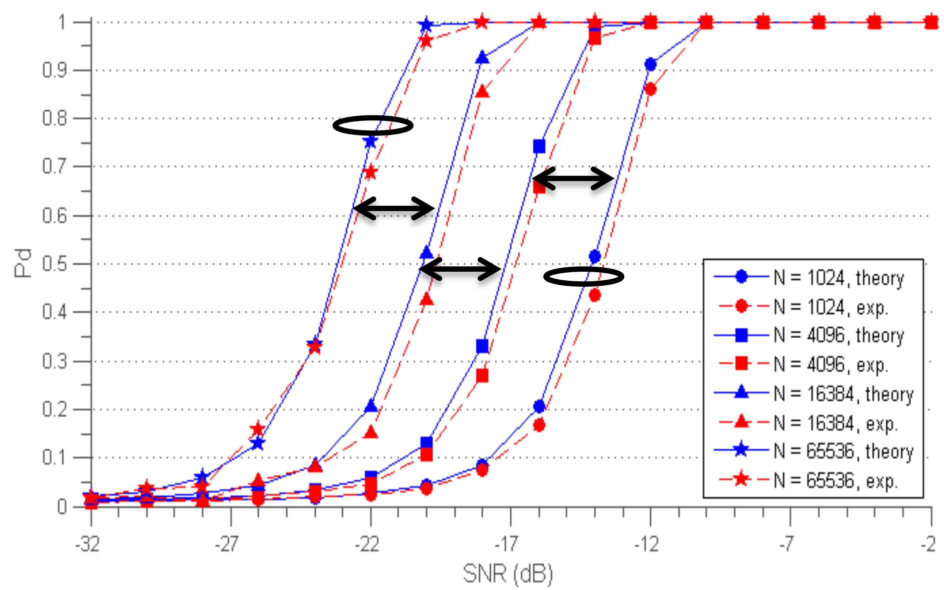
Input Signal	ISDBT_QPSK_2/3
Central frequency [MHz]	2401
Receiving bandwidth [MHz]	10
Attenuation [dB]	6
Noise level [dBm]	-74.4581(measured) -74.5(specifications)
Cable loss [dB]	1.4 dB
Input signal power [dBm]	-105:2:-75
Resulting SNR [dB]	-31.94:2:-1.94

Anritsu MS2690A measurement configuration

EGC and MV results



P_d vs SNR, $K = 5$, $M = 10^7$, $P_{fa} = 1\%$,
theoretical and experimental EGC results



P_d vs SNR, $K = 5$, $M = 10^7$, $P_{fa} = 1\%$,
theoretical and experimental MV results

- Constant **3dB** EGC/MV detection performance increase with each **sample size quadrupling**
- The experimental results prove the **validity of derived EGC/MV analytical models**

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Capacity aware optimization (1/2)

- Spectrum sensing techniques tend to utilize spectrum sensing setups (e.g. no. of signal samples, no. of noise samples, no. of cooperating nodes, control channel bandwidth etc.) that are optimal for achieving the best signal detection performance
  - Might be suboptimal regarding the achieved SU system performance
- However, in order to achieve better overall SU system performance, it is more beneficial to optimize the cooperative sensing process regarding the SU capacity rather than the signal detection
  - Complying with the PU protection criteria (e.g. P_d = 99%, time between sensing < 1s *)

System parameters:

- ***K*** → number of cooperating users in the SU system
- ***PU SNR*** → minimal received SNR at the SUs for which the PU system can be detected with an accuracy of Pd_{min} [%]
- ***1/α*** → noise estimation rate
- ***N*** → number of signal samples
- ***M*** → number of noise samples
- ***W*** → SU system bandwidth
- B_c → SU control channel bandwidth
- T_s → sensing period
- T_c → control channel latency
- ***T*** → SU system frame duration

* OFCOM, "Digital dividend: cognitive access ",Statement on license-exempting cognitive devices using interleaved spectrum, July 2009

Capacity aware optimization (2/2)

- The SU system capacity is defined as:

$$C_{SU} = \frac{T - T_s - T_c}{T} \cdot \Theta \cdot (1 - Q_{fa})\ (1 \text{-} \frac{B_c}{W})$$

