

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

ERICSSON INC. AND TELEFONAKTIEBOLAGET
LM ERICSSON (“Ericsson”),
Petitioner

v.

REGENTS OF THE UNIVERSITY OF MINNESOTA (“REGENTS”),
Patent Owner

U.S. Patent Nos. 8,588,317, 8,718,185, and 8,774,309

DECLARATION OF DAVID BADER

I, David Bader, hereby declare as follows:

1. I am a librarian at Haynes and Boone, LLP. I have worked in this capacity since March 1, 2000.

2. **Exhibit 1007** is a true and accurate copy of a paper that I purchased from IEEE which is authored by Dr. Giannakis et al., entitled “Non-Data-Aided Carrier Offset Estimators for OFDM With Null Subcarriers: Identifiability, Algorithms, and Performance,” and which indicates that it was published in the *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 12, December 2001. I understand that the *IEEE Journal on Selected Areas in Communications* is a well-known periodical that began publications in 1983 and that is published on a monthly basis. I understand that IEEE is a commercial database carrying documents available to the public. IEEE is accessible to the public at the websites www.IEEE.org. Our library regularly relies upon the IEEE database for access to such public documents. I understand that **Exhibit 1007** will be submitted with a Petition for *inter partes* review in the above noted proceeding.

3. Attached as **Appendix A** is a true and accurate copy of Dr. Georgios B. Giannakis’ *Curriculum Vitae (CV)*. I obtained **Appendix A** by first accessing Dr. Giannakis’ profile page, hosted by the University of Minnesota at <http://spincom.umn.edu/georgios/>, opening (or clicking on) the hyperlink “Curriculum Vitae,” then downloading and printing the resulting webpage. The *CV*

of Dr. Giannakis, provided in **Appendix A** on page 49 at item [J280], indicates that the paper identified as **Exhibit 1007**, authored by Dr. Giannakis, entitled “Non-Data-Aided Carrier Offset Estimators for OFDM With Null Subcarriers: Identifiability, Algorithms, and Performance,” was published in *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 12, pp. 2504-2515, December 2001.

4. Attached as **Appendix B** is a true and accurate copy of Dr. Giannakis’ Google Scholar profile page. I obtained **Appendix B** by first accessing Dr. Giannakis’ profile page, hosted by the University of Minnesota at <http://spincom.umn.edu/georgios/>, opening (or clicking on) the hyperlink “Google Scholar profile page,” then downloading and printing the resulting webpage. The Google Scholar profile of Dr. Giannakis, provided in **Appendix B** on page 4, indicates that the paper identified as **Exhibit 1007**, authored by Dr. Giannakis, entitled “Non-Data-Aided Carrier Offset Estimators for OFDM With Null Subcarriers: Identifiability, Algorithms, and Performance,” was published in *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 12, pp. 2504-2515, December 2001.

5. Attached as **Appendix C** is a true and accurate copy of a paper authored by Dr. Mounir Ghogho et al., entitled “A Highly Accurate Blind Frequency-Offset Synchronization for OFDM,” that I obtained from

www.semanticscholar.org. I understand that Semantic Scholar provides a database that makes available technical and academic documents to the public. A librarian would reasonably rely upon this database for access to public documents.

6. Attached as **Appendix D** is a true and accurate copy of Dr. Ghogho's profile page at the University of Leeds. I obtained **Appendix D** by first accessing Dr. Ghogho's profile page hosted by the University of Leeds at https://engineering.leeds.ac.uk/staff/289/mounir_ghogho, opening (or clicking on) the hyperlink "Conference papers," then downloading and printing the resulting webpage. Dr. Ghogho's profile page provided in **Appendix D** indicates that the paper identified as **Appendix C**, authored by Dr. Ghogho, entitled "A Highly Accurate Blind Frequency-Offset Synchronization for OFDM," was presented at the European Wireless Conference (EW2002), Florence, Italy, 25-28 February 2002.

7. Notably Dr. Ghogho's paper, identified as **Appendix C**, at footnote [5] cites to the paper authored by Dr. Giannakis, identified as **Exhibit 1007**, which indicates that persons of skill in the art were aware of the paper identified as **Exhibit 1007** soon after it was published in December 2001. Further, since the paper identified as **Appendix C** was presented at the conference in February 2002 (as indicated by **Appendix D**) persons of ordinary skill in the art would have also

been aware of the paper identified as **Exhibit 1007** at least as of the conference date.

8. I hereby declare under penalty of perjury under the laws of the United States of America that the foregoing is true and correct, and that all statements made of my own knowledge are true and that all statements made on information and belief are believed to be true. I understand that willful false statements are punishable by fine or imprisonment or both. *See* 18 U.S.C. § 1001.

Date: March 20, 2017

Respectfully submitted,



David Bader

APPENDIX A

CURRICULUM VITAE

Georgios B. Giannakis

Home address

2561 Abbey Hill Dr.
Minnetonka, MN 55305

Tel.: (952) 546-0161
Cell: (612) 220-6151

Work address

Dept. of ECE and Digital Tech. Center
University of Minnesota
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Tel.: (612) 625-4287; and (612) 626-7781
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URL: <http://spincom.umn.edu>

Updated: January 21, 2017

PROFESSIONAL OBJECTIVE

Teaching, research and leadership in the following and related technical areas:

➤ **Areas of Expertise**

Signal processing, communications and networking, estimation, detection, time-series analysis, and machine learning. Past areas have included: (poly)spectra, wavelets, cyclostationary, and non-Gaussian signal analysis with applications to equalization, sensor arrays and image processing.

➤ **Current Research Topics**

Learning from Big Data, wireless cognitive radios, and network science with applications to social, brain, and power networks with renewables.

