Univerzitet Crne Gore
**ELEKTROTEHNIČKI FAKULTET**
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Univerzitet Crne Gore

Broj: 02/1-999/1
Datum: 20.07.2020

**UNIVERZITET CRNE GORE**

**- Centru za doktorske studije -**

**- Senatu -**

**O V D J E**

U prilogu dostavljamo Odluku Vijeća Elektrotehničkog fakulteta sa sjednice od 20.07.2020. godine i obrazac **D2**, sa pratećom dokumentacijom, za kandidatkinju MSc **Isidoru Stanković**, na dalji postupak.

**D E K A N,**

**Prof. dr Saša Mujović**

Univerzitet Crne Gore Elektrotehnički fakultet

# ISPUNJENOST USLOVA DOKTORANDA

<table>
<tr><th colspan="4">OPŠTI PODACI O DOKTORANDU</th></tr>
<tr><td>Titula, ime, ime roditelja, prezime</td><td colspan="3">MSc Isidora Ljubiša Stanković</td></tr>
<tr><td>Fakultet</td><td colspan="3">Elektrotehnički fakultet</td></tr>
<tr><td>Studijski program</td><td colspan="3">Doktorske studije elektrotehnike</td></tr>
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<tr><td>Na službenom jeziku</td><td colspan="3">Analiza nestacionarnih signala: doprinos kompresivnog odabiranja u smanjenju interferencija u disperzivnim kanalima</td></tr>
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<tr><th colspan="4">MENTOR/MENTORI</th></tr>
<tr><td>Prvi mentor</td><td>Prof. dr Miloš Daković</td><td>Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora</td><td>Elektrotehnika/ Obrada signala</td></tr>
<tr><th colspan="4">KOMISIJA ZA PREGLED I OCJENU DOKTORSKE DISERTACIJE</th></tr>
<tr><td colspan="2">Prof. dr Irena Orović</td><td>Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora</td><td>Elektrotehnika/ Obrada signala</td></tr>
<tr><td colspan="2">Prof. dr Miloš Daković</td><td>Elektrotehnički fakultet, Univerzitet Crne Gore, Podgorica, Crna Gora</td><td>Elektrotehnika/ Obrada signala</td></tr>
<tr><td colspan="2">Prof. dr Cornel Ioana</td><td>GIPSA Lab, Grenoble Institute of Technology (Grenoble INP), University of Grenoble Alpes, Grenobl, Francuska</td><td>Elektrotehnika/ Obrada signala</td></tr>
<tr><th colspan="4">Datum značajni za ocjenu doktorske disertacije</th></tr>
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</table>

**Spisak radova doktoranda iz oblasti doktorskih studija koje je publikovao u časopisima sa (upisati odgovarajuću listu)**

**Spisak radova iz oblasti doktorskih studija koje je kandidat publikovao u časopisima sa SCI/SCIE liste:**

[1] **I. Stanković**, M. Brajović, M. Daković, C. Ioana, and LJ. Stanković, "Quantization in Compressive Sensing: A Signal Processing Approach," *IEEE Access*, early access publication, 10 March 2020, doi: 10.1109/ACCESS.2020.2979935

**Link na rad:** https://ieeexplore.ieee.org/document/9031296
**Informacija o IMPACT faktoru časopisa:**
https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=6287639

[2] **I. Stanković**, M. Brajović, M. Daković, C. Ioana, and LJ. Stanković, "Bit-depth quantization and reconstruction error in images," *Signal, Image and Video Processing*, accepted, 2020.

**Link na rad:** https://link.springer.com/article/10.1007/s11760-020-01694-4
**Informacija o IMPACT faktoru časopisa:**
https://www.springer.com/journal/11760

[3] **I. Stanković**, M. Daković, and C. Ioana, "Decomposition and Analysis of Signals Sparse in the Dual Polynomial Fourier Transform," *Microprocessors and Microsystems*, vol. 63, pp. 209-215, November 2018.

**Link na rad:**
https://www.sciencedirect.com/science/article/abs/pii/S0141933118301492
**Informacija o IMPACT faktoru časopisa:**
https://www.sciencedirect.com/journal/microprocessors-and-microsystems

[4] **I. Stanković**, I. Orović, M. Daković, and S. Stanković, "Denoising of Sparse Images in Impulsive Disturbance Environment," *Multimedia Tools and Applications*, vol. 77, no. 5, pp. 5885–5905, March 2018, DOI: https://doi.org/10.1007/s11042-017-4502-7

**Link na rad:** https://link.springer.com/article/10.1007/s11042-017-4502-7
**Informacija o IMPACT faktoru časopisa:** https://www.springer.com/journal/11042

[5] **I. Stanković**, C. Ioana, and M. Daković, "On the reconstruction of nonsparse time-frequency signals with sparsity constraint from a reduced set of samples," *Signal Processing*, vol. 142, January 2018, pp. 480-484, DOI: http://dx.doi.org/10.1016/j.sigpro.2017.07.036

**Link na rad:**
https://www.sciencedirect.com/science/article/abs/pii/S0165168417302827
**Informacija o IMPACT faktoru časopisa:**
https://www.sciencedirect.com/journal/signal-processing

[6] LJ. Stanković, M. Brajović, **I. Stanković**, C. Ioana, and M. Daković, "Reconstruction Error in Nonuniformly Sampled Approximately Sparse Signals," *IEEE Geoscience and Remote Sensing Letters*, Vol: 17, 2020, in print, doi: 10.1109/LGRS.2020.2968137

**Link na rad:** https://ieeexplore.ieee.org/document/8981905
**Informacija o IMPACT faktoru časopisa:**
https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=8859

[7] N. A. Khan, M. Mohammadi, and **I. Stanković**, "Sparse Reconstruction based on iterative TF domain filtering and Viterbi based IF estimation Algorithm," *Signal Processing*, vol. 166, January 2020, DOI: https://doi.org/10.1016/j.sigpro.2019.107260

**Link na rad:**
https://www.sciencedirect.com/science/article/pii/S0165168419303123
**Informacija o IMPACT faktoru časopisa:**
https://www.sciencedirect.com/journal/signal-processing

[8] LJ. Stanković, M. Daković, **I. Stanković**, and S. Vujović, "On the Errors in Randomly Sampled Nonsparse Signals Reconstructed with a Sparsity Assumption," *IEEE Geoscience and Remote Sensing Letters*, Vol: 14, Issue: 12, Dec. 2017, pp. 2453 - 2456 , DOI: 10.1109/LGRS.2017.2768664

**Link na rad:** https://ieeexplore.ieee.org/document/8110831
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https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=8859

[9] M. Brajović, **I. Stanković**, M. Daković, C. Ioana, and LJ. Stanković, "Error in the Reconstruction of Nonsparse Images," *Mathematical Problems in Engineering*, Volume 2018 (2018), Article ID 4314527, 10 pages https://doi.org/10.1155/2018/4314527

**Link na rad:** https://www.hindawi.com/journals/mpe/2018/4314527/
**Informacija o IMPACT faktoru časopisa:** https://www.hindawi.com/journals/mpe/

[10] LJ. Stanković, **I. Stanković**, and M. Daković, "Nonsparsity Influence on the ISAR Recovery from Reduced Data," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 52, Issue: 6, Dec. 2016, pp. 3065 - 3070, DOI: 10.1109/TAES.2016.160312

**Link na rad:** https://ieeexplore.ieee.org/document/7855605
**Informacija o IMPACT faktoru časopisa:**
https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=7

**Poglavlja u knjigama:**

[11] L. Stanković, M. Daković, and **I. Stanković**, "Compressive Sensing Methods for Reconstruction of Big Sparse Signals," *in "Biomedical Signal Processing in Big Data"*, E. Sejdic ed., CRC Press, 2017.

**Radovi publikovani u drugim časopisima:**

[12] **I. Stanković**, M. Brajović, M. Daković, and L. Stanković, "Analysis of Noise in Complex-Valued Binary and Bipolar Sigmoid Compressive Sensing," Telfor Journal, Vol. 11, No. 1, 2019.

[13] L. Stanković, and **I. Stanković**, "Reconstruction of Sparse and Sonsparse Signals From a Reduced Set of Samples," ETF Journal of Electrical Engineering, Vol. 21, pp. 147-169, December 2015.

**Međunarodne konferencije (indeksirane u bazi SCOPUS):**

[14] **I. Stanković**, M. Brajović, M. Daković, LJ. Stanković, and C. Ioana, "Quantization Effect in Nonuniofrm Nonsparse Signal Reconstruction," *9th Mediterranean Conference on Embedded Computing, MECO 2020*, Budva, Montenegro, June 2020.

[15] M. Daković, M. Ponjavić, **I. Stanković**, J. Lerga, and C. Ioana, "Time-Frequency Analysis of Ionospheric Whistler Signals," *27th Telecommunications Forum TELFOR 2019*, Belgrade, Serbia, Nov. 2019.

[16] **I. Stanković**, M. Brajović, M. Daković, C. Ioana, and LJ. Stanković, "On the Quantization and the Probability of Misdetection in Compressive Sensing," *27th Telecommunications Forum TELFOR 2019*, Belgrade, Serbia, Nov. 2019.

[17] **I. Stanković**, J. S. Sewada, M. Geen, C. Ioana, M. Daković, and J. Mars, "Transmitted Sequence Influence to Sonar Target Detection using Compressive Sensing," *IEEE OCEANS 2019*, Seattle, WA, USA, October 2019.

[18] **I. Stanković**, C. Ioana, M. Brajović, M. Daković, and LJ. Stanković, "Time-Varying Cross-Range in Wideband Sonar Imaging," *11th Int'l Symposium on Image and Signal Processing and Analysis (ISPA 2019)*, Dubrovnik, Croatia, September 2019.

[19] M. Brajović, **I. Stanković**, LJ. Stanković, and M. Daković, "Decomposition of Two-Component Multivariate Signals with Overlapped Domains of Support," *11th Int'l Symposium on Image and Signal Processing and Analysis (ISPA 2019)*, Dubrovnik, Croatia, September 2019.

[20] **I. Stanković**, A. Digulescu, C. Ioana, and K. Dayet, "Electric arc detection using compressive sensing," *27th Symposium GRETSI 2019*, Lille, France, August 2019.

[21] **I. Stanković**, C. Ioana, and M. Daković, "Sequence Comparison in Reconstruction and Targeting in Underwater Sonar Imaging," *IEEE OCEANS 2019*, Marseille, France, June 2019.

[22] **I. Stanković**, M. Brajović, M. Daković, and C. Ioana, "Gradient-Descent Algorithm Performance With Reduced Set of Quantized Measurements," *8th Mediterranean Conference on Embedded Computing, MECO 2019*, Budva, Montenegro, June 2019.

[23] **I. Stanković**, M. Brajović, M. Daković, and LJ. Stanković, "Complex-Valued Binary Compressive Sensing," *26th Telecommunications Forum (TELFOR 2018)*, November 20 - 21, 2018, Belgrade, Serbia

[24] **I. Stanković**, C. Ioana, M. Daković, and LJ. Stanković, "Analysis of off-grid effects in wideband sonar images using compressive sensing," *IEEE OCEANS 2018*, Charleston, South Carolina, USA, October 2018.

[25] M. Brajović, **I. Stanković**, C. Ioana, M. Daković, and LJ. Stanković, "Reconstruction of Rigid Body with Noncompensated Acceleration After Micro-Doppler Removal," *5th International Workshop on Compressed Sensing applied to Radar, Multimodal Sensing, and Imaging (CoSeRa)*, Siegen, Germany, September 2018.

[26] LJ. Stanković, M. Brajović, **I. Stanković**, C. Ioana, and M. Daković, "Analysis of Initial Estimate Noise in the Sparse Randomly Sampled ISAR Signals," *5th International Workshop on Compressed Sensing applied to Radar, Multimodal Sensing, and Imaging (CoSeRa)*, Siegen, Germany, September 2018.

[27] **I. Stanković**, M. Brajović, M. Daković, and C. Ioana, "Effect of Random Sampling on Noisy Nonsparse Signals in Time-Frequency Analysis," *26th European Signal Processing Conference EUSIPCO 2018*, Rome, Italy, September 2018.

[28] **I. Stanković**, I. Djurović, and M. Daković, "Adaptive average BM3D filter for reconstruction of images with combined noise," *7th Mediterranean Conference on Embedded Computing, MECO 2018*, Budva, Montenegro, June 2018.

[29] **I. Stanković**, C. Ioana, M. Daković, and I. Candel, "Sparse Signal Reconstruction in Dual Polynomial Fourier Transform," *7th Mediterranean Conference on Embedded Computing, MECO 2018*, Budva, Montenegro, June 2018.