$\Theta = W \cdot ld(1+\overline{\gamma})$ – Shannon Capacity of the SU system

$\overline{\gamma}$ – average SNR in the SU system

Q_{fa} – false alarm probability of the sensing technique

- In the case of cooperative ENP, the SU system capacity is defined as:

$$C_{SU} = \frac{T - T_s(N,M) - T_c(B_c)}{T} \cdot \Theta \cdot (1 - Q_{fa}^{ENP}(N,M,B_c))(1 \text{-} \frac{B_c}{W})$$

- The capacity aware ENP optimization can be defined as:

$$\max_{\arg N,M,B_c} \left\{ C_{SU} = \frac{T - T_s(N,M,\alpha) - T_c(B_c)}{T} \cdot \Theta \cdot (1 - Q_{fa}^{ENP}(N,M,B_c,\alpha))(1 \text{-} \frac{B_c}{W}) \right\}$$

$$s.t.\ \ Q_d^{ENP}(N,M,B_c,\alpha) \geq Q_{d\min}$$

Performance analysis

Scenario description

- Assess the performance and behavior of the:
  - EGC based ENP approach
  - MV based ENP approach

- Parameters of interest:
  - Achievable SU capacity

$$R = \frac{C_{SU}}{\Theta}$$

  - Optimal number of noise *M* and signal *N* samples
  - Optimal control channel bandwidth

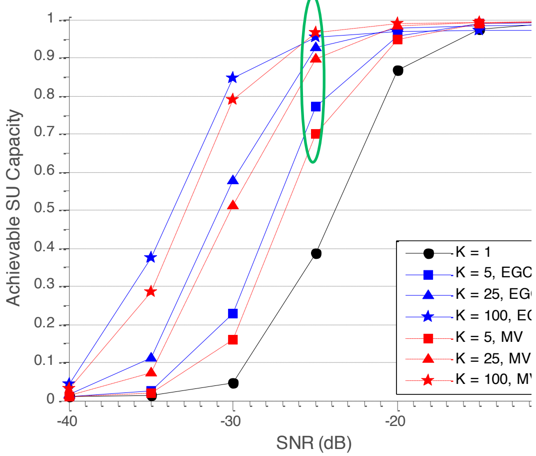
$$B_c = \frac{K}{T_c}$$

Parameters	**Values**
no. of signal samples [$N = 2^i$]	2^4 -:- 2^{21}
no. of noise samples [$M = m * N$]	2^5 -:-2^{30}
Cooperating users [K]	1 -:- 100
PU SNR [dB]	-45 -:- -10
Control channel bandwidth (B_c) [kHz] (BPSK modulation assumed)	1 -:- 200
MV fusion data size per node [bits]	1
EGC fusion data size per node [bits]	14
Qd_{min}[%]	99%
Noise estimation rate [α]	[1, 10, 100, 100]
Sampling rate [f_s]	8MHz
SU system frame duration [T]	1s

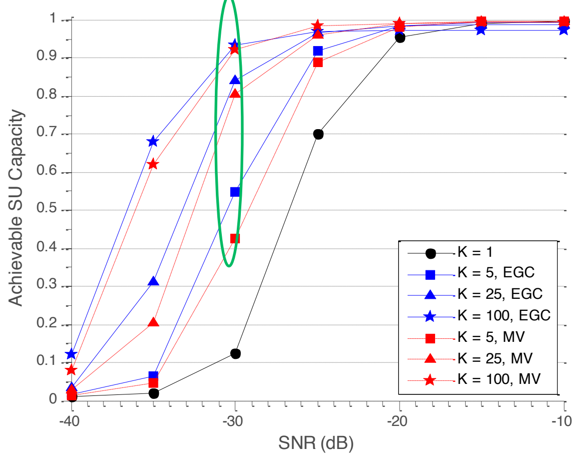
Achievable SU capacity

K, CSS	*i*	*m*	*Bc* (Hz)
5, EGC	19	2	$2*10^4$
5, MV	19	2	$1*10^4$
25, EGC	17	2	$6*10^4$
25, MV	18	2	$2*10^4$
100, EGC	15	3	$1*10^5$
100, MV	16	2	$4*10^4$

Optimal *i* ($N = 2^i$), *m* ($M = m*N$) and *Bc* for SNR = -25dB and α = 1



a)



b)