EDUCATION

1984 - 1986: *Ph.D. in Electrical Engineering*, University of Southern California, Los Angeles, CA

1984 - 1986: *M.Sc. in Mathematics*, University of Southern California, Los Angeles, CA

1982 - 1983: *M.Sc. in Electrical Engineering*, University of Southern California, Los Angeles, CA

1976 - 1981: *5-year Diploma in Electrical & Electronic Engr.*, Ntl. Tech. Univ. of Athens, Greece

PROFESSIONAL EMPLOYMENT HISTORY

2016 - Pres.: *McKnight Presidential Chair*, University of Minnesota (UMN)

2008 - Pres.: *Director*, Digital Technology Center, UMN

2001 - Pres.: *ADC Chair in Wireless Telecomm.*, Dept. of Electrical & Comp. Engr. (ECE), UMN

1999 - 2001: *Professor*, Dept. of ECE, UMN

1998 - 1999: *Director*, Communications, Controls, & Signal Proc. Lab, EE, Univ. of Virginia (UVA)

1997 - 1999: *Professor*, Dept. of Electrical Engr., University of Virginia

1992 - 1996: *Associate Professor*, Dept. of Electrical Engr., University of Virginia

1987 - 1991: *Assistant Professor*, Dept. of Electrical Engr., University of Virginia

1986 - 1987: *Instructor & Research Associate*, EE-Systems Dept., Univ. of Southern Cal. (USC)

1982 - 1986: *Research Assistant*, EE-Systems Department, University of Southern California

1982 - 1985: *Teaching Assistant / Grader*, EE-Systems Dept., University of Southern California

1981 - 1982: *Instructor* for a private educational center, Athens, Greece.

➤ **Courses Taught**

- * ECE 8581, “Estimation and Detection,” S’99, F’99, S’02, S’03, S’04, S’05, S’07, S’08, S’11, S’14, S’15, 3 credit hrs., 15-25 students (UMN)
- * ECE 5542, “Adaptive Signal Processing,” S’01, S’07, 3 credit hrs., 25 students (UMN)
- * ECE 5505, “Wireless Communications,” S’12, 3 credit hrs., 30 students (UMN)
- * ECE 5501, “Digital Communications,” S’00,F’00,F’01,F’03,F’06,F’07, 3 credit hrs., 30 students (UMN)
- * ECE 4541, “Digital Signal Processing,” F’16, 3 credit hrs., 35 students (UMN)
- * EE 814, “Advanced Detection and Estimation,” F’87, 3 credit hrs., 10 students (UVA)
- * EE 793, “Spectral analysis and time series,” F’88, 3 credit hrs., 6 students (UVA)
- * EE 781, “Pattern Recognition,” S’98, 3 credit hours, 8 students (UVA)
- * EE 774, “Statistical Signal Processing,” F’88, S’90, S’92, S’96, 3 credit hrs., 12 students (UVA)
- * EE 712, “Digital Communications,” S’97, 20 students (UVA)
- * EE 676, “Multidimensional Signal & Image Processing,” S’91, S’97, 15 students (UVA)
- * EE 614, “Estimation Theory,” S’90, S’92, 3 credit hrs., 10 students (UVA)
- * EE 576, “Digital Signal Processing,” S’88,89, F’90,91,92,96,97, 3 credit hrs., 35 students (UVA)
- * EE 420, “Communications II,” F’89, F’90, 3 credit hrs., 25 students (UVA)
- * EE 324, “Signals and Systems II,” S’93, S’94, S’95, 3 credit hrs., 60 students (UVA)
- * EE 323, “Signals and Systems I,” F’94, F’95, 3 credit hrs., 55 students (UVA)
- * ENGR203, “Electrical Science I,” S’91, 3 credit hrs., 15 students (UVA)

➤ **New Courses Introduced**

- * EE 793, “Spectral analysis and time series,” F’88 (UVA)
- * EE 687, “Wireless Communications (Lab),” F’97 (UVA)
- * EE 676, “Multidimensional Signal & Image Processing,” F’89 (UVA)
- * EE 614, “Estimation Theory,” F’89, S’96 (UVA)

UNIVERSITY SERVICE**➤ Departmental committees**

- ▷ *Preliminary Exam Committee*, F'00, S'01, F'04, F'06, F'07, S'16 (UMN)
- ▷ *Endowed Chair Selection Committee*, F'01, S'02 (UMN)
- ▷ *Faculty Search Committee*, F'99, S'00, F'00, S'01, F'01, S'02, S'03, S'04, F'06, S'07, S'10 (UMN)
- ▷ *Industrial Relations Committee*, S'00, F'00, S'01 (UMN)
- ▷ *Graduate Committee*, (chair), F'97, S'98 (UVA); S'12, F'13
- ▷ *IEEE Student Advisor (UVA-EE Chapter)*, F'96, S'97 (UVA)
- ▷ *Eminent Speakers Series*, (chair), F'95, S'96, F'96, S'97 (UVA)
- ▷ *Chairman's Search Committee*, (member), F'95, S'96 (UVA)
- ▷ *Graduate Committee*, (member), F'91, S'92, F'92, F'94, F'96 (UVA)
- ▷ *Doctoral Exam Ad hoc Committee*, (chair), F'94 (UVA)
- ▷ *Computer Equipment Committee*, (member), F'88, S'89, F'89, F'90, S'91, F'91, F'94 (UVA)
- ▷ *Personnel Committee*, (member), F'88, S'89, F'89, S'90, F'90, S'91, F'91, S'92 (UVA)
- ▷ *Undergraduate Committee*, (member), S'88 (UVA), S'16 (UMN)
- ▷ *Graduate Student Advisory Committees*: 50 (as chairman or member), 25 (as advisor) (UVA/UMN)

➤ School of Engineering committee

- ▷ *CSE Promotion and Tenure Advisory Committee*, S'16 (UMN)
- ▷ *Endowed Chair Search Committee*, Digital Technology Center, F'01, S'02, chair; F'02, S'03, S'04 member (UMN)
- ▷ *By-laws Committee*, S'94, F'94 (UVA)

➤ International Committees

- ▷ *Co-Advisor* and member of a Ph.D. Thesis in Univ. of Padua, Italy, 2010
- ▷ *Co-Advisor* and member of two Ph.D. defenses in Carlos III Univ., Madrid, Spain, 2006 and 2007
- ▷ *Juror* of a Ph.D. defense in Telecom, Paris, France, June 2001
- ▷ *Opponent* for a PhD defense in KTH, Stockholm, Sweden, November 1998
- ▷ *Member* of a Ph.D. Thesis Committee, Univ. of Cergy Pontoise, France, October 1998
- ▷ *Member* of an Assist. Prof. Election Committee in Telecom, Paris, France, October 1998

- ▷ *Reader* of a Ph.D. Thesis, Grenoble, France, 1995
- ▷ *Reader* of a Ph.D. Thesis, IIT, Madras, India, 1994