[30] **I. Stanković**, C. Ioana, and M. Daković, "High-Resolution Local Polynomial Fourier Transform in Acoustic Signal Analysis," *59th International Symposium ELMAR 2017*, September 18-20, Zadar, Croatia

[31] **I. Stanković**, C. Ioana, and M. Daković, "Model-based decomposition of acoustic signals in dispersive environment," *26th Symposium GRETSI 2017*, September 5-8, Juan-les-Pins, France

[32] **I. Stanković**, M. Daković, and C. Ioana, "Time-Frequency Signal Reconstruction of Nonsparse Audio Signals," *22nd International Conference on Digital Signal Processing IEEE DSP 2017*, August 23-25, London, United Kingdom

[33] M. Daković, LJ. Stanković, B. Lutovac, and **I. Stanković**, "On the Fixed-point Rounding in the DFT," *17th IEEE International Conference on Smart Technologies*, IEEE EUROCON 2017, Ohrid, Macedonia, July 2017.

[34] **I. Stanković**, M. Daković, and C. Ioana, "Decomposition of Signals in Dispersive Channels using Dual Polynomial Fourier Transform," *6th Mediterranean Conference on Embedded Computing MECO*, Bar, Montenegro, June 2017

[35] M. Daković, **I. Stanković**, M. Brajović, and LJ. Stanković, "Sparse Signal Reconstruction Based on Random Search Procedure," *40th International Convention on Information and Communication Technology, Electronics and Microelectronics MIPRO*, Opatija, Croatia, May 2017

[36] **I. Stanković**, M. Daković, and I. Orović, "Overlapping Blocks in Reconstruction of Sparse Images," *40th International Convention on Information and Communication Technology, Electronics and Microelectronics MIPRO*, Opatija, Croatia, May 2017

[37] M. Daković, **I. Stanković**, J. Ender, and LJ. Stanković, "Sample Selection Strategy in DFT based Compressive Sensing," *24th Telecommunications Forum TELFOR 2016*, Belgrade, Nov 22-23, 2016

[38] LJ. Stanković, **I. Stanković**, and M. Daković, "Analysis of Noise and Nonsparsity in the ISAR Image Recovery from a Reduced Set of Data," *4th International Workshop on Compressed Sensing Theory and its Applications to Radar, Sonar and Remote Sensing (CoSeRa) 2016*, 19-22 September, Aachen, Germany, 2016.

[39] **I. Stanković**, and W. Dai, "Reconstruction of Global Ozone Density Data using a Gradient-Descent Algorithm," *58th International Symposium ELMAR-2016*, Zadar, Croatia, September 2016.

[40] S. Vujović, **I. Stanković**, M. Daković, and LJ. Stanković, "Comparison of a Gradient-Based and LASSO (ISTA) Algorithm for Sparse Signal Reconstruction," *5th Mediterranean Conference on Embedded Computing MECO 2016*, Bar, June 2016

[41] **I. Stanković**, I. Orović, S. Stanković, and M. Daković, "Iterative Denoising of Sparse Images," *39th International Convention on Information and Communication Technology, Electronics and Microelectronics*, MIPRO 2016

[42] **I. Stanković**, and A. Draganić, "Compressive Sensing Reconstruction of Video Data based on DCT and Gradient-Descent Method," *23rd Telecommunications Forum*, TELFOR 2015

[43] **I. Stanković**, I. Orović, and S. Stanković, "Image Reconstruction from a Reduced Set of Pixels using a Simplified Gradient Algorithm," *22nd Telecommunications Forum TELFOR 2014*, Belgrade, Serbia

**Obrazloženje mentora o korišćenju doktorske disertacije u publikovanim radovima**

Doktorand MSc Isidora Stanković je većinu svojih istraživanja na kojima je zasnovana doktorska disertacija prezentovala kroz 10 radova, koji su publikovani u renomiranim međunarodnim časopisima sa SCI/SCIE liste, sa **IMPACT Factor-ima** od **1.01** do **4.38**. Na **5** radova, kandidat je **prvi** autor. Dio rezultata je objavljen i u radovima (njih ukupno **30**) koji su izloženi na međunarodnim konferencijama koje su indeksirane u bazi SCOPUS, kao i kroz dva rada u drugim časopisima. Kandidat je, pored toga, autor jednog poglavlja u monografiji renomiranog medjunarodnog izdavača. Dio istraživanja je obavljen na Politehničkom Institutu u Grenoblu (Grenoble INP) na Univerzitetu u Grenoblu (University of Grenoble Alpes) u skladu sa *cotutelle* ugovorom izmedju Univerziteta Crne Gore i Univerziteta u Grenoblu. U nastavku slijedi obrazloženje ključnih rezultata publikovanih kroz 8 radova u renomiranim međunarodnim časopisima, koji predstavljaju i temelj predmetne doktorske disertacije.

Naučni rad "*Quantization in Compressive Sensing: A Signal Processing Approach*" publikovan je u renomiranom časopisu IEEE Access sa IMPACT Factor-om **3.75** i u njemu je predstavljena analiza uticaja kvantizacije na rekonstrukciju rijetkih i nerijetkih signala sa nedostajućim obircima. Analiza je sprovedena pretpostavljajući razne faktore i nivoe kvantizacije koji mogu da utiču na rekonstrukciju. Izvedena je egzatna greška u rekonstrukciji kvantizovanih signala. Različiti algoritmi za rekonstrukciju signala na osnovu redukovanog skupa dostupnih odbiraka su koršćeni. Pored diskretne Furijeove transformacije, razmatrani su i drugi domeni signala kao što su Gausova i Bernulijeva transformacija. Rad sadrži opsežne numeričke rezultate, koji potvrđuju tačnost rezultata egzatne greške. Sadržaj rada je pokriven u drugoj glavi disertacije.

U naučnom radu „*On the reconstruction of nonsparse time-frequency signals with sparsity constraint from a* *reduced set of samples*", koji je publikovan u renomiranom časopisu Signal Processing, sa IMPACT Factor-om **4.38**, uticaj nedostajućih odbiraka na rekonstrukciju nestacionarnih signala u vremensko-frekvencijskom domenu je analizirana. Nestacionarni signali po prirodu nisu potpuno rijetki signali, iako se broj bitnih komponenti može računati kao mali (rijetki). Rekonstrukcija Predloženi pristup omogućava izdvajanje nestacionarnih komponenti signala uprkos njihovom preklapanju u vremensko-frekvencijskoj ravni, što predstavlja veoma značajan prilog rješavanju problema koji je odavno poznat u vremensko-frekvencijskoj analizi. Sadržaj rada je obrađen u drugoj glavi doktorske disertacije.

U naučnom radu "*Decomposition and Analysis of Signals Sparse in the Dual Polynomial Fourier Transform*", koji je publikovan u renomiranom časopisu Microprocessors and Microsystems, sa IMPACT Factor-om **1.16**, razmatrana je analizia i dekompozicija rijetkih signala u dualnoj formi polinomijalne Furijeove transformacije. Pokazano je da akustični signali, zbog svoje prirode, se bolje analiziraju u dualnom domenu zbog svoje brze frekvencijske promjene u kratkom vremenskom periodu. Uspješnost dekomopozicije i rekonstrukcije je predstavljena u nekoliko primjera, pokazajući težinu problema u ne-idealnim uslovima akustičnih signala. Sadržaj rada je obrađen u četvrtoj glavi disertacije.

Algoritam za rekonstrukciju slika baziran na spuštanju gradijenta predstavljen je u radu "*Denoising of Sparse Images in Impulsive Disturbance Environment*", publikovanom u renomiranom naučnom časopisu Multimedia Tools and Applications, sa IMPACT Factor-om **2.31**. Algoritam se zasniva na slijepom nalaženju oštećenih piksela i rekonstrukciju istih. Jedini uslov je da je slika rijetka u transformacionom domenu i da oštećeni pikseli degradira ovo svojstvo. Algoritam je testiran na mnogim primjerima, sa različitim brojem oštećenih piksela i sa različitim nivoima rijetkosti. Poređenjem sa drugim savremenim algoritmima dokazana je njegova robusnost. Sadržaj rada je obrađen u petoj glavi disertacije.

Rad "*Error in the Reconstruction of Nonsparse Images*" publikovan u renomiranom časopisu Mathematical Problems in Engineering, sa IMPACT Factor-om **1.01**, sadrži analizu kompresivnog odabiranja u domenu dvodimenzione DCT. U radu je izveden egzaktan izraz za energiju greške u rekonstrukciji signala koji nijesu rijetki u ovom domenu, a rekonstruisani su uz pretpostavku o rijetkosti. Posebno razmatran kontekst primjene odnosi se na digitalne slike. Sadržaj rada pokriven je u petoj glavi doktorske disertacije.

Iako rijetki signali imaju mali broj nenultih komponenti, kada je signal odabiran nausmično odabiran, gubi svoju karakteristiku rijetkosi. U radu "*On the Errors in Randomly Sampled Nonsparse Signals Reconstructed with a Sparsity Assumption*" uticaj nasumičnog odabiranja u kompresivnom odabiranju je analiziran. Rad je publikovan u časopisu IEEE Geoscience and Remote Sensing Letters, sa IMPACT Factor-om **3.83**. Najbitniji aspekti ovog rada obrađeni su u drugoj glavi doktorske disertacije.

U radu "*Reconstruction Error in Nonuniformly Sampled Approximately Sparse Signals*" koji je publikovan u renomiranom časopisu IEEE Geoscience and Remote Sensing Letters, sa IMPACT Factor-om **3.83**, predstavljena je generalizacija računanja egzatne greške rekonstrukcije signala približno rijetkih u transformacionom domenu, zasnovano na neuniformno odabiranje signala. Neuniformno odabiranje signala može doći zbog podrhtavanja senzora kao i njegovih fizičkih nedostataka. Kao dva posebna slučaja odvajaju se uniformno i nasumično odabiranje. Rad je obrađen u drugoj glavi disertacije.

Konačno, u radu "*Nonsparsity Influence on the ISAR Recovery from Reduced Data*" uticaj nerijetkosti na radarskim signalima (kao što su ISAR slike) koriteći mali set raspoloživih odbiraka. Rad je publikovan u renomiranom časopisu IEEE Transactions on Aerospace and Electronic Systsems, sa IMPACT Factor-om **3.67**. Rezultati rada pokriveni su u drugoj glavi disertacije.

Jedan dio rezultata kandidata publikovan je i kroz 30 rada izložena na renomiranim međunarodnim konferencijama koje su indeksirane u bazi SCOPUS, među kojima su i konferencija EUSIPCO, koja je široko poznata kao jedna od najznačajnih konferencija u svijetu u oblasti obrade signala, IEEE OCEANS, jedna od najvećih konferencija iz oblasti okeanskog inžinjeringa, pokrivajući sve njegove aspekte (kao što su sonarni sistemi i obrada sonarsnih signala), zatim konferencije MECO, CoSeRa, DSP i brojne druge konferencije prepoznatljivog međunarodnog renomea.

**Datum i ovjera (pečat i potpis odgovorne osobe)**

U Podgorici,
20.04.2020.

UNIVERZITET CRNE GORE
Elektrotehnički fakultet
MP

DEKAN

**Prilog dokumenta sadrži:**

1. Potvrdu o predaji doktorske disertacije organizacionoj jedinici
2. Odluku o imenovanju komisije za pregled i ocjenu doktorske disertacije
3. Kopiju rada publikovanog u časopisu sa odgovarajuće liste
4. Biografiju i bibliografiju kandidata
5. Biografiju i bibliografiju članova komisije za pregled i ocjenu doktorske disertacije sa potvrdom o izboru u odgovarajuće akademsko zvanje i potvrdom da barem jedan član komisije nije u radnom odnosu na Univerzitetu Crne Gore

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# P O T V R D A

MSc **Isidora Stanković**, student doktorskih studija na Elektrotehničkom fakultetu u Podgorici, dana 16.07.2020. godine dostavila je ovom Fakultetu doktorsku disertaciju pod nazivom: „**Analiza nestacionarnih signala: doprinos kompresivnog odabiranja u smanjenju interferencija u disperzivnim kanalima**“, na dalji postupak.

**D E K A N,**

**Prof. dr Saša Mujović**

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Na osnovu člana 64 Statuta Univerziteta Crne Gore, u vezi sa članom 41 Pravila doktorskih studija, na predlog Komisije za doktorske studije, Vijeće Elektrotehničkog fakulteta u Podgorici, na sjednici od 20.07.2020. godine, donijelo je

**ODLUKU**

**I** Utvrđuje se da su ispunjeni uslovi iz Pravila doktorskih studija za dalji rad na doktorskoj disertaciji **„Analiza nestacionarnih signala: doprinos kompresivnog odabiranja u smanjenju interferencija u disperzivnim kanalima“**, kandidata MSc **Isidore Stanković.**

**II Predlaže se Komisija za ocjenu navedene doktorske disertacije, u sastavu:**

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2. Prof. dr Miloš Daković, Elektrotehnički fakultet Univerziteta Crne Gore,
3. Prof. dr Cornel Ioana, Institute Polytechnique de Grenoble, Grenoble, Francuska.

Komisija iz tačke II ove Odluke podnijeće Izvještaj Vijeću Fakulteta u roku od 45 dana od dana imenovanja.