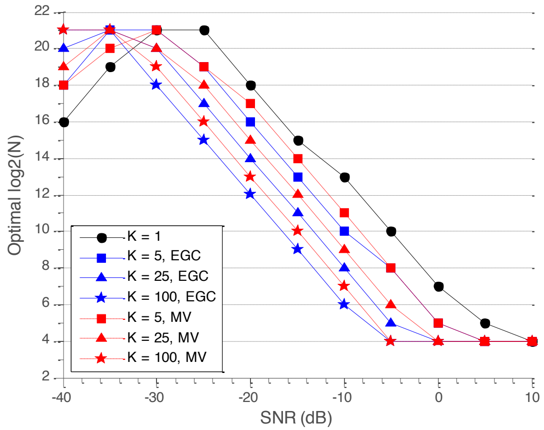
Achievable capacity R (SNR) for T=1s, sampling rate= 8MHz: a) α = 1 b) α = 100

K, CSS	*i*	*m*	*Bc* (Hz)
5, EGC	21	13	$2*10^4$
5, MV	21	15	$1*10^4$
25, EGC	20	6	$6*10^4$
25, MV	20	12	$2*10^4$
100, EGC	18	10	$1*10^5$
100, MV	19	5	$4*10^4$

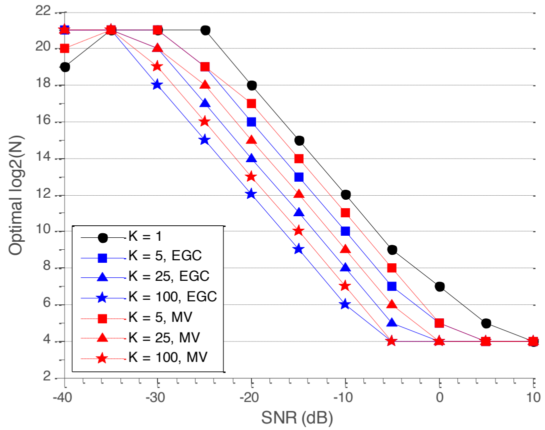
Optimal *i* ($N = 2^i$), *m* ($M = m*N$) and *Bc* for SNR = -30dB and α = 100

- The **achievable capacity increases** with the number of cooperating users ***K*** and the primary signal (PU) **SNR** requirement
- **MV** provides **better capacity** in the case of **higher PU SNR** and **EGC** provides **better capacity** in the case of **lower PU SNR**
- The **increase of *α*** (decrease of noise estimation rate) provides **better capacity** performances
- For **low SNR** regimes (e.g. < -30dB → **realistic scenarios**) the **single** node ENP approach is highly **suboptimal**

Optimal number of signal and noise samples

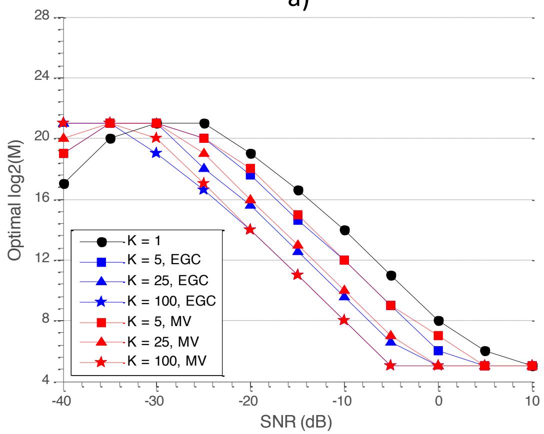


a)

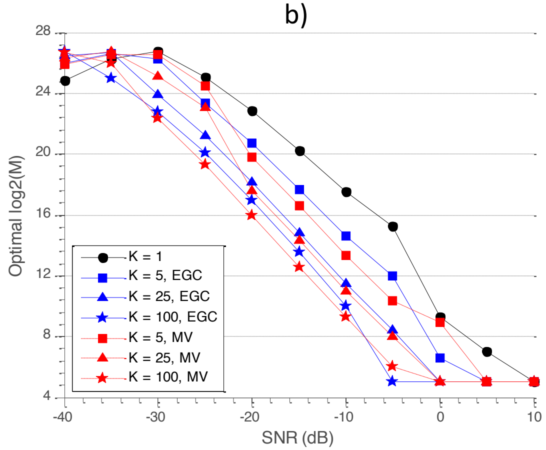


b)