PROFESSIONAL ACTIVITIES

➤ Major IEEE Activities

- ▷ *Member* of the Nominations & Appointments Cmt., IEEE Signal Proc. Soc. (term: 01/16 - 12/17)
- ▷ *Member* of the Editorial Board for IEEE J. on Special Topics in Signal Proc. (term: 01/16 - 12/17)
- ▷ *Chair* of the Technical Committee on Signal Processing for Communications, IEEE Signal Processing Society (term: 05/98 - 12/01)
- ▷ *Member & Secretary* of the Steering Committee for the IEEE Transactions on Wireless Communications (term: 05/01 - 01/06)
- ▷ *Editor-in-Chief* for the IEEE Signal Processing Letters (term: 01/00 - 01/02)
- ▷ *Member* of the IEEE Fellow Election Committee (term: 06/99 - 06/02)
- ▷ *Member* of the Editorial Board, Proceedings of the IEEE (term: 01/00 - 01/03)
- ▷ *Member-at-Large*, Board of Governors, IEEE Signal Processing Society (term: 01/01-12/04)
- ▷ *Member* of the Publications Board, IEEE Signal Processing Society (term : 02/96 - 01/02)
- ▷ *Member & Vice Chair* of the Statistical Signal & Array Processing Committee (term: 05/91 - 03/98)
- ▷ *Associate Editor* for the IEEE Transactions on Signal Processing (Area: Spectrum Estimation & Modeling; term : 03/91 - 03/93)
- ▷ *Associate Editor* for the IEEE Signal Processing Letters (Area : Statistical Signal Processing, 1st term: 06/95 - 06/98; 2nd term: 07/98-07/2001)
- ▷ *Secretary & Member* of the Conference Board, IEEE Signal Processing Society (term: 06/95 - 06/98)
- ▷ *Co-organizer & lead guest editor* (with C. Cendrillon, V. Cevher, A. Swami, and Z. Tian) of the Special Issue on “Signal Processing for Big Data,” IEEE Journal on Special Topics in Signal Processing, June 2015.
- ▷ *Co-organizer & lead guest editor* (with F. Bach, C. Cendrillon, M. Mahoney, and J. Neville) of the Special Issue on “SP for Big Data,” IEEE Signal Processing Magazine, September 2014.
- ▷ *Co-organizer & guest editor* (with N. Al Dhahir, B. Hochwald, B. Hughes, and T. Marzetta) of the Special Issue on “Signal Processing Techniques for Space-Time Coded Transmissions,” IEEE Transactions on Signal Processing, October 2002.
- ▷ *Organizer & guest editor* of the Special Issue on “Signal Processing Advances in Wireless and Mobile Communications,” IEEE Signal Processing Magazine, May 2000.

- ▷ *Organizer & guest editor* of the “50th Anniversary of Signal Processing Series: Highlights of Signal Processing for Communications,” IEEE Signal Processing Magazine, March 1999.
- ▷ *Organizer & guest co-editor* (with G. Xu) of the Special Issue on “Signal Processing for Advanced Communications,” for the IEEE Transactions on Signal Processing, January 1997.
- ▷ *Organizer & guest co-editor* (with A. Swami) of the Special Issue on “Higher-order Statistics,” for the Signal Processing Journal, EURASIP, August 1996.
- ▷ *Organizer & guest editor* of the Special Issue on “Adaptive Signal Processing using Higher-Order Statistics,” for the Intl. J. of Adaptive Control and Signal Processing, Wiley, March 1996.

➤ **Plenary, Keynote, and Tutorial Talks**

- ▷ **Plenaries in 2016:** Ntl. Renewable Energy Lab (NREL), Golden, CO, Jan. 26-28, 2016; Intl. Conf. on Comp., Networking and Comm. (ICNC), Kauai, Hawaii, Feb. 15-18, 2016; Intl. Workshop on Signal, Array, and Comm. (IWSAC), Xi’an, China, March 2016; SPAWC, Edinburg, Scotland, July 3-6, 2016; STATOS, Budapest, Hungary, Sept. 2, 2016; Globalsip, Washington DC, Dec. 7-9, 2016; **Tutorials in 2016:** SPAWC, Edinburg, Scotland, July 3-6, 2016;
- ▷ **Plenaries in 2015:** Conf. on Information Sciences and Systems, John Hopkins Univ., Baltimore, March 18-20, 2015; Center for Advanced Signal and Image Sciences, Lawrence Livermore Ntl. Lab, May 13, 2015; **Tutorials in 2015:** CTTC, Barcelona, Spain, Oct. 26-27, 2015; Intl. Conf. of Acoust. Speech and Signal Proc., Gold Coast, Australia, April 19-24, 2015; EUSIPCO, Nice, France, Aug. 31-Sept. 4, 2015.
- ▷ **Plenaries in 2014:** Signal Processing Algorithms and Applications (SPA), Poznan, Poland, Sept. 22-24, 2014; Intl. Conf. on Wireless Communications and Signal Processing (WCSP), Hefei, P. R. China, Oct. 23-25, 2014; Asilomar Conf. on Signals, Systems, and Computers, Pacific Grove, CA, Nov. 2-5, 2014; GlobalSIP, Atlanta, GA, Dec. 3-5, 2014 (keynote). **Tutorials in 2014:** Intl. Conf. of Acoust. Speech and Signal Proc., Florence, Italy, May 4-9, 2014; Sensor Array and Multichannel(SAM) SP Workshop, A Coruna, Spain, June 22-25, 2014; IEEE-SPS Summer School on Signal Processing and Machine Learning for Big Data, Vancouver, CA, July 29-31, 2014; EUSIPCO, Lisbon, Portugal, Sept. 1-5, 2014.
- ▷ **Plenaries in 2013:** Intl. Workshop on Cross-Layer Designs, Qingdao, P. R. China, October 27-28, 2013; 10th Intl. Symp. on Wireless Comm. Systems, TU Ilmenau, Germany, Aug. 27-30, 2013; Intl. Black Sea Conf. on Communications and Networking, Batumi, Georgia, July 3-5, 2013; and STATOS: Statistics, Optimization, and Signal Processing Meeting, Darmstadt, June 15-16, 2013. **Tutorials in 2013:** Intl. Conf. of Acoust. Speech and Signal Proc., Vancouver, Canada, May 26-31, 2013; Intl. Conf. on Communications, Budapest, June 9-13, 2013; EUSIPCO, Marrakech, Morocco, September 9-13, 2013; GLOBECOM Conference, Atlanta, December 9-13, 2013; and CAMSAP Workshop, St. Martin, December 15-18, 2013.
- ▷ **Plenaries in 2012:** 2nd Greek SP Jam, Thessaloniki, Greece, May 2012; Intl. Work. on Math. Issues in Info. Sciences (MIIS), Xi’an, China, July 2012; 3rd IFAC Work. on Distr. Estimation and Control in Networked Systems, Santa Barbara, CA, Sept. 2012.
- ▷ **Plenary in 2011:** National URSI Symposium, Madrid, Spain, Sept. 2011.