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- Senatu,
- Centru za doktorske studije,
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**Vodeći naučni časopisi (SCI/SCIE lista):**

1. **I. Stanković**, M. Daković, and C. Ioana, "Decomposition and Analysis of Signals Sparse in the Dual Polynomial Fourier Transform," *Microprocessors and Microsystems*, vol. 63, pp. 209-215, November 2018.
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1. **I. Stanković**, J. S. Sewada, M. Geen, C. Ioana, M. Daković, and J. Mars, "Transmitted Sequence Influence to Sonar Target Detection using Compressive Sensing," *IEEE OCEANS 2019*, Seattle, WA, USA, October 2019.
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Short communication

# On the reconstruction of nonsparse time-frequency signals with sparsity constraint from a reduced set of samples☆

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ABSTRACT

Nonstationary signals, approximately sparse in the joint time-frequency domain, are considered. Reconstruction of such signals with sparsity constraint is analyzed in this paper. The short-time Fourier transform (STFT) and time-frequency representations that can be calculated using the STFT are considered. The formula for error caused by the nonreconstructed coefficients is derived and presented in the form of a theorem. The results are examined statistically on examples.



## 1. Introduction

Nonstationary signals that cover most of the time and frequency domain may be well localized in the joint time-frequency domain. These signals are dense in both time and frequency, considered separately. However, they could be located within much smaller regions in the joint domain using appropriate representations [1–6]. The basic time-frequency tepresentation is the short-time Fourier transform (STFT). It can be easily related to the Wigner distribution and its cross-terms reduced versions [7]. These representations will be considered in this paper. The signals are sparse in the time-frequency domain if the number of nonzero coefficients in this domain is much smaller than the total number of coefficients. For example, a sum of few nonstationary signal components, being well localized in the STFT at each considered time instant, is a sparse signal in this domain.

A signal that is sparse in a certain domain can be reconstructed with fewer samples than the Shannon–Nyquist sampling theorem requires. Compressive sensing is the field dealing with the problem of signal recovery with reduced number of available samples [8–14]. Reducing the number of available samples in the analysis manifests as a noise, whose properties in the discrete Fourier transform (DFT) domain are studied in [15]. These results will be used to define reconstruction properties in the STFT case. The influence of noise in the two-dimensional DFT is examined in [16]. If a nonsparse signal is reconstructed with a reduced set of available samples then the noise due to the missing samples of nonreconstructed coefficients will be considered as an additive input noise in the reconstructed signal.

In the compressive sensing literature, only the general bounds for the reconstruction error for nonsparse signals (reconstructed with the sparsity assumption) are derived [10,17,18]. In this manuscript, we have presented an exact relation for the expected squared errot in approximately sparse or nonsparse signals in the time-frequency domain, reconstructed from a reduced set of signal samples, under the sparsity constraint. The error depends on the number of available samples and the assumed sparsity, that is crucial for any compressive sensing based reconstruction. The results are given in the form of a theorem. Theory is illusrrared and checked on statistical examples.

The noise in the reconstructed STFT influences other time-frequency representations that can be calculated using this STFT. The S-method [6,7] is considered as an example of such signal tepresentations.

The paper is organized as follows. The theoretical background of compressive sensing and time-frequency signal analysis is presented in Section 2. The theorem and formula of nonsparsity influence on the reconstructed signal is presented in Section 3. The numerical results are given in Section 4. The conclusions are presented in Section 5.

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## 2. Theoretical background

Let us consider a multicomponent signal

$$x(n)=\sum_{l=1}^{C}x_l(n), \tag{1}$$

where components $x_l(n)$ are nonstationary and the total number of components is $C$. Assume that the signal is sparse in the STFT domain. The STFT of the discrete-time signal is defined as

$$S_N(n,k)=\sum_{m=-N/2}^{N/2-1}x(n+m)w(m)e^{-j\frac{2\pi}{N}mk}, \tag{2}$$

at an instant $n$ and a frequency $k$. The window function of length $N$ is $w(m)$. The windowed signal $x(n,m)=x(n+m)w(m)$, which is $K$-sparse in the STFT domain, can be written in the form

$$x(n,m)=\sum_{i=1}^{K}A_i(n)e^{j2\pi mk_i/N}. \tag{3}$$

The signal and its STFT in a vector form are

$$\mathbf{S}_N(n)=\mathbf{W}_N\mathbf{H}_N\mathbf{x}(n) \tag{4}$$

$$\mathbf{H}_N\mathbf{x}(n)=\mathbf{W}_N^{-1}\mathbf{S}_N(n), \tag{5}$$

where $\mathbf{S}_N(n)=[S_N(n,0),S_N(n,1),\dots,S_N(n,N-1)]^T$ is the STFT calculated at time instant n, $\mathbf{x}(n)$ is the original signal (column) vector within the window, $\mathbf{W}_N$ is the DFT matrix of size $N\times N$ with coefficients $W(m,k)=e^{(-j2\pi km/N)}$ and $\mathbf{H}_N$ is a diagonal matrix with the window values at its diagonal. Analysis and reconstruction of the whole signal based on the STFT is straightforward with appropriate overlapping. It is presented in [1,2,6].

With the assumption that the signal is sparse in the STFT domain, we can reconstruct it with a reduced number of samples, according to the compressive sensing theory [8,10,17,18,21].

The number of randomly positioned available samples for the reconstruction is $N_A\ll N$. For a given n the available signal samples are at the positions

$$n+m\in\{n+m_1,n+m_2,\dots,n+m_{N_A}\}.$$

The number of unavailable/missing samples is $N_M=N-N_A$. The available samples (measurements) of the windowed signal are then defined as

$$\mathbf{y}_n=[x(n+m_1)w(m_1),\dots,x(n+m_{N_A})w(m_{N_A})]^T. \tag{6}$$

Note that

$$\mathbf{y}_n=\mathbf{A}\mathbf{S}_N(n),$$

where $\mathbf{A}$ is the measurement matrix. The matrix $\mathbf{A}$ is obtained by keeping the rows of the inverse DFT matrix corresponding to the available samples

$$\mathbf{A}=\begin{bmatrix}\psi_0(m_1) & \psi_1(m_1) & \cdots & \psi_{N-1}(m_1)\\ \psi_0(m_2) & \psi_1(m_2) & \cdots & \psi_{N-1}(m_2)\\ \vdots & \vdots & \ddots & \vdots\\ \psi_0(m_{N_A}) & \psi_1(m_{N_A}) & \cdots & \psi_{N-1}(m_{N_A})\end{bmatrix} \tag{7}$$

where $\psi_k(m)$ are the inverse DFT matrix coefficients $\psi_k(m)=\frac{1}{N}\exp(j2\pi mk/N)$.

The goal of compressive sensing is to reconstruct the original sparse signal (using its windowed overlapped versions) from the available samples. A general compressive sensing formulation is

$$\min\|\mathbf{S}_N(n)\|_0 \text{ subject to } \mathbf{y}_n=\mathbf{A}\mathbf{S}_N(n).$$

Here we will assume that the initial STFT is calculated using the available samples only

$$S_{N0}(n,k)=\sum_{i=1}^{N_A}x(n+m_i)w(m_i)e^{-j\frac{2\pi}{N}m_ik} \tag{8}$$

$$\mathbf{S}_{N0}(n)=N\mathbf{A}^H\mathbf{y}_n, \tag{9}$$

where superscript $H$ denotes the Hermitian transpose.

The mean and the variance of this STFT, at a given instant $n$, calculated using the available signal samples only, are [15]

$$E\{S_{N0}(n,k)\}=\sum_{i=1}^{K}N_AA_i(n)\delta(k-k_i) \tag{10}$$

$$\text{var}\{S_{N0}(n,k)\}=N_A\frac{N_M}{N-1}\sum_{i=1}^{K}|A_i(n)|^2(1-\delta(k-k_i)), \tag{11}$$

where $\delta(k)=1$ only for $k=0$ and $\delta(k)=0$, elsewhere.

In general, time-varying signals are not strictly sparse in the STFT domain. Because of their nature, most of these signals are either approximately sparse or nonsparse. A signal is $K$-sparse in a transformation domain (in our case, in the STFT domain) if it has only $K$ ($K\ll N$) nonzero coefficients in this domain at positions $k\in\mathbb{K}=\{k_1,k_2,\dots,k_K\}$. Other coefficients, for $k\notin\mathbb{K}$, are zero-valued. A signal is approximately sparse if the coefficients for $k\in\mathbb{K}$ are significantly larger than rhe coefficients at $k\notin\mathbb{K}$. A signal is not $K$-sparse if the coefficients for $k\notin\mathbb{K}$ are of the same order as the coefficients at the positions $k\in\mathbb{K}$. If we want to use the compressive sensing based theory for any of these signals the sparsity assumption has to be made. In this paper, we will analyze the error in these signals reconstructed under the $K$-sparsity assumption in the STFT domain.

Signal reconstruction is done using estimation of the nonzero coefficient positions, based on (8) and calculating the unknown coefficients $A_i(n)$ based on rhe known signal values $x(n+m_i)$. Various reconstruction algorithms can be used. For the numerical verification of the results we will use an iterative form of the OMP algorithm. The reconstruction algorithm used in this paper is an iterative form of the OMP algorithm, introduced in [19,20]. Since the introduction of compressive sensing, many reconstruction algorithms have been developed. A review of reconstruction algorithms can be found in [21]. The main reason to use the presented algorithm is the fact that it uses rhe sparsity assumption in an explicit way (producing $K$ nonzero coefficients in the reconstructed signal). Also, its computational complexity is low. Other algorithms that also exploit the sparsity assumprion in an explicit way can be used as well.

In the first step, the position of the maximal STFT coefficient is found as

$$k_1=\arg\max\{\mathbf{S}_{N0}(n)\}.$$

Matrix $\mathbf{A}_1$ is formed from matrix $\mathbf{A}$ by omitting all columns except the column corresponding to $k_1$. The first STFT estimate is

$$\mathbf{S}_R(n)=(\mathbf{A}_1^H\mathbf{A}_1)^{-1}\mathbf{A}_1^H\mathbf{y}_n.$$

The signal is reconstructed and subtracted from the original signal at the positions of available samples. The STFT estimate is calculated again with this new signal and its maximum position $k_2$ is found. A new set $\mathbb{K}=\{k_1,k_2\}$ is formed with corresponding matrix $\mathbf{A}_2$. The new estimate $\mathbf{S}_R(n)$ is calculated and the signal is reconstructed. The procedure is repeated $K$ (assumed sparsity) times, with the final reconstruction

$$\mathbf{S}_R(n)=(\mathbf{A}_K^H\mathbf{A}_K)^{-1}\mathbf{A}_K^H\mathbf{y}_n.$$

The reduced measurement matrix $\mathbf{A}_K$ is obtained from $\mathbf{A}$ by selecting the columns corresponding to $K$ detected nonzero coefficient positions

$$\mathbf{A}_K = \begin{bmatrix} \psi_{k_1}(m_1) & \psi_{k_2}(m_1) & \cdots & \psi_{k_K}(m_2) \\ \psi_{k_1}(m_2) & \psi_{k_2}(m_2) & \cdots & \psi_{k_K}(m_2) \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{k_1}(m_{N_A}) & \psi_{k_2}(m_{N_A}) & \cdots & \psi_{k_K}(m_{N_A}) \end{bmatrix}. \tag{12}$$

## 3. Nonsparsity in time-frequency signal analysis

The reconstruction error of sparse signals is an important topic in compressive sensing. Its general bounds can be found in [10,17]. An exact formula for the expected squared reconstruction error, with the STFT as a sparsity domain, is presented by the next theorem.