Optimal log2(N) vs. SNR, T=1s, sampling rate = 8MHz (and the optimal M, Bc settings) for:
a) α = 1 b) α = 100



c)

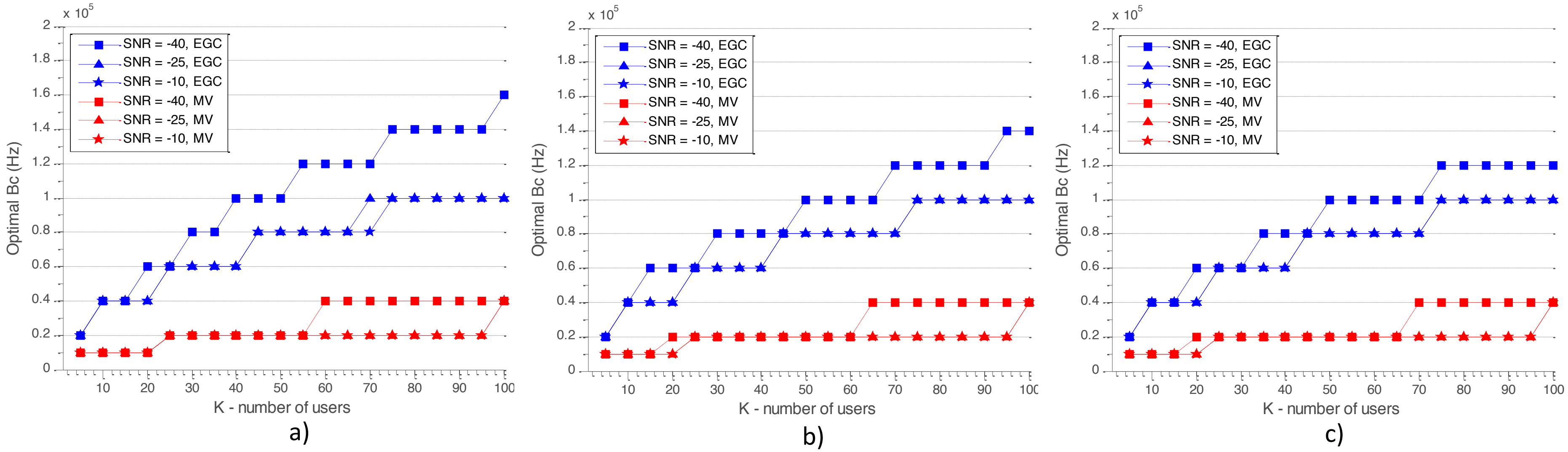


d)

Optimal log2(M) vs. SNR, T=1s, sampling rate = 8MHz (and the optimal N, Bc settings)
c) α = 1 d) α = 100

- The **optimal *N* and *M* decrease** with the **increase of** the number of users ***K*** and the **increase of** the **PU SNR**
- **MV** requires slightly **higher number** of **noise and signal samples in most cases**
- The **noise estimation rate coefficient *α*** only affects the **optimal number of noise samples *M***

Optimal control channel bandwidth



Optimal $B_c(K)$, T = 1s, sampling rate = 8MHz (and the optimal M, N settings) for: a) α = 1 b) α = 10 c) α = 100

- The **optimal B_c bandwidth** (achieving the optimal SU capacity) **increases** with the **increase of** the number of users ***K*** and the **decrease of** the **PU SNR**
- **EGC** generally **requires** a **higher B_c** due to the higher amount of control information
- The **decrease** of the **noise estimation rate decreases** the optimal **B_c bandwidth**

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Conclusion

- The ENP approach can overcome the noise SNR wall problem
- This work presents the extension of the ENP theory to the cooperative spectrum sensing
  - The experimental results prove the validity of the derived analytical models
- The ENP capacity aware cooperative spectrum sensing:
  - Enhances the SU system performance in terms of the SU capacity
  - Gives an insight of the optimal behavior of EGC and MV in terms of number of cooperating nodes, amount of noise statistics and control channel bandwidth
- Future directions
  - Exploit the information regarding the optimal behavior of the proposed approach for advanced Radio Resource Management
  - Extend the Higher Orders Statistics (HOS) based sensing with the cooperative ENP and capacity aware spectrum sensing

THANK YOU FOR YOUR KIND ATTENTION!

QUESTIONS?

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