- ▷ **Plenaries in 2010:** Australian Communication Theory Symposium (AusCTW), Canberra, Australia, Feb. 2010; Intl. Conf. on Telecommunications (ICT), Doha, Qatar, April 2010; Cognitive Information Processing (CIP), Elba, Italy, June 2010; Signal Proc. Advances in Wireless Communications (SPAWC), Marrakech, Morocco, June 2010; Wireless Advanced Symposium, London, UK, July 2010. **Tutorials in 2010:** Intl. Conf. on Telecommunications (ICT), Doha, Qatar, April 2010; and Intl. Conf. on Communications (ICC), Cape Town, South Africa, May 2010.
- ▷ **Plenaries in 2008:** EE-PanIranian Conf., Tehran, Iran, June 2008; Intl. Conf. on Communications (ICC), Beijing, PRC, June 2008; ISABELE Conf., Aalborg, Denmark, Oct. 2008; and Intl. Conf. on Electronics Engr. (ICEE), Mexico City, Mexico, Oct. 2008. **Tutorials in 2008:** Intl. Conf. on Acoust., Speech, and Signal Proc. (ICASSP), Las Vegas, May 2008.
- ▷ **Plenaries in 2007:** SIU Signal Proc. and Comm. Applications Conf., Eskisehir, Turkey, June 2007; URSI Intl. Symp. on Signals, Systems and Electronics, Montreal, Canada, July 2007; Intl. Workshop on Advances in Wireless Sensor Networks, Philadelphia, PA, August 2007; EUSIPCO, Poznan, Poland, September 2007; Intl. Workshop on Computational Advances in Multi-Sensor Adaptive Processing, St. Thomas, U.S. Virgin Islands, Dec. 2007. **Tutorials in 2007:** Intl. Conf. on Communications, Glasgow, UK, June 2007; also at the Intl. Conf. on Acoust. Speech and Signal Proc., Honolulu, Hawaii, April 2007; and at Univ. of Santa-Fe, Argentina, March 2007.
- ▷ **Plenary in 2006:** Last Mile Wireless Workshop, Dublin, Ireland, August 2006. **Tutorials in 2006:** A-Star, Singapore, March 2006; Intl. Conf. Ultra-Wideband Comms., Waltham, MA, Sept. 2006.
- ▷ **Tutorials in 2005:** Intl. Conf. on Communications, Seoul, Korea, May 2005.
- ▷ **Plenaries in 2004:** IEEE Intl. Conf. on Electronic Design, Veracruz, Mexico, November 2004; and IASTED Conf., Hawaii, August 2004. **Tutorials in 2004:** Globecom Conf., Dallas, TX, Dec. 2004; Vehicular Tech. Conf., Los Angeles, CA, Sept. 2004; Intl. Conf. on Acoustics, Speech and Signal Processing, Montreal, Quebec, Canada, May 2004; and Wireless Comm. and Networking Conf., Atlanta, GA, March 2004.
- ▷ **Plenaries in 2003:** Intl. Symp. on Signal Proces. and Info. Technology, Darmstadt, Germany, Dec. 2003; 6th Baiona Workshop on Signal Proc. in Communications, Baiona, Spain, Sept. 2003; Signal Proc. Advances in Wireless Communications Workshop, Rome, Italy, June 2003; and Intl. Conf. on Acoust. Speech, and Signal Processing, Hong Kong, April 2003 (never delivered because meeting was cancelled due to SARS). **Tutorials in 2003:** Conf. on Ultra Wideband Systems and Technologies, Reston, Virginia, Nov. 2003; MILCOM Conf., Boston, MA, October 2003; and Vehicular Tech. Conf., Orlando, FL, October 2003.
- ▷ **Plenary in 2002:** Sensor Array and Multichannel Processing Workshop, Washington DC, on Aug. 2002. **Tutorials in 2002:** Intl. Conf. on ASSP, Orlando, FL, May 2002; and Wireless Communications and Networking Conf., Orlando, FL, March 2002.
- ▷ **Plenary in 2001:** Statistical Signal Processing Workshop, Singapore, August 2001. **Tutorials in 2001:** GLOBECOM Conf., San Antonio, TX, Nov. 2001; Army Research Laboratory, Adelphi, MD, May 2001; and Intl. Conf. on Acoust., Speech, and Signal Proc., Salt Lake City, Utah, May 2001.
- ▷ **Keynote address on “Single- and Multi-User Multi-Carrier Communications,”** Balkan Workshop on Signal Processing and Communications, Isik Univ., Istanbul, Turkey, June 2000.

- ▷ Plenary talk on “Cyclostationary Signal Processing: An Overview,” (Sunuhara Plenary Lecture), at the 10th Symposium on System Theory and Statistics, Kyoto, Japan, November 1998.
- ▷ Expert-Summary talk on “Statistical Signal and Array Processing,” papers presented at the Intl. Conf. on Acoust., Speech, and Signal Proc., Munich, Germany, April 1998.
- ▷ Plenary talk on “High-Order Cyclostationary Signal Processing,” at the 5th IEEE-SP Workshop on Higher-Order Statistics, Banff, Alberta, Canada, July 1997.
- ▷ Tutorial on “Theory and Applications of Cyclostationary Signal Analysis,” at the Intl. Conf. on Acoust., Speech, and Signal Proc., Adelaide, Australia, April 1994.
- ▷ Keynote address on “HOS based linear system identification: basic advances and future directions,” ATHOS-ESPRIT Workshop on System Identification and Higher-Order Statistics, Sophia Antipolis, France, September 1993.