**Theorem 1.** *Consider a signal $x(n)$ with time-varying components. Its STFT values are denoted by $\mathbf{S}_N(\mathrm{n}) = [S_N(n,0), S_N(\mathrm{n},1), \ldots, S_N(\mathrm{n}, N-1)]^T$. The total number of signal samples within a window is $N$. Assume that the available signal samples are at $N_A$ random positions, defined by $\mathrm{n}+m \in \mathbb{N}_A$, and $N_M = N - N_A$ is the number of unavailable/missing samples. The signal is reconstructed under the assumption as it were K-sparse in the STFT domain (with the assumption that the reconstruction conditions are met for this sparsity). The reconstructed signal with $K$ nonzero STFT coefficients at $k \in \mathbb{K}$ is denoted by $\mathbf{S}_{NR}(n)$. The error in the $K$ reconstructed STFT coefficients is:*

$$\|\mathbf{S}_{NK}(n) - \mathbf{S}_{NR}(n)\|_2^2 = K\frac{N_M}{N_A N}\|\mathbf{S}_N(\mathrm{n}) - \mathbf{S}_{NK}(\mathrm{n})\|_2^2. \tag{13}$$

*The K-sparse version of $\mathbf{S}_N(n)$ is denoted by $\mathbf{S}_{NK}(n)$. The elements of vector $\mathbf{S}_{NK}(n)$ are $S_{NK}(n,k) = S_N(n,k)$ for $k \in \mathbb{K}$, and $S_{NK}(\mathrm{n},k) = 0$ for $k \notin \mathbb{K}$. The reconstructed STFT $\mathbf{S}_{NR}(\mathrm{n})$ is formed in the same way, with coefficients for $k \in \mathbb{K}$ being obtained by the reconstruction procedure and the remaining coefficients, for $k \notin \mathbb{K}$ being set to 0.*

*Notation $\|\mathbf{S}_N(n)\|_2^2$ is used for the expected value of the squared norm-two, i.e. $\|\mathbf{S}_N(n)\|_2^2 = E\{\sum_k |S_N(\mathrm{n},k)|^2\}$.*

**Proof.** Assume that the compressive sensing conditions for the reconstruction are satisfied for the assumed sparsity and the number of available samples [17]. Then we can reconstruct $K$ coefficients $(A_1(n), A_2(n), \ldots, A_K(n))$ using, for example, the iterative OMP procedure explained at the end of Section 2. The result is $\mathbf{S}_R(n)$ with $K$ reconstructed coefficients. The remaining (nonreconstructed) $N-K$ signal coefficients with amplitudes $(A_{K+1}(n), A_{K+2}(n), \ldots, A_N(n))$ produce noise in these $K$ reconstructed coefficients. As defined in (11), the noise variance from one nonreconstructed coefficient is

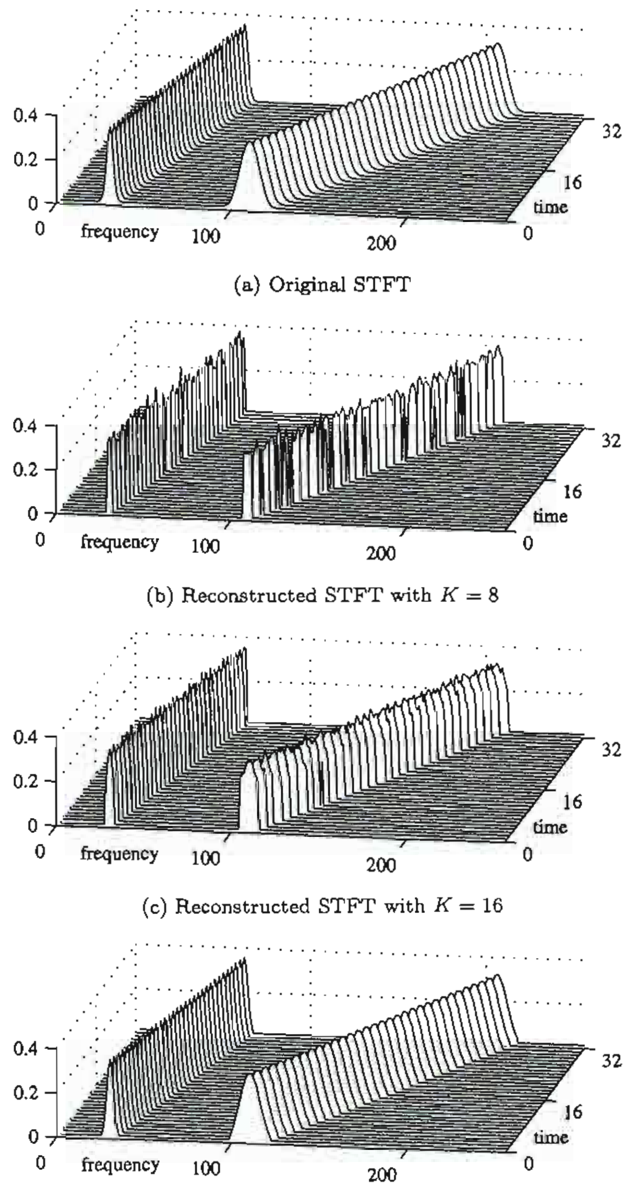
$$|A_i(n)|^2 N_A N_M/(N-1). \tag{14}$$

The signal amplitudes in $\mathbf{S}_{N0}(n)$ are proportional to $N_A$. The amplitudes are recovered to their original values, proportional to $N$, the same as if all samples were available. The scaling factor is then $N/N_A$ for the reconstructed coefficients. Consequently, the scaling factor for the noise variance in the reconstructed coefficients is $(N/N_A)^2$. That is, the noise variance of a reconstructed coefficient caused by a nonreconstructed coefficient is

$$|A_i(n)|^2\frac{N^2}{N_A^2}\frac{N_A N_M}{N-1} \cong |A_i(\mathrm{n})|^2 N\frac{N_M}{N_A}. \tag{15}$$

The white noise energy in the reconstructed coefficients of $\mathbf{S}_R(n)$ will be $K$ times larger than the variance in one reconstructed coefficient. The total noise energy caused by the nonreconstructed coefficients $(A_{K+1}(n), A_{K+2}(n), \ldots, A_N(n))$, in $K$ reconstructed coefficients is

$$\|\mathbf{S}_{NR}(n) - \mathbf{S}_{NK}(n)\|_2^2 = KN\frac{N_M}{N_A}\sum_{i=K+1}^{N}|A_i(n)|^2, \tag{16}$$




(a) Original STFT

(b) Reconstructed STFT with $K = 8$

(c) Reconstructed STFT with $K = 16$

(d) Reconstructed STFT with $K = 32$

**Fig. 1.** Reconstructed STFT with varying assumed sparsity $K$ with $N_A = 2N/3$ available samples.

**Table 1**
The error in the reconstructed coefficients and the total error (in dB) for $N_A = 2N/3$ and $N_A = 3N/4$, and various assumed sparsity levels $K$.

| $N_A$ | $K$ | Error in the reconstructed coefficients | | Total error | |
|---|---|---|---|---|---|
| | | Statistics | Theory | Statistics | Theory |
| 2N/3 | 4 | −21.4 | −21.5 | −0.4 | −0.4 |
| 2N/3 | 8 | −19.8 | −20.5 | −2.3 | −2.3 |
| 2N/3 | 16 | −23.0 | −23.5 | −8.3 | −8.3 |
| 2N/3 | 32 | −40.9 | −41.8 | −29.4 | −29.5 |
| 2N/3 | 64 | −53.5 | −54.8 | −45.1 | −45.2 |
| 3N/4 | 4 | −22.8 | −23.3 | −0.4 | −0.4 |
| 3N/4 | 8 | −21.9 | −22.3 | −2.4 | −2.4 |
| 3N/4 | 16 | −25.0 | −25.3 | −8.4 | −8.4 |
| 3N/4 | 32 | −42.6 | −43.6 | −29.5 | −29.6 |
| 3N/4 | 64 | −54.4 | −56.6 | −45.2 | −45.5 |

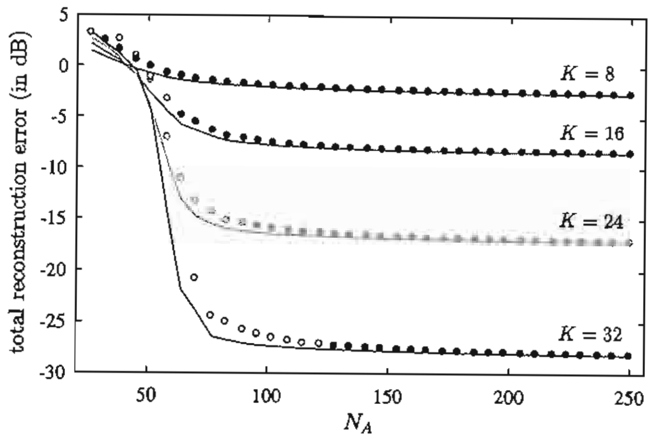



**Fig. 2.** Total reconstruction error as a function of the number of available samples $N_A$ for various assumed sparsity $K$. Theoretical results are presented by lines and the statistical with dots. Dots for $N_A > 4K$, when the reconstruction is possible with a high probability, are filled.

where $\mathbf{S}_{NR}(n)$ is obtained from $\mathbf{S}_R(n)$, as defined in the theorem. Energy of the STFT, corresponding to the nonreconstructed coefficients only, can be written as

$$\|\mathbf{S}_N(n)-\mathbf{S}_{NK}(n)\|_2^2 = \sum_{l=K+1}^{N} |NA_i(n)|^2. \quad (17)$$

From (16) and (17) follows

$$\|\mathbf{S}_{NR}(n)-\mathbf{S}_{NK}(n)\|_2^2 = K\frac{N_M}{N_A N}\|\mathbf{S}_N(n)-\mathbf{S}_{NK}(n)\|_2^2.$$

In the case when the original signal is $K$-sparse, i.e. $\mathbf{S}_N(n) = \mathbf{S}_{NK}(n)$, or when all samples are available, i.e. $N_A = N$ and $N_M = 0$, there is no error

$$\|\mathbf{S}_{NR}(n)-\mathbf{S}_{NK}(n)\|_2^2 = 0. \quad \square \quad (18)$$

## 4. Numerical results

Consider a combination of two linear frequency modulated signal components

$$x(n) = 1.5\exp(j192\pi n/N + j48\pi n^2/N^2 + j\varphi_1) + \exp(j48\pi n/N + j16\pi n^2/N^2 + j\varphi_2) \quad (19)$$

for $0 \le n \le 1280$. The STFT is calculated using a Hamming window of the length $N = 256$ with a step in time of 32. Note that the signal is not sparse in the DFT domain since its components sweep almost the whole frequency range. Various numbers of randomly positioned available samples $N_A$ have been considered. The phases $\varphi_1$ and $\varphi_2$ are random between 0 and $2\pi$. In the reconstruction a $K$-sparse signal in the STFT domain is assumed, with various $K = 4, 8, 16, 32, 64$. Illustration of the reconstructed signal STFTs for $N_A = 192$ randomly positioned available samples and $K = 8, 16, 32$ is shown in Fig. 1.

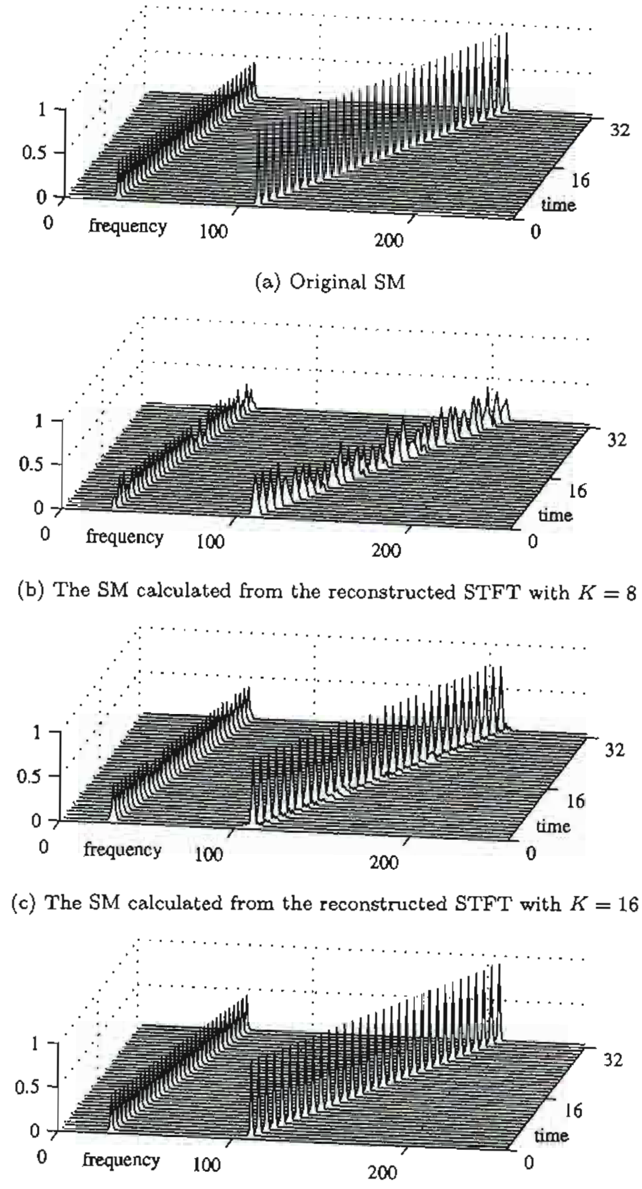
The statistical error $E_s$, and the derived (theoretical) error $E_t$, in the reconstructed coefficients, are calculated as

$$E_s = 10\log\left(\|\mathbf{S}_{NK}(n)-\mathbf{S}_{NR}(n)\|_2^2\right) \quad (20)$$

$$E_t = 10\log\left(K\frac{N_M}{N_A N}\|\mathbf{S}_N(n)-\mathbf{S}_{NK}(n)\|_2^2\right) \quad (21)$$

where $\mathbf{S}_N(n)$ is the original STFT of the signal, $\mathbf{S}_{NK}(n)$ is equal to $\mathbf{S}_N(n)$ for its $K$ reconstructed coefficients and $\mathbf{S}_{NR}(n)$ is the reconstructed STFT with $K$ nonzero values. The total reconstruction errors can be calculated as

$$E_s^{tot} = 10\log\left(\|\mathbf{S}_N(n)-\mathbf{S}_{NR}(n)\|_2^2\right) \quad (22)$$




(a) Original SM

(b) The SM calculated from the reconstructed STFT with $K = 8$

(c) The SM calculated from the reconstructed STFT with $K = 16$

(d) The SM calculated from the reconstructed STFT with $K = 32$

**Fig. 3.** The S-method (SM) calculated from the reconstructed STFT with varying assumed sparsity $K$ and $N_A = 2N/3$ available samples.

$$E_t^{tot} = 10\log\left(\left(K\frac{N_M}{N_A N}+1\right)\|\mathbf{S}_N(n)-\mathbf{S}_{NK}(n)\|_2^2\right). \quad (23)$$

The reconstruction error values averaged over 100 realizations, calculated using (20), (21), (22), and (23), are shown in Table 1.