➤ **Consulting and Short Courses**

- ▷ Consulted for TRW, CA, 1994; Amoco, OK (1996-1998); Globespan (2000-2001); CalAmp (2002), ATC (2003); Inter-Digital (2004), and WiAV Solutions, LLC (2009-10); Dorsey & Whitney LLC, Law Firm (2011-12), Schwegman, Lundberg & Woessner, P.A. (2014).
- ▷ Taught an one-day short course on “Signal processing with higher-order spectra,” Mitre Corp., Boston, MA, June 1991; E-Systems, College Station, PA, June 1992.

➤ **Professional Society Memberships**

- ▷ Institute of Electrical Electronic Engineers (IEEE), Student Member 1984-1986, Member 1986-1991, Senior Member 1991-1996, Fellow Member 1996-present.
- ▷ IEEE Communications Society, 1999-present.
- ▷ IEEE Information Theory Society, 1990-present.
- ▷ IEEE Signal Processing Society, 1984-present.
- ▷ European Association for Signal Processing (EURASIP), Member, 1990-present
- ▷ Institute of Mathematical Statistics (IMS), Member, 1987-present
- ▷ Technical Chamber of Greece, and Greek Association of Electrical and Electronic Engineers, Member, 1981-present
- ▷ Geophysics, Associate Member, 1984-1989
- ▷ Eta Kappa Nu, Member, 1984-present

➤ Conference Organization - General Chairmanships

- ▷ *General Co-Chair and Co-Organizer* (with S. Dhople and S. Low, Caltech) of the NSF-sponsored *Workshop on Computing, Control, and Signal Processing Challenges in Future Power Systems*, Arlington, VA, November 15-16, 2013; see URL <http://www.dtc.umn.edu/seminars/>
- ▷ *General Co-chair and Co-organizer* (with N. Sidiropoulos, and M. Kaveh as Honorary Chair) of the *Statistics, Optimization, and Signal Processing (STATOS) Workshop in memory of Prof. Alex B. Gershman*, Darmstadt, Germany, June 15-16, 2013.
- ▷ *Co-Organizer/Steering Committee* (with N. Sidiropoulos as General Chair) of the NSF-sponsored *Workshop on Big Data: From Signal Processing to Systems Engineering*, Arlington, VA, March 21-22, 2013; see URL <http://www.dtc.umn.edu/bigdata/>
- ▷ *General Co-chair and Co-organizer* (with H. Delic) of the 13th IEEE Workshop on Signal Processing Advances in Wireless Communications, Cesme, Turkey, June 17-20, 2012.
- ▷ *Technical Committee Chair*, 32nd Annual Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, November 1998.
- ▷ *General Co-Chairman and Co-organizer* (with L. Tong and J.-F. Cardoso) of the 1st IEEE Workshop on Signal Processing Advances in Wireless Communications, Paris, France, April 16-18, 1997.
- ▷ *General Co-Chairman and Co-Organizer* (with A. Swami), 8th Statistical Signal and Array Processing Workshop, Corfu, Greece, June 24-26, 1996.
- ▷ *General Co-Chairman and Co-Organizer* (with A. Swami), IEEE Signal Processing Workshop on Higher-Order Statistics, Lake Tahoe, CA, June 1993.

➤ Conference Committee Memberships

- ▷ Member of Intl. Scientific Com., *3rd Workshop on Signal Processing Advances in Wireless Communications*, Taiwan, March 2001.
- ▷ Member of Intl. Scientific Com., *Workshop on Statistical Signal and Array Processing*, Poconos, Pennsylvania, August 2000.
- ▷ Member of Intl. Scientific Com., 3rd Intl. IMACS Conf. on Circuits, Sys., Com., and Computers, Athens, Greece, July 4-8, 1999.
- ▷ Technical Area Coordinator, 31st Asilomar Conf. on Signals, Systems, and Computers, Pacific Grove, Monterey, CA, November 2-5, 1997.
- ▷ Member of the Intl. Advisory Board, Intl. Conf. on Information, Communications, and Signal Proc., Singapore, September 9-12, 1997.
- ▷ Member of the Scientific Committee, European Conf. on Signal Analysis and Prediction, Prague, Czech Republic, June 1997.
- ▷ Member of the Technical Committee, 4th Intl. Symposium on Signal Proc. and its Applications, Gold Coast, Australia, August 24-26, 1996.

- ▷ Member of Program Committee, SPIE Conf. on Wavelet Applications in Signal and Image Processing IV, Denver, CO, August 4-9, 1996.
- ▷ Member of the Intl. Program Committee, Inaugural Symposium of the Intl. Inst. for General Systems Studies, Slippery Rock, PA, July 13-15, 1995.
- ▷ Member of the Intl. Tech. Program Committee, Intl. Conf. on Digital Signal Proc., Limassol, Cyprus, June 26-28, 1995.
- ▷ Member, Technical Committee, 27th Asilomar Conference, on “Signals, Systems, and Computers,” Pacific Grove, CA, Nov. 1993.
- ▷ Member, Steering Committee (Publications Chairman), Workshop on Higher-Order Spectral Analysis, Vail, Colorado, June 1989.
- ▷ Organizer, Session FP2 on “Cumulants in Signal Processing and System Identification,” American Control Conference, Atlanta, Georgia, June 1988.

➤ **Conference Session Chairmanships**

- ▷ More than 250 (1987-present)

➤ **Reviewer Activities**

- Proceedings of the IEEE - IEEE Trans. on Info. Theory - IEEE Trans. on Wireless Communications
- IEEE Transactions on Communications - Wireless Communications and Mobile Computing
- IEEE Journal on Selected Areas in Communications - IEEE Transactions on Signal Processing
- IEEE Transactions on Speech Processing - IEEE Transactions on Image Processing
- IEEE Transactions on Automatic Control - IEEE Transactions on Circuits and Systems
- IEEE Transactions on Geoscience and Remote Sensing - Geophysics
- International Journal of Adaptive Control and Signal Processing - Automatica
- Signal Processing (EURASIP) - Multidimensional Systems and Signal Processing
- Annals of Mathematical Statistics - Journal of Time Series Analysis
- IEE Proceedings, Part F (Radar and SP)
- ▷ National Science Foundation - Army Research Office (reviewer for approx. six proposals/year)
- ▷ National Institutes of Health, Oct. 13-15, 1993 (committee member for the review of the Biomedical Engr. and Instrumentation Program, NCRR).
- ▷ ONR/NSF Workshop on Signal Processing for Manufacturing and Machine Monitoring, March 12-15, 1996 (invited participant to report on emerging signal processing basic research concepts that support machine monitoring).

- ▷ NSF-CAREER Panelist for MIPS - Signal Processing Systems Program, November 1997; and November 2000 (reviewed 12 proposals in signal processing for communications subjects per year).
- ▷ NSF Panelist for CISE/CCR; Communications Program (1999, 2000); and Major Research Infrastructure Proposals (2000).
- ▷ Reviewer for: International Science Foundation of Israel (3 proposals), Science Council of Hong-Kong (2 proposals), and the Australian Research Council (4 proposals).
- ▷ Book review 1 : “Lessons in Digital Estimation Theory,” by J. M. Mendel, Prentice-Hall, 1987 (review appeared in Automatica, 1989).
- ▷ Book review 2 : Review on the first edition of “Signals and Systems,” by A. Oppenheim, and A. Willsky, Prentice-Hall, 1983 (review requested in preparing the second edition of the book).
- ▷ Book review 3 : Review of “Analog and Digital Signal Processing,” by H. Baher, John Wiley and Sons, 1990.

HONORS and AWARDS

- ☆ *McKnight Presidential Chair*, ¹ University of Minnesota (2016)
- ☆ *Technical Field Award - IEEE Fourier Award*, (2015)² First recipient worldwide “For contributions to the theory and practice of statistical signal processing with applications to wireless communications.”
- ☆ *Board of Regents*, University of Patras, Greece; elected member (2013-2016).
- ☆ *IEEE Signal Processing Society’s Best Paper Award*, 2011; for the paper (co-authored with P. Xia) that was published in the May 2006 issue of the IEEE Transactions on Signal Processing.
- ☆ *EURASIP’s Best Paper Award*, 2009; for the paper (co-authored with P. Anghel and Z. Wang) that was published in the February 2005 issue of the Journal for Applied Signal Processing.
- ☆ *Fellow of the European Association of Signal Processing (EURASIP)*, 2008; the association’s most prestigious honor to recognize outstanding achievements of its members and volunteers.
- ☆ *Highly Cited Researcher*, included in the Thomson ISI Web of Knowledge List of Highly Cited Researchers in Comp. Science and Engrg., 2007; with an **h-index=123** (top in the IEEE Signal Processing Society; and top twenty across Eng. and Comp. Sci. authors worldwide).
- ☆ *Distinguished Lecturer of the IEEE*, Signal Processing Society, 2006-2008. Invited by 20 chapters worldwide to deliver lectures on multi-carrier, ultra-wideband and space-time coded wireless communications, and distributed estimation-detection using wireless sensor networks.

¹Presidential Endowed Chair acknowledges the critical contributions of important University faculty who have distinguished themselves and their departments in the missions of research, education and public engagement; see also <https://twin-cities.umn.edu/news-events/georgios-giannakis-awarded-prestigious-mcknight-presidential-endowed-chair>

²Selection criteria: Impact on the field of signal processing technology, including innovation; leadership; and seminal contributions as evidenced by publications or patents or transition to practice.

- ☆ *Technical Achievement Award*, The European Association for Signal, Speech and Image Processing (EURASIP), 2005. This is the highest award given to an individual by EURASIP in recognition of fundamental contributions to the advancement of science.
- ☆ *G. W. Taylor Award for Distinguished Research*, Information Technology, University of Minnesota, 2004; “For outstanding contributions to telecommunications, including wireless systems and networks”.
- ☆ *IEEE Signal Processing Society’s Technical Achievement Award*³, 2000, “For fundamental contributions to non-Gaussian and non-stationary signal analysis, system identification, and equalization of single- and multi-user communication systems.”
- ☆ *IEEE Communications Society’s Guglielmo Marconi Prize Paper Award*, 2004; for the paper (co-authored with Ph.D. students Y. Xin and Z. Wang) that was published in the March 2003 issue of the IEEE Transactions on Wireless Communications.
- ☆ *IEEE Signal Processing Society’s SP Magazine Best Paper Award*, 2003; for the paper (co-authored with Ph.D. student Z. Wang) that was published in the May 2000 issue of the IEEE Signal Processing Magazine.
- ☆ *IEEE Signal Processing Society’s Best Paper Award*, 2001; for the paper (co-authored with N. Sidiropoulos and R. Bro) that was published in the August 2000 issue of the IEEE Transactions on Signal Processing.
- ☆ *IEEE Signal Processing Society’s Best Paper Award*, 2000; for the paper (co-authored with A. Scaglione and S. Barbarossa) that was published in the July 1999 issue of the IEEE Transactions on Signal Processing.
- ☆ *Asilomar Conference Appreciation Plaque for Technical Service*, 2000.
- ☆ *Board of Governors*, IEEE SP Society, elected member (2001-2004).
- ☆ *Editorial Board* of the Proceedings of the IEEE, elected member (2000-2003).
- ☆ *IEEE Fellow Election Committee*, elected member (1999-2002).
- ☆ *IEEE Signal Processing Society’s Paper Award*, 1998, (under 30 years old category; awarded to co-author M. K. Tsatsanis) for the paper published in the August 1995 issue of the IEEE Transactions on Signal Processing.
- ☆ *IEEE Fellow*, 1996-97, “For contributions to System Identification and Statistical Signal Processing.”
- ☆ *IEEE Signal Processing Society’s Young Author Paper Award*, 1992, for the paper (co-authored with J. M. Mendel) published in the March 1989 issue of the IEEE Transactions on Acoustics, Speech, and Signal Processing.
- ☆ *Outstanding Young Faculty Teaching Award*, Department of Electrical Engineering, University of Virginia, 1992.

³Honors a person who, over a period of years, has made outstanding technical contributions to the theory and/or practice in technical areas within the scope of the IEEE-SP Society, as demonstrated by publications, patents, or recognized impact on the field.