The total reconstruction error as a function of the number of available samples is presented in Fig. 2. The number of available samples is varied from 25 to 250. We assumed the sparsity values $K = 8, 16, 24$, and 32. The theoretical results are presented with solid lines and the statistical results are given by dots. Filled marks indicate the region when the reconstruction is possible with a high probability, $N_A \ge 4K$, [17]. Note that any exact recovery can be expected only if $N_A > 2K$.

The results can be easily applied to other time frequency-representations whose realization can be implemented using the

STFT. For example, the pseudo Wigner distribution can be calculated as

$$WD(n,k)=\sum_{i=-N/2}^{N/2} S_N(n,k+i)S_N^*(n,k-i). \quad (24)$$

Its cross-terms free (reduced) version, is the S-method

$$SM(n,k)=\sum_{i=-L}^{L} S_N(n,k+i)S_N^*(n,k-i), \quad (25)$$

where $L$ should be sufficiently large to include auto-terms, but not too large to produce cross-terms [7]. The S-method calculated from the reconstructed STFT is shown in Fig. 3.

The noise analysis in these distribution can be easily done based on the derived relations for the noise in the STFT and the results in [22]. Sparse reconstruction of bilinear time-frequency distributions is reviewed in [23].

## 5. Conclusions

The influence of nonsparsity to the reconstruction of signals that are approximately sparse in the time-frequency domain is analyzed in this paper. The relation for the reconstruction error is derived. The reconstruction results are statistically checked. Statistical results are in high agreement with the derived theoretical results.

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# Decomposition and analysis of signals sparse in the dual polynomial Fourier transform

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ABSTRACT

The acoustic waves transmitted through a dispersive environments can be quite complex for decomposition and localization. A signal which is transmitted through a dispersive channel is usually non-stationary. Even if a simple signal is transmitted, it can change its characteristics (phase and frequency) during the transmission through an underwater acoustic dispersive communication channel. Commonly, several components with different paths are received. In this paper, we present a method for decomposition of multicomponent acoustic signals using the dual polynomial Fourier transform and time-frequency methods. In real-world signals, some disturbances are introduced during the transmission. Common form of disturbances are the sinusoidal signals, making some of the frequency domain signal samples unreliable. Since the signal components can be considered as sparse in the dual polynomial Fourier transform domain, these samples can be omitted and reconstructed using the compressive sensing methods. The acoustic signal decomposition and its reconstruction from a reduced set of frequency domain samples is demonstrated on examples.



## 1. Introduction

The dispersivity in underwater channels has been a challenging topic in the recent years. Many channels with the phenomena of dispersion have been studied. A dispersive channel in underwater acoustics is a system which produces nonlinear signal transformations [1–5]. That is, it shifts the propagating signal in the phase which will cause shifts in frequency and time in the received signal. Another characterization of dispersive channels is that it produces multicomponent signals due to mulripath propagation which can occur for various reasons. The main one is the scatrering of acoustic signals on the sea bottom.

The received signal in a dispersive channel is different from the transmitted signal. It is a complex and non-stationary signal. Because of the non-stationary nature of these signals, the time-frequency signal analysis is a suitable tool for analysis. It can help in detection, extraction and localization of transmitted signals. The most common tool for the analysis of non-stationary signals is the time-frequency signal analysis [6–13]. A common problem in practice is strong harmonic disturbances. After these disturbances are removed, the signal components should be reconstructed.

In the theory of sparse signal reconstruction, a signal is sparse if it has only few non-zero components in comparison to the total length of the signal. If the signal is sparse, it can be reconstructed with less measurements [14–18]. The considered acoustic signal is sparse in the dual polynomial Fourier transform (DPFT) domain, and the noisy measurements (impulses) occur in frequency domain. The impulses in frequency domain will introduce sinusoids in time domain. These disturbances are removed, and the signal components can be reconsrructed by compressive sensing methods, such as the matching pursuit algorithm. In this paper, we present a merhod for decomposition of a signal which was transmitted through a dispersive environment.

The paper is organized as follows. In Section 2, the received signal from a dispersive channel will be modelled and explained. In Section 3 basic theory of compressive sensing is introduced. The polynomial Fourier transform for analysis and localization of acoustic signals will be presented in Section 4. Numerical results and conclusions are given in Sections 6 and 7, respectively.

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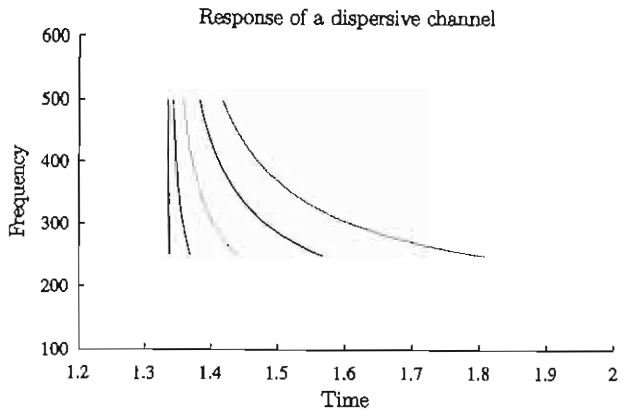


**Fig. 1.** The time-frequency representation of the impulse response of five modes.

## 2. Modelling of the received signals from dispersive channels

Let us assume that an underwater acoustic wave is transmitted. Assume a linearly frequency modulated (LFM) signal of the form

$$u(n) = e^{j\pi\alpha n^2}. \tag{1}$$

The signal propagates through an isovelocity underwater dispersive channel [2], having the same velocity of sound over all volume [1–5]. We will assume that the transmitter is located at the depth of $z_t$ meters. The receiver is located at the depth of $z_r$ meters. The distance between the transmitter and the receiver is denoted by $r$. The transfer function of the channel is

$$\begin{aligned} H(f) &= \sum_{m=1}^{+\infty} g_m(z_t)g_m(z_r)\frac{\exp(jk_r(m,f)r)}{\sqrt{k_r(m,f)r}} \\ &= \sum_{m=1}^{+\infty} A_t(m,f,r)\exp\left(jk_r(m,f)r\right), \end{aligned} \tag{2}$$

where $g_m(z_t)$, $g_m(z_r)$ are the modal functions of the $m$-th mode for the transmitter and the receiver, respectively. The attenuation rate is $A_t(m,f,r) = A(m,f)/\sqrt{r}$ . The transfer function depends on the number of modes, and the modes are dependent on wavenumbers $k_r(m,f)$ [2]

$$k_r(m,f) = \left(\frac{2\pi f}{c}\right)^2 - \left((m-0.5)\frac{\pi}{D}\right)^2 \tag{3}$$

where $D$ is the channel depth. The sound speed in the case of underwater communications is $c = 1500$ m/s. The modal functions $g_m$ are the solutions [2] of

$$\frac{\partial^2 g}{\partial z^2} + \left(\left(\frac{2\pi f}{c}\right)^2 - k_r^2(m,f)\right)g = 0. \tag{4}$$

It is obvious that the transfer function of a dispersive channel is of a multicomponent structure. The components depend on the wavenumbers $k_r(m,f)$ and their frequencies, on modal functions $g_m$ and the distance $r$.

The received signal is then

$$x(n) = u(n) * h(n), \tag{5}$$

where $h(n)$ is the impulse response of (2). An ideal time-frequency representation of the impulse response of a dispersive channel environment is shown in Fig. 1. Our goal is to decompose the mode functions, which will make the problem of detecting the transmitted signal straightforward. This decomposition makes compressive sensing methods application possible to use as well. The decomposition method will be formulated within the compressive sensing approach.

In some real-world scenarios, the signal will be received with a kind of disturbance. Here, we will assume that the signal is corrupted with strong sinusoidal disturbances

$$x_d(n) = x(n) + \sum_{l=1}^{N_M} B_i e^{j(\omega_l n + \psi_l)}. \tag{6}$$

The strong periodic disturbances should be detected and removed. Methods for detecting and removing strong disturbances will be presented next.

## 3. Sparse signal reconstruction

Assume a signal $x(n)$, $0 \le n < N$ and its linear transform $X(k)$, which will be defined as

$$X(k) = \sum_n \psi_k(n)x(n) \tag{7}$$

where $\psi_k(n)$ is the basis function of the transform used. In the vector form they are written as

$$\mathbf{x} = [x(0), x(1), \ldots, x(N-1)]^T \tag{8}$$

$$\mathbf{X} = [X(0), X(1), \ldots, X(N-1)]^T. \tag{9}$$

They are related via $N \times N$ transformation matrix $\mathbf{A}_N$ as

$$\mathbf{X} = \mathbf{A}_N\mathbf{x}. \tag{10}$$

We will assume that signal $x(n)$ is sparse. It means that the signal $\mathbf{x}$ has only $K \ll N$ samples $x(n_1), x(n_2), \ldots, x(n_K)$ that are nonzero. When the signal is sparse in one of its domains, it can be reconstructed with less measurements in one of its transformation domains, i.e. with $N_A < N$. The signal measurements in this case are coefficients of its transform at positions $\mathbb{N}_A = \{k_1, k_2, \ldots, k_{N_A}\}$ . The measurement vector is defined by

$$\mathbf{y} = [X(k_1), X(k_2), \ldots, X(k_{N_A})]^T. \tag{11}$$

Vector form of the measurements equation is

$$\mathbf{y} = \mathbf{A}\mathbf{x} \tag{12}$$

where $\mathbf{A}$ is a $N_A \times N$ matrix

$$\mathbf{A} = \begin{bmatrix} \psi_{k_1}(0) & \psi_{k_1}(1) & \cdots & \psi_{k_1}(N-1) \\ \psi_{k_2}(0) & \psi_{k_2}(1) & \cdots & \psi_{k_2}(N-1) \\ \vdots & \vdots & \ddots & \vdots \\ \psi_{k_{N_A}}(0) & \psi_{k_{N_A}}(1) & \cdots & \psi_{k_{N_A}}(N-1) \end{bmatrix} \tag{13}$$

where $\psi_k(n)$ are the transform coefficients. The matrix is obtained by keeping only the rows of $\mathbf{A}$ corresponding to the available measurements.

The goal of compressive sensing is to reconstruct the signal by minimizing $\mathbf{x}$ using the available measurements $\mathbf{y}$

$$\min \|\mathbf{x}\|_0 \quad \text{subject to} \quad \mathbf{y} = \mathbf{A}\mathbf{x}. \tag{14}$$

It is assumed that the reconstruction conditions are met. The solution of problem (14) can be found in various ways. One of the common algorithms to solve the problem is the orthogonal matching pursuit (OMP) [18]. In the first step of the OMP, the position of the largest component is found

$$n_1 = \arg\max\{\mathbf{x}_0\} \tag{15}$$

using the initial estimate $\mathbf{x}_0 = \mathbf{A}^H\mathbf{y}$, calculated using only the available measurements. A new partial matrix of the matrix $\mathbf{A}$ is formed, omitting all columns except the row which corresponds to the estimated position $n_1$. New matrix is then $\mathbf{A}_1$. The estimate of the first component in the time domain is

$$\mathbf{x}_1 = (\mathbf{A}_1^H\mathbf{A}_1)^{-1}\mathbf{A}_1^H\mathbf{y}. \tag{16}$$

The signal is reconstructed at the position $n_1$ and subtracted from the original signal measurements. The estimate of the non-zero position is calculated again with this signal and its maximum position is found at $n_2$. A new set $\mathbb{K} = \{n_1, n_2\}$ is formed with the corresponding matrix $\mathbf{A}_2$. The new estimate $\mathbf{x}_2$ is calculated and the signal is reconstructed. The procedure is repeated until all $K$ components are reconstructed. For the case when the signal samples are spread, we may use few samples around $n_i$ in each reconstruction step.

We will assume that the signal is $K$-sparse in the time domain, and we will consider dual polynomial transform coefficients as measurements.

## 4. Dual polynomial Fourier transform

Several techniques were developed for the localization non-stationary dispersive channels. Decomposition, localization and reconstruction of sparse signals in the dual polynomial Fourier transform is examined in this paper.