- ☆ *Institutional Junior Faculty Research Award*, School of Engineering, University of Virginia, 1988.
- ☆ *Best Conference Paper Award* in Identification Session, American Control Conference, 1986 and 1988.
- ☆ *Best Student Paper Awards* (8 in the last 8 years) won by student co-authors in Wireless Symposium, ICASSP, CROWNCOM and Asilomar Conferences.
- ☆ *City of Corinth excellence award* for top grade in 1976 Entrance Examination of Greek Universities.

STUDENT ADVISING

➤ Completed Ph.D. Theses

1. J. M.-M. Anderson, “One- and two-dimensional system identification using higher-order statistics,” May 1992; with the Dept. of Electrical Engr., University of Florida, Gainesville, FL (**Associate Professor**; received NSF-Career Award, 1996); now with Howard Univ. (**Professor**);
2. M. K. Tsatsanis, “On Wavelets and Time-Varying Systems,” September 1992; formerly with the Dept. of Electrical Engr., Stevens Institute of Technology, N.Y. (**Associate Professor**; received NSF-Career Award, 1998); Chief Tech. Officer with Voyan Technologies Inc., CA; *co-founder* of Aktino Inc., Irvine, CA; now with Entropic Communications, San Diego, CA; **IEEE Fellow**).
3. B. Sadler, “Polyspectral Techniques for Detection and Estimation in Gaussian and non-Gaussian noise,” December 1992; now with the US Army Lab (**ARL Fellow** and **IEEE Fellow**), Adelphi, MD, and the Johns Hopkins Univ. Whiting Institute (Instructor).
4. A. Dandawate, “Exploiting Cyclostationarity and Higher-Order Statistics in Signal Processing,” January 1993; now with **Intel Corp.**, NJ.
5. S. Shamsuder, “Array and Multichannel Signal Processing using Higher-Order and Cyclic Statistics,” November 1993; formerly with the Dept. of Electrical Engr., Colorado State University, Fort Collins, CO (**Assistant Professor**); **Lucent Tech.**; now with **Verizon, Director 5G Wireless**.
6. T. E. Hall, “Estimation and Validation of Image Models using Higher-Order Statistics with Applications to Textures,” August 1994; now with the Information Technology & Communications Center, University of Virginia, Charlottesville, VA (**Consultant** for scientific computing).
7. G.-T. Zhou, “Random Amplitude and Polynomial Phase Modeling of Non-Stationary Processes using High-Order and Cyclic Statistics,” November 1994; now with the School of Electrical Engr., Georgia Tech., Atlanta, GA; **Professor**; received NSF-Career Award, 1997; **IEEE Fellow**.⁴⁵
8. S. D. Halford, “Blind Channel Equalization for Wireless Communications,” November 1996; now with Intersil Corporation, Palm Bay, FL (**Research Engineer**).
9. E. Serpedin, “Blind Equalization of Linear and Nonlinear Volterra Channels using Transmitter or Receiver Diversity,” December 1998; now with the Dept. of ECE, Texas A&M University (**Professor**; received NSF-Career Award, 2000; **IEEE Fellow**).

⁴Received the School of Engr. and Applied Sciences, Allan Talbott Gwathmey Memorial Research Award, Univ. of Virginia, April 1995.

⁵Received NSF Fellowship to attend Summer Program in Japan, June-August 1995.

10. A. Stamoulis, “Integrated Services in Wireless Networks with Jointly Designed Physical, Data, and Network Layers,” December 2000; was with the ATT Shannon Labs; now with Qualcomm (**Research Engineer**).
11. A. Scaglione, “Filterbank Precoding in Communications,” U. of Rome, Italy; co-advised with prof. S. Barbarossa; formerly with Cornell University and UC Davis (**Professor**; now with Arizona State University; received NSF-Career Award 2001; **IEEE Fellow**).
12. C. Tepedelenlioglu, “Modeling and Mitigation of Time- and Frequency-Selective Fading in Single- and Multi-Carrier Communications,” May 2001; now with the Arizona State University (**Professor**; received NSF-Career Award 2001).
13. Z. Liu, “Space-Time Coding for Broadband Wireless Communication Systems,” November 2001; formerly with the University of Iowa (**Assistant Professor**); now with the National Research Lab., Washington, DC.
14. Z. Wang, “Linear Precoding in Wireless Communication Systems,” April 2002; (**Professor**), now with Iowa State University (**IEEE Fellow**).
15. S. Zhou, “Chip-Interleaving and Space-Time Coding for Wireless” May 2002; ⁶; **Professor**, now with the University of Connecticut (**IEEE Fellow**).
16. Y. Xin, “Space-Time Coding with Linear Constellation Precoding” April 2003; formerly with the National University of Singapore (**Assistant Professor**); then NEC, NJ; now with Samsung.
17. X. Ma, “Doubly-Selective Fading Channels: Estimation, Capacity, and Space-Time Coding,” May 2003; **Professor** now with Georgia Inst. of Technology (**IEEE Fellow**).
18. L. Yang, “Ultra-Wideband Wireless Communications: From Concept to Reality,” June 2004; ⁷ Formerly with the University of Florida, Gainesville (**Professor**; received NSF-Career Award, 2009); now with Colorado State University **IEEE Fellow**).
19. W. Zhao, “Space-Time Coding and Low-Complexity Decoding for Coherent and Non-Coherent MIMO Communications,” May 2005; now with Qualcomm, CA (**Research Engineer**).
20. P. Xia, “Multi-Input Multi-Output Communications with Partial Channel State Information,” July 2005; formerly with Samsung Inc., CA; Huawei Tech.; now with Broadcom (**Research Engineer**); and with Tongji Univ., P. R. China (**Professor**).
21. R. Wang, “Distributed Coding for Multi-Source Cooperative Networks,” March 2006; now with Qualcomm, CA (**Research Engineer**).
22. Q. Liu, “Cross-Layer Design and Modeling for Wireless Communication Networks,” April 2006; Navini Networks Inc., Dallas, TX; now with PureWave Networks, (**Research Engineer**); and with Tongji Univ., P. R. China (**Professor**).
23. X. Luo, “Synchronization and (De-) Modulation for Ultra-Wideband Access,” May 2006; was with Qualcomm, CA (**Senior Staff Engineer**); now with Shanghai Tech., P. R. China (**Assoc. Professor**).

⁶Won the ONR Young Investigator Award, 2007; PECASE Award, 2008

⁷Won the Best Dissertation Award in the Physical Sciences and Engineering, Graduate School, University of Minnesota, 2005; and the ONR Young Investigator Award, 2007.