### 4.1. Polynomial Fourier transform (PFT)

The idea behind the traditional PFT is to find the parameters where the signal transform achieves the maximum concentration. In this way we can extract all components and localize their positions [6,7]. Let us assume a signal $x(n)$. Its PFT is calculated as [8–10]

$$X_{\alpha_2,\alpha_3,\ldots,\alpha_N}(k) = \sum_n x(n) e^{-j\frac{2\pi}{N}(kn+\alpha_2 n^2+\alpha_3 n^3+\ldots+\alpha_N n^N)}, \tag{17}$$

where $\alpha_2, \alpha_3, \ldots, \alpha_N$ are the parameters.

Assume that the analyzed signal is a polynomial phase signal (PPS) of the $P$-th order

$$x(n) = Ae^{j\frac{2\pi}{N}\sum_{i=1}^{P} a_i n^i}.$$

The signal will be highly concentrated in the PFT space of parameters where the maximum of the transform is achieved (where the transform of this signal is the best concentrated), i.e.

$$(\hat{a}_2, \hat{a}_3, \ldots, \hat{a}_P) = \arg \max_{(k,\alpha_2,\ldots,\alpha_P)} |X_{\alpha_2,\ldots,\alpha_P}(k)|. \tag{18}$$

It means that the PFT of a signal $x(n)$ will have the best concentration when $(\alpha_2, \ldots, \alpha_P) = (a_2, \ldots, a_P)$. Then the goal to estimate $a_2 \approx \hat{a}_2, \ \ldots, a_P \approx \hat{a}_P$ is achieved.

### 4.2. Dual extension of PFT

For the signals whose spectral content is concentrated within short time interval, with changes in ftequency the dual PFT (DPFT) is more appropriate tool. Like for PFT, the goal of DPFT is to find the parameters where the transform of the signal produces the highest concentration, meaning maximal sparsity.

The considered signal is a polynomial phase signal

$$X(k) = Ae^{-j\frac{2\pi}{N}\sum_{i=1}^{P} b_i k^i}. \tag{19}$$

in the frequency domain.

The discrete dual PFT is defined as [19]

$$x_{\beta_2,\beta_3,\ldots,\beta_P}(n) = \sum_k X(k) e^{j\frac{2\pi}{N}(nk+\beta_2 k^2+\ldots+\beta_P k^P)}. \tag{20}$$

The maximum of DPFT, i.e., the maximum of the Eq. (20) is achieved when

$$(\hat{b}_1, \hat{b}_2, \ldots, \hat{b}_P) = \arg \max_{(n,\beta_2,\ldots,\beta_P)} |x_{\beta_2,\ldots,\beta_P}(n)|. \tag{21}$$

Ideally, the best DPFT concentration is when $(\beta_2, \ldots, \beta_P) = (b_2, \ldots, b_P)$ . Our goal is to estimate the parameters such that $\hat{b}_2 \approx b_2, \ldots, \hat{b}_P \approx b_P$ .

A local form of the dual PFT, corresponding to the local PFT (known as LPFT) would be obtained using a frequency domain window function $W(k)$. It reads

$$x_{\beta_2,\beta_3,\ldots,\beta_P}(n,k) = \sum_l W(l) X(k+l) \times e^{j\frac{2\pi}{N}(nk+\beta_2 k^2+\ldots+\beta_P k^P)}.$$

This kind of transform can be used for analysis of quite complex non-stationary acoustic signals in the dispersive media.

## 5. Sparsity in DPFT

The reconstruction of signals sparse in the PFT representation domain is shown in [20]. In this paper, we will consider the DPFT case when some unavailable coefficients are in the frequency domain (due to denoising procedure on harmonic disturbances).

Without loss of generality, we will consider the analysis to the third order DPFT. Consider that $\mathbf{X}$ has disturbed samples which are found and set as unavailable. The third order DPFT estimated using only the available samples of $\mathbf{X}$ is [21]

$$x_{\beta_2,\beta_3}(n) = \sum_{k\in\mathbb{N}_A} X(k) e^{j\frac{2\pi}{N}(nk+\beta_2 k^2+\beta_3 k^3)} \tag{22}$$

for

$$X(k) = Ae^{-j\frac{2\pi}{N}(b_1 k+b_2 k^2+b_3 k^3)}. \tag{23}$$

Assume that parameters $\beta_2$, $\beta_3$ are found by a direct search over the interval of their possible values. When the parameters are correctly estimated $(\beta_2, \beta_3) = (b_2, b_3)$, the DPFT is

$$x_{b_2,b_3}(n) = \sum_k Ae^{j\frac{2\pi}{N}k(n-b_1)} = A\delta(n-b_1). \tag{24}$$

Obviously it is sparse. In the case of multicomponent signals, i.e.

$$X(k) = \sum_{m=1}^{M} A_m e^{-j(b_{1m}k+b_{2m}k^2+b_{3m}k^3)}, \tag{25}$$

the parameters of each component are estimated in iterative way. Without loss of generality, assume that $A_1 > A_2 > \ldots > A_M$ . When the first component is matched with

$$(\beta_{21}, \beta_{31}) = (b_{21}, b_{31})$$

we may consider that all other components are spread and negligible. The measurements matrix is obtained from this signal definition (22) assuming that only the values $k \in \mathbb{N}_A$ are available. This relation for various $n$ can be written as

$$\begin{bmatrix} x_{b_{21},b_{31}}(n_1) \\ x_{b_{22},b_{32}}(n_2) \\ \vdots \\ x_{b_{2K},b_{3K}}(n_K) \end{bmatrix} = \mathbf{A}_K^H \begin{bmatrix} X(k_1) \\ X(k_2) \\ \vdots \\ X(k_{N_A}) \end{bmatrix} \tag{26}$$

where the measurement matrix is defined by

$$\mathbf{A}_K = \begin{bmatrix} e^{-j\frac{2\pi}{N}(n_1 k_1+\phi_1)} & \ldots & e^{-j\frac{2\pi}{N}(n_K k_1+\phi_1)} \\ \vdots & \ddots & \vdots \\ e^{-j\frac{2\pi}{N}(n_1 k_{N_A}+\phi_{N_A})} & \ldots & e^{-j\frac{2\pi}{N}(n_K k_{N_A}+\phi_{N_A})} \end{bmatrix}$$

with $\phi_i = k_i^2 b_{21} + k_i^3 b_{31}$ for $i = 1, \ldots, N_A$ . Starting from the available values $X(k)$, $k \in \mathbb{N}_A$, we reconstruct the non-zero values in time $[x_{b_{21},b_{31}}(n_1), x_{b_{22},b_{32}}(n_2), \ldots, x_{b_{2K},b_{3K}}(n_K)]$ using the iterative OMP procedure, starting with

$$\mathbf{x}_1 = (\mathbf{A}_1^H \mathbf{A}_1)^{-1} \mathbf{A}_1^H \mathbf{y}. \tag{27}$$

After the DPFT sample at $n_1$ is reconstructed then the remaining unavailable values $X(k)$ are calculated for the first component. This

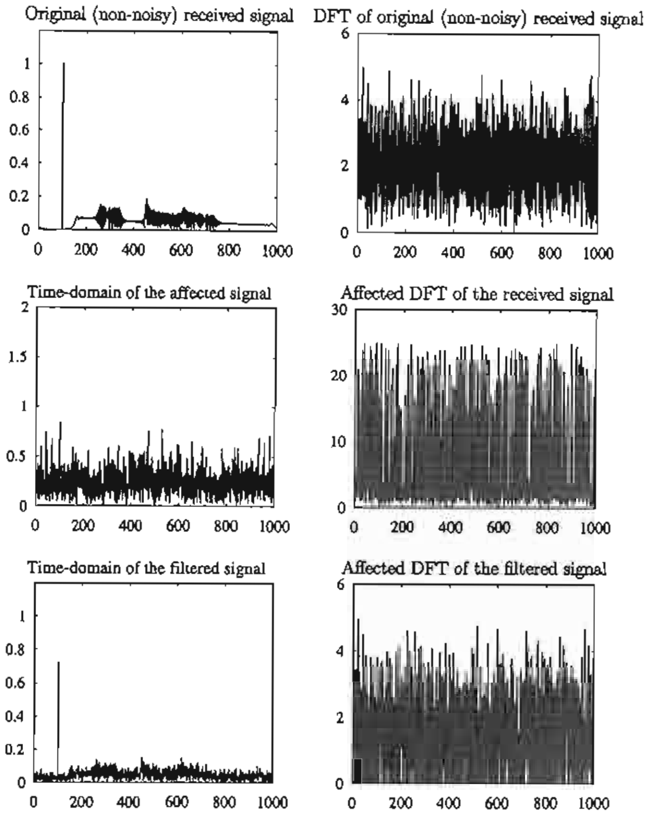


**Fig. 2.** Received signal in the time domain (left); in the frequency domain (right): without disturbance (top), with disturbance (middle), and the filtered signal (bottom).

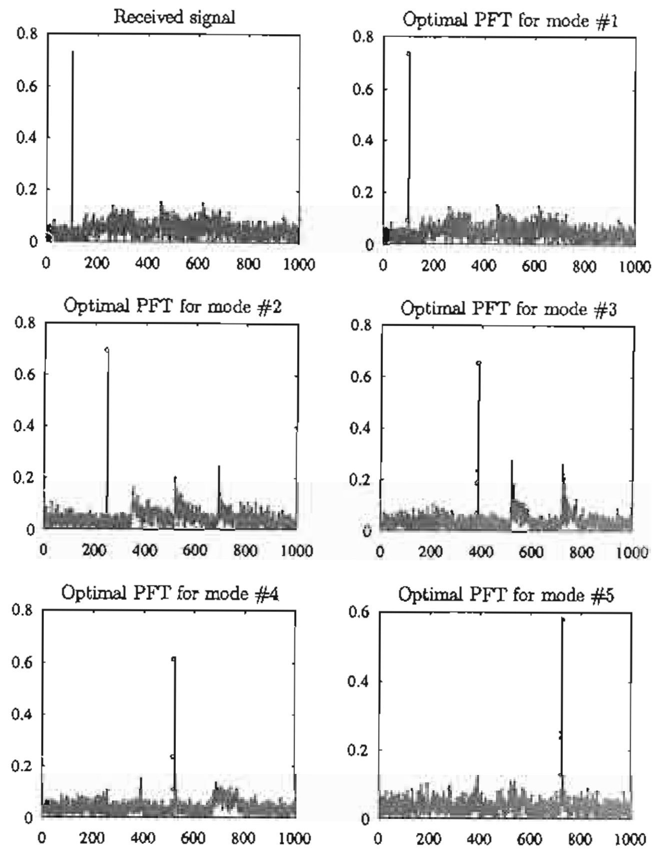


**Fig. 3.** Decomposition of the components using DPFT .

component is removed from the original measurements. The procedure is repeated for the second component. After the parameters of the second component are found as $(\beta_{22}, \beta_{32}) = (b_{22}, b_{32})$, both the first and second component are reconstructed using both components

$$(\beta_{21}, \beta_{31}) = (b_{21}, b_{31}), \text{ and } (\beta_{22}, \beta_{32}) = (b_{22}, b_{32}).$$

After the first two values are reconstructed, the procedure is continued for all $n_i$. For the case when the DPFT values are not on the grid, we may use few samples around $n_i$ in the reconstruction. The stopping criterion can be the energy of the remaining signal after the reconstructed components are removed.

## 6. Numerical results

The application of the proposed theory is demonstrated on examples. In the first example a theoretical signal that fully fits the assumed model is considered. A simulated acoustic signal, that only approximately behaves as the assumed theoretical model, is analyzed in other two examples.

**Example 1.** Let us consider an ideal case of a polynomial phase signal of form (19). Assume that the signal is received with 5 components

$$\begin{aligned} X(k) = {} & e^{(j2\pi 100k/N)} + e^{(j2\pi 150k/N + j2\pi 0.1k^2/N)} \\ & + e^{(j2\pi 250k/N + j2\pi 0.1k^2/N + j2\pi 0.00005k^3/N)} \\ & + e^{(j2\pi 450k/N + j2\pi 0.0001k^3/N)} \\ & + e^{(j2\pi 600k/N + j2\pi 0.05k^2/N + j2\pi 0.0001k^3/N)} \end{aligned} \quad (28)$$

with $k = 0, \dots, N-1$ and $N = 1000$ . This signal in the time domain, along with the corresponding frequency domain, is presented in Fig. 2 (top). Additionally, we assume that 30% of randomly positioned samples in the frequency domain are strongly disturbed. This will exhibit in the time domain by disturbing sinusoids. The affected signal is shown in Fig. 2 (middle). The disturbance components are first filtered with a simple notch filter and set to zero (hard thresholding). The signal after filtering is shown in Fig. 2 (bottom).