24. A. Cano, “Differential Modulation for Wireless Collocated and Distributed MIMO Systems,” June 2006 (co-advised with Prof. Javier Ramos, Univ. of Madrid, Spain); ⁸ formerly with Rey-Juan Carlos Univ., Spain (**Assistant Professor**); then Broadcom, and now with Metronic (**Research Engineer**).
25. A. Ribeiro, “Wireless Cooperative Communications and Networking,” January 2007; now with the University of Pennsylvania (**Associate Professor**; received NSF-Career Award, 2010).
26. A. Garcia-Marques, “Power-Efficiency Wireless Communications and Sensor Networks,” February 2007 (co-advised with Prof. Javier Ramos, Univ. of Madrid, Spain); now with Rey-Juan Carlos University, Madrid, Spain (**Associate Professor**).
27. Y. Yu, “Cross-Layer Medium Access and Congestion Control for Wireless Networks,” May 2007; was with Qualcomm, CA; now with Samsung, CA (**Senior Staff Engineer**).
28. T. Wang, “Complex-Field Network Coding in High-Throughput Anti-Jam Wireless Networks,” August 2008; was with Seagate, MN (**Research Engineer**); now with Pillsbury Winthrop Shaw Pittman LLP (**Patent Law Clerk**).
29. E. Dall’Anese, “Spatio-temporal Spectrum Reuse based on Channel Gain Cartography,” Dec. 2010 (co-advised with Prof. S. Pupolin, Univ. of Padova, Italy); now with Ntl. Renewable Energy Lab (NREL), Denver, CO (**Research Engineer**).
30. S. Farahmand, “Distributed and Robust Tracking by Exploiting Set-Membership and Sparsity,” June 2011; now in Iran (**Research Engineer**).
31. I. D. Schizas, “Exploiting Sparsity for Data Dimensionality-Reduction,” July 2011; now with the University of Texas at Arlington (**Associate Professor**).
32. E. Msechu, “Estimation with Wireless Sensor Networks: Censoring and Quantization Perspectives,” July 2011; now with Intel, CA (**Research Engineer**).
33. G. Mateos, “Sparsity Control for Robustness and Social Data Analysis,” Jan. 2012; now with the University of Rochester (**Assistant Professor**).
34. P. Forero, “Distributed and Robust Techniques for Statistical Learning,” April 2012; now with SPAWAR, San Diego (**Research Engineer**).
35. N. Gatsis, “Resource Management for Wireless Networks and the Smart Power Grid,” May 2012; now with the University of Texas at San Antonio (**Assistant Professor**).
36. K. Rajawat, “Cross-Layer Designs with Network Coding,” May 2012; now with the Indian Inst of Tech. (IIT), Kanpur, India (**Assistant Professor**).
37. H. Zhu, “Sparsity-Cognizant Algorithms for Monitoring the Smart Power Grid,” June 2012; now with the University of Illinois at Urbana-Champaign (**Assistant Professor** received NSF-Career Award, 2017).
38. J.-A. Bazergue, “Sparse Structural Equation Modeling and Nonparametric Tensor Completion for Gene Expression Networks,” May 2013; formerly with UTE, Uruguay (**Research Engineer**); now with Univ. de la Republica, Uruguay (**Associate Professor**).

⁸Won the Best Dissertation Award in Telecommunication Technologies at the Univ. of Madrid, Spain, 2006.

39. N. Yahya Soltani, “Dynamic Learning and Resource Management Under Uncertainties for Smart Grid and Cognitive Radio Networks,” May 2014; now with **(TBD)**.
40. M. Mardani, “Sparsity and Low Rank for Big Data and Dynamic Networks,” April 2015; now post-doctoral researcher at Stanford U.
41. Y. Zhang, “Energy Management for Sustainable Power (Micro) Grids: Distributed, Robust and Risk-Limiting Designs,” May 2015; now postdoctoral researcher at U. of Cal., Berkeley.
42. B. Baingana, “Dynamic Learning and Cartography for Time-Varying Social Networks,” January 2016; now with Wind Logic (**Research Engineer**).

➤ **Ph.D. Theses in progress**

42. F. Sheikholeslami, “TBD” (Expected graduation date: Dec. 2017).
43. D. Lee, “TBD” (Expected graduation date: Dec. 2017).
44. D. Berberidis, “TBD” (Expected graduation date: May 2018).
45. P. Traganitis, “TBD” (Expected graduation date: May 2018).
46. T. Chen, “TBD” (Expected graduation date: May 2019).
47. G. Wang, “TBD” (Expected graduation date: May 2019).
48. G. V. Karanikolas, “TBD” (Expected graduation date: May 2019).
49. Y. Shen, “TBD” (Expected graduation date: May 2019).
50. L. Zhang, “TBD” (Expected graduation date: May 2019).
51. M. Ma, “TBD” (Expected graduation date: May 2020).
52. A. Sadeghi, “TBD” (Expected graduation date: May 2020).
53. V. Ioannidis, “TBD” (Expected graduation date: May 2021).

➤ **Completed M.Sc. Theses**

1. A. Dandawate, “Noise cancelers using higher-order statistics with application to speech enhancement,” October 1989.
2. M. Tsatsanis, “Detection, estimation and classification using matched filtering and higher-order statistics,” April 1990.⁹
3. M. Rangoussi, “Signal reconstruction algorithms and the use of inverse higher-order statistics,” May 1990; now with the Dept. of Electrical Engr., Ntl. Tech. Univ. of Athens, Greece (Research Assist. Prof.).

⁹Received the Best Graduate Engineering Thesis Award (NEC Award), University of Virginia, 1990.

4. A. Delopoulos, "Estimation of autocorrelation and spectra using cumulants and polyspectra: non-parametric and parametric adaptive approaches," May 1990; now with the Dept. of Electrical Engr., Aristotelian Univ. of Thessaloniki, Greece (Associate Professor).
5. C. Grobmyer, "Adaptive phase correction of one-sided asymmetric interferograms," May 1992.
6. G. Zhou, "Amplitude modulated time series, higher-order statistics, and cyclostationarity," December 1992.
7. C. Malek, "Topics in chaos and fractal signal processing," May 1993.
8. R. W. Heath Jr., "