For the analysis of this signal we have used the DPFT of the third order as in Eq. (22). Values of $\beta_2$, $\beta_3$ are varied in the range of −0.2 to 0.2 and −0.3 to 0.3, respectively. The optimal parameter values for various modes are detected iteratively. When we find the first set of parameters $\beta_2$, $\beta_3$, the peak in the DPFT corresponds to the single component. We can remove the component from the DPFT and continue to estimate other components. This decomposition using the DPFT is shown in Fig. 3.

The decomposition results are non-stationary single component signals. The dual S-method representation as an improved version of short-time Fourier transform [11,19] is used for displaying the time-frequency content of the individual components and the reconstructed signal. Since all analyzed modes (components) are spread over a wide frequency range, we will analyze the signal in the frequency domain using the dual STFT. It is defined by

$$STFT_D(k,n) = \sum_{p=-N_s/2}^{N_s/2-1} X(p-k)W(p)e^{j\frac{2\pi}{N_s}pn}, \quad (29)$$

where $X(k)$ is Fourier transform of the considered component and $W(k)$ is the analysis window.

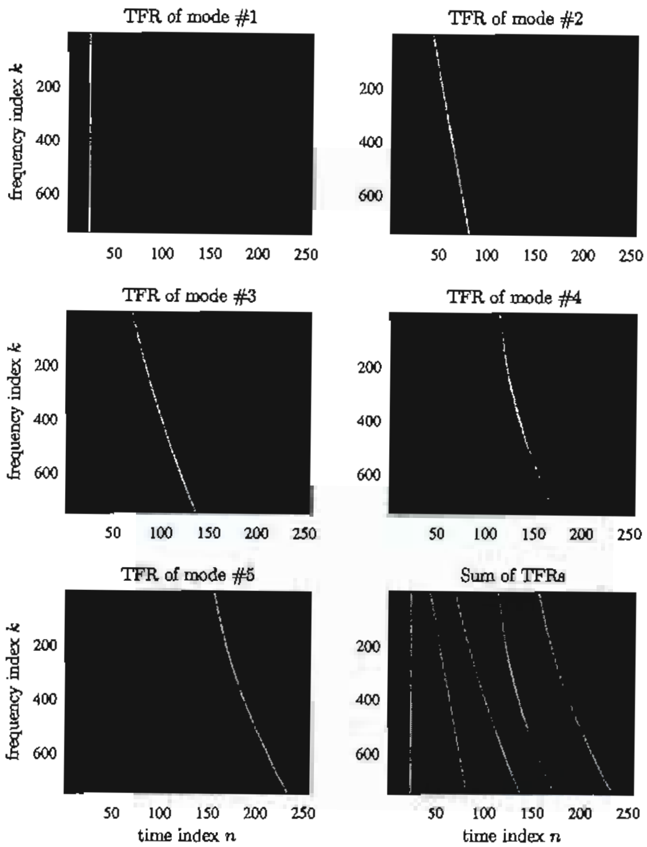


**Fig. 4.** S-method decomposition of the components .

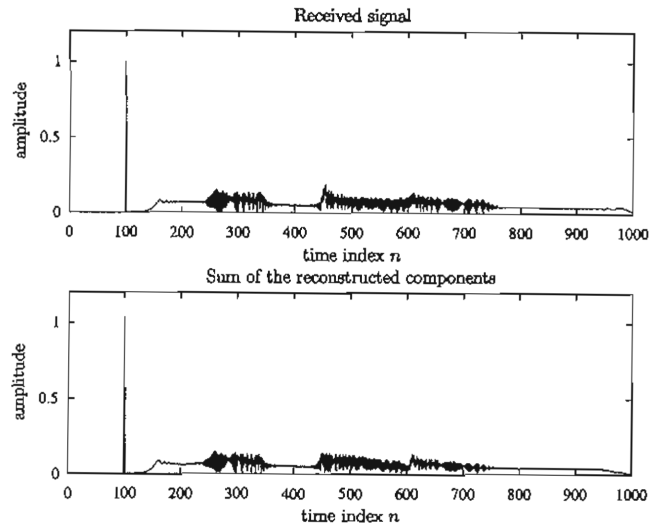


**Fig. 5.** The original signal (top) and the reconstructed signal (bottom).

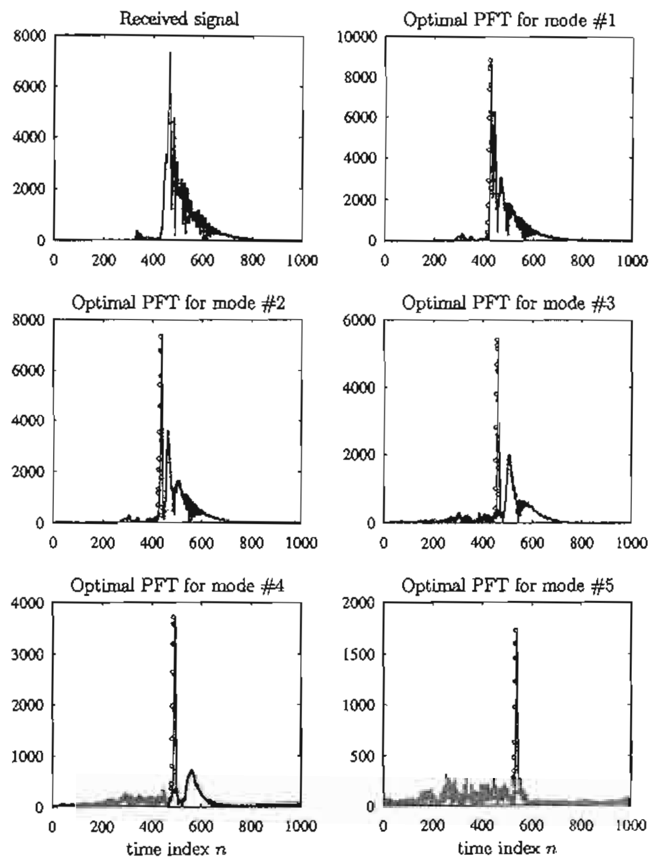


**Fig. 6.** Decomposition of the modes in time-domain: Received signal (top left); Optimal dual PFT for each mode separately. Samples associated to the current mode are marked with red circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Therefore, the dual S-method could be then calculated as

$$SM_D(k,n) = \sum_{i=-L}^{L} STFT_D(k, n+i) STFT_D^*(k, n-i) \tag{30}$$

where $2L+1$ is the time domain window size [6,7,11]. In this example, we use $L = 16$ and the Hanning window of size $W_s = 256$.

The received signal is decomposed and reconstructed using the OMP algorithm. The S-method of the reconstructed components is shown in Fig. 4. The sum of normalized representations of the five components is also shown Fig. 4 (bottom right subplot). The original non-noisy signal and the final reconstructed signal are presented in Fig. 5.

**Example 2.** Here we will analyze the simulated acoustic signal as described in Section 2. In this case, the signal is not of an ideal polynomial phase structure.

A signal of form (1) is transmitted through a dispersive channel with $M = 5$ modes. We will assume that the received signal is of form (5), where the signal depends on the transfer function as in Eq. (2) and Eq. (3). The channel depth is $D = 20$ meters and the distance between the transmitrer and receiver is $r = 2000$ meters. The frequency range $f$ is between $f_{\min} = 250$ Hz and $f_{\max} = 500$ Hz. The received signal is shown in Fig. 6 (top left). Amplitude is attenuated $A_m = (6 - m)W(f)$, where $W(f)$ is the Hanning window in the frequency domain.

For the analysis of this signal we have used the third order DPFT, with $\beta_2$, $\beta_3$ being varied in the range of $-0.2$ to 0.2 and $-0.3$ to 0.3. The decomposition of the modes is shown in Fig. 6.

For the dual S-method, we use $L = 16$ and the Hanning window of size $W_s = 512$ for the dual STFT calculation. The S-method of the five modes, obtained by decomposition using DPFT before the compressive sensing framework, is shown in Fig. 7. Sum of the normalized representations of the five modes is also shown Fig. 7 (bottom right subplot). Sum of the decomposed components and amplitudes of individual components are given in Fig. 8.

**Example 3.** In this example, we will examine the case when the signal is corrupted with strong sinusoidal disturbances (6).

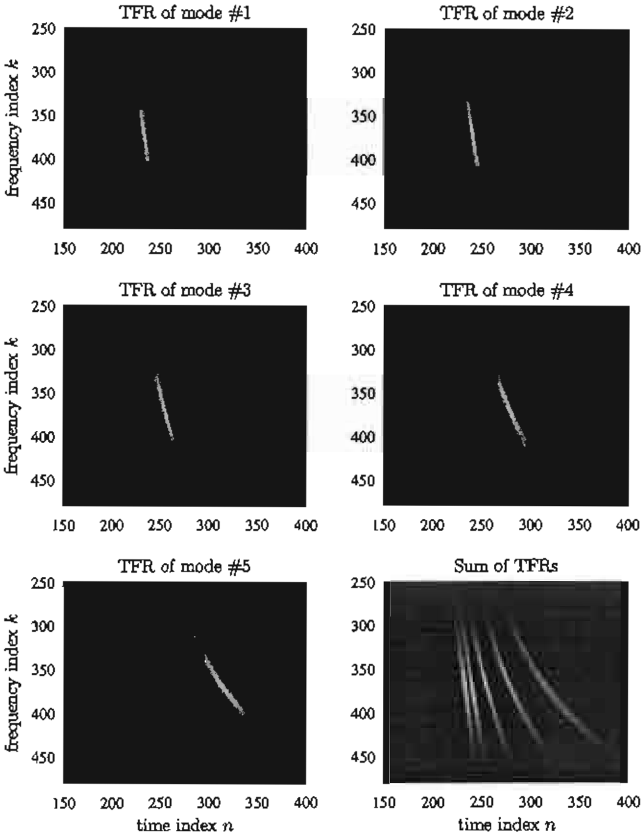


Fig. 7. S-method of the decomposed modes 1, 2, 3, 4 and 5 and sum of the normalized representations of all modes.

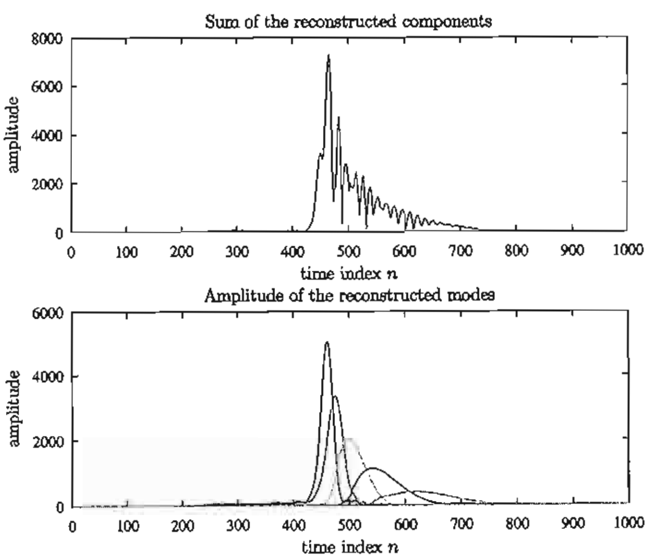


Fig. 8. Sum of the reconstructed modes (top) and amplitudes of individual modes (bottom).

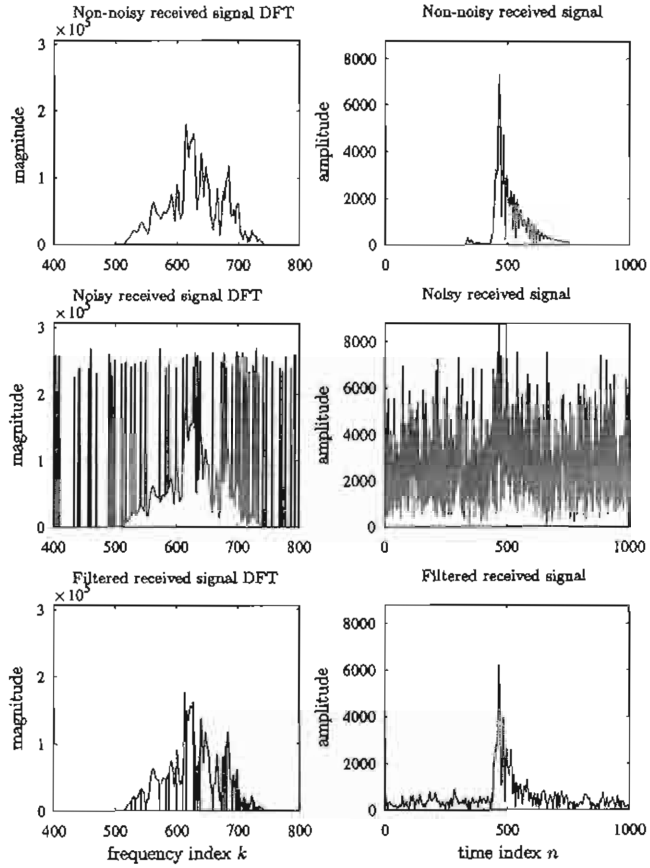


Fig. 9. DFT of received signal (left) and the received signal in time domain (right): without disturbances (top); disturbed (middle) and filtered (bottom).

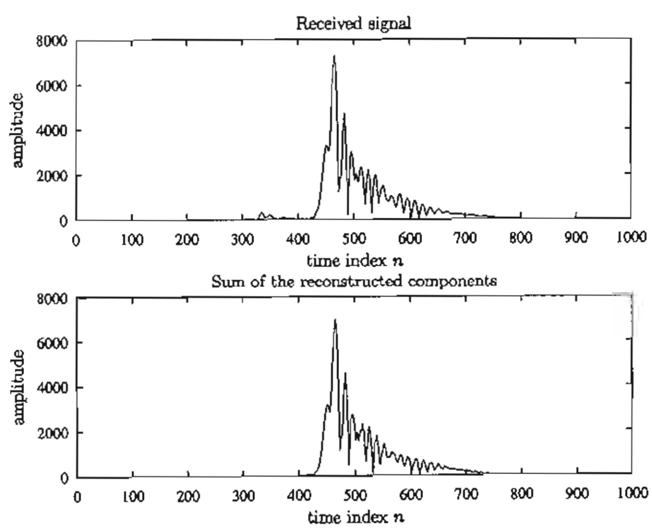


Fig. 10. Comparison: non-noisy received signal (top); signal reconstructed after OMP (bottom).

Assume the case same as in Example 2. The received signal without disturbances is shown in Fig. 9 (top subplots). It is assumed that the received signal has disturbances in frequency domain in the form of high-impulses in 15% of the spectrum. The disturbed received signal is illustrated in Fig. 9 (middle subplots).

Firstly, we remove the components which are affected by the noise (disturbances) using hard thresholding. The noisy spectral samples are considered as unavailable. The frequency and time domains of the received signal after filtering are shown in Fig. 9 (bottom subplots).

After that, the parameters are found using a third order DPFT. For the comparison, the received non-noisy signal and the reconstructed signal are shown in Fig. 10.

Since the compressive sensing based reconstruction is able to recover the original values of the disturbed coefficients, the obtained results are almost identical with the results presented in Example 2, when the non-disturbed signal is analyzed.

The presented algorithm belongs to the class of OMP algorithms. Its FPGA realization can be implemented following the one presented in [22]. Other hardware architecture for CS methods presented in [23,24] can be used also.

## 7. Conclusions

Decomposition and reconstruction of acoustic signals are considered. These signals are sparse in the dual polynomial Fourier transform. The analyzed signals are obtained as a result of the transmission through a dispersive underwater channel environment. The received multicomponent signal is decomposed using the dual polynomial Fourier transform. In such a way, individual propagation modes are obtained. The case when the received signal is corrupted with strong impulses in the frequency domain, corresponding to harmonic disturbances in the time domain, is analyzed. The original signal is reconstructed using compressive sensing methods, with the dual polynomial Fourier transform sparsity assumption. Further research on this topic could be dedicated to the hardware implementation of the presented method.

## Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi: 10.1016/j.micpro.2018.09.005

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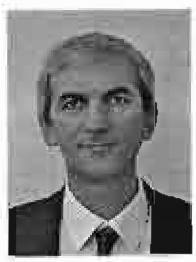

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**Prof. dr Irena Orović**

**BIOGRAFIJA**

Irena Orović je rođena 21.02.1983.god. u Podgorici. Završila je studije na Elektrotehničkom fakultetu u Podgorici 2005. godine. Diplomirala je sa ocjenom 10 u Julu 2005. godine u Brestu, Francuska, gdje je boravila po osnovu bilateralne saradnje između Univerziteta Crne Gore i ENSIETA-e Brest. Od 2005-2010 godine bila je saradnik u nastavi na Elektrotehničkom fakultetu, zatim od 2010-2015 docent na Univerzitetu Crne Gore, od 2015-2020 vanredni profesor. U junu 2020. izabrana je u zvanje redovnog profesora.

Postdiplomske studije je upisala u septembru 2005. godine na Elektrotehničkom fakultetu (odsjek Elektronika, telekomunikacije i računari, smjer Računari).

Magistarsku tezu „**Primjena vremensko-frekvencijske analize na watermarking govornih signala**" odbranila je sa ocjenom 10 u Decembru 2006. godine.

Doktorsku disertaciju: "**Vremensko-frekvencijske distribucije i neki aspekti primjene**" odbranila je 19.02.2010. godine.

Dobitnik je brojnih nagrada i priznanja, među kojima treba istaknuti:

- Studentsku nagradu "19. decembar" (2003),
- Nagradu Crnogorske akademije nauka i umjetnosti (2004),
- Nagradu Univerziteta Crne Gore (2004),
- Više puta je nagrađivana od strane Elektrotehničkog fakulteta kao najbolji student generacije
- Dobitnik je Plakete Univerziteta Crne Gore za najboljeg diplomiranog studenta iz oblasti tehničkih, prirodno-matematičkih i medicinskih nauka (2005. godine),
- Dobitnik je nagrade Elektrotehničkog fakulteta za izvanredne naučno-istraživačke rezultate tokom rada na doktorskoj tezi (2010. godine).
- Dobitnik je internacionalne nagrade za najbolju doktorsku disertaciju TRIMO 2011 Ljubljana, Slovenija
- Nagrada Ministarstva nauke za najuspješniju ženu u nauci - 2012 godine

Boravci na inostranim naučnim institucijama: Dr. Orović je boravila na instituciji ENSIETA iz Bresta, Francuska (2005 i 2006.), University Bonn-Rhien-Sieg iz Bona, Njemačka (2007), Institut Polytechnique de *Grenoble*, Francuska (2008. i 2009.), Villanova University, Philadelphia USA (2010, 2011, 2012).

Prof. dr Irena Orović je do sada objavila oko 130 naučnih radova od čega oko 60 u vodećim svjetskim časopisima (časopisi sa SCI/SCIE liste sa impact faktorom), kao i veći broj radova u drugim međunarodnim časopisima i na konferencijama.

Objavila je kao koautor 5 udžbenika na našem jeziku. Od knjiga i monografija inostranih izdavača objavila je dvije knjige: "Multimedia Signals and Systems", Springer 2012 na engleskom jeziku publikovanu od strane svjetskog izdavača Springer-a, kao i „Multimedia Signals and Systems: Basic and Advanced Algorithms for Signal Processing", zatim poglavlje u medjunarodnoj monografiji "Time-Frequency Analysis of Micro-Doppler Signals Based on Compressive Sensing," Compressive Sensing for Urban Radar, CRC-Press, 2014", poglavlje u enciklopediji: „Sparse Signal Reconstruction" in Encyclopedia of Electrical and Electronics Engineering, Wiley 2017.

Recenzent je u mnogobrojnim časopisima, među kojima je više njih iz IEEE i IEE izdanja.

Bila je rukovodilac Računarskog centra na Elektrotehničkom fakultetu, i šef studijskog programa Elektronika, telekomunikacije, računari.

U periodu od 2011.-2015. godina dr Irena Orović je bila potpredsjednik i član Savjeta za naučno-istraživačku djelatnost u Crnoj Gori (Ministarstvo nauke Crne Gore).

Od decembra 2017. godine obavlja funkciju Prorektora za nauku i istraživanje.

Predsjednik je Naučnog odbora Univerziteta Crne Gore.

Skupština Crne Gore izabrala je u junu 2020. godine za člana nacionalnog Savjeta za visoko obrazovanje.

Više detalja i kompletan spisak referenci može se pronaći na sajtu www.tfsa.ac.me.

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Prim. 05.06.2020
02/1 608

Na osnovu člana 72 stav 2 Zakona o visokom obrazovanju („Službeni list Crne Gore" br 44/14, 47/15, 40/16, 42/17, 71/17, 55/18, 3/19, 17/19, 47/19) i člana 32 stav 1 tačka 9 Statuta Univerziteta Crne Gore, Senat Univerziteta Crne Gore na sjednici održanoj 04.06.2020. godine, donio je

## O D L U K U
## O IZBORU U ZVANJE

**Dr Irena Orović** bira se u akademsko zvanje redovni profesor Univerziteta Crne Gore za **oblasti Računarstvo i Digitalna obrada signala,** na Elektrotehničkom fakultetu Univerziteta Crne Gore, na neodređeno vrijeme.

**SENAT UNIVERZITETA CRNE GORE**
**PREDSJEDNIK**

**Prof. dr Danilo Nikolić, rektor**

**Prof. dr Miloš Daković**

## BIOGRAFIJA

Miloš Daković je rođen 1970. godine u Nikšiću, Crna Gora. Diplomirao je 1996., magistrirao 2001. i doktorirao 2005. godine, na Elektrotehničkom fakultetu Univerziteta Crne Gore. Redovni je profesor na Univerzitetu Crne Gore od 2017. godine.

Učestvovao je u više od 10 naučno-istraživačkih projekata finansiranih od strane Volkswagen fondacije, crnogorskog Ministarstva nauke i kanadske vlade (DRDC). Recenzent je u više međunarodnih časopisa, među kojima su: IEEE Transactions on Signal Processing, IEEE Signal Processing Letters, IEEE Transactions on Image Processing, IET Signal Processing, Signal processing i Geoscience and Remote Sensing Letters.

Dosadašnji naučno-istraživački rad profesora Dakovića rezultovao je objavljivanjem više od 100 radova, od čega je preko 40 u vodećim međunarodnim časopisima. Koautor je knjige *Time-Frequency Signal Analysis with Applications* čiji je izdavač Artech House, Boston.

Oblasti njegovog naučno-istraživačkog interesovanja su: obrada signala, vremensko-frekvencijska analiza signala, obrada radarskih signala i compressive sensing.

Dr Daković je dobitnik Godišnje nagrade za naučna dostignića u 2015. godini, u kategoriji pronalazač – inovator za najuspješnije inovativno rješenje, koju uručuje Vlada Crne Gore.

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**O D L U K U**
**O IZBORU U ZVANJE**

**Dr Miloš Daković** bira se u akademsko zvanje **redovni profesor Univerziteta Crne Gore** za oblast **Digitalna obrada signala i adaptivni sistemi na Elektrotehničkom fakultetu** i na nematičnim fakultetima, na neodređeno vrijeme.

**R E K T O R**
**Prof. Radmila Vojvodić**

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| Primljeno: 17.01.2017 | | | |
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| Org. jed. | Broj | Prilog | Vrijednost |
| 02/1 | 55 | | |

**Prof. dr Cornel Ioana**

## BIOGRAFIJA

**Cornel Ioana** received the Dipl.-Eng. degree in electrical engineering from the Romanian Military Technical Academy of Bucharest, Romania, in 1999 and the M.S. degree in telecommunication science and the Ph.D. degree in the electrical engineering field, both from University of Brest-France, in 2001 and 2003, respectively. Between 1999 and 2001, he activated as a Military Researcher in a research institute of the Romanian Ministry of Defense (METRA), Bucharest, Romania. Between 2003 and 2006, he worked as Researcher and Development Engineer in ENSIETA, Brest, France. Since 2006, he has been an Associate Professor-Researcher with the Grenoble Institute of Technology/GIPSA-lab. His current research activity deals with the signal processing methods adapted to the natural phenomena. His scientific interests are nonstationary signal processing, natural process characterization, underwater systems, electronic warfare, and real-time systems.

## PREVOD BIOGRAFIJE

**Cornel Ioana** je diplomirao je elektrotehniku na Rumunskoj vojno-tehničkoj akademiji iz Bukurešta, Rumunija, 1999. godine. Zvanje magistra u oblasti telekomunikacije i doktora nauka na polju elektrotehnike stekao je na Univerzitetu u Brest-France, 2001., odnosno 2003. godine. Između 1999. i 2001. radio je kao vojni istraživač u institutu Ministarstva odbrane Rumunije (METRA), Bukurešt, Rumunija. Između 2003 i 2006, radio je kao istraživač i inženjer razvoja u ENSIETA-i, Brest, Francuska. Od 2006. godine je vanredni profesor-istraživač u Grenoble-ovom tehnološkom institutu/laboratorija GIPSA. Njegova trenutna istraživačka aktivnost su metode obrade signala prilagođenim prirodnim pojavama. Njegova naučna interesovanja su nestacionarna obrada signala, karakterizacija prirodnog procesa, podvodni sistemi, elektronsko ratovanje i sistemi u realnom vremenu.

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# ATTESTATION EMPLOYEUR

Je, soussignée AUBERT Céline, Directrice Administrative de l'Ecole Nationale Supérieure de l'Energie, l'Eau et l'Environnement certifie que

Monsieur Ioana Cornel est Fonctionnaire titulaire - Enseignant Chercheur, Maître de Conférences à Grenoble INP Ense3, et au laboratoire de recherche Gipsa-Lab.

Fait pour servir et valoir ce que de droit,

Céline AUBERT
Directrice Administrative
Ecole Nationale Supérieure
de l'Energie, l'Eau
et l'Environnement

*Attestation établie à la demande de l'intéressé*

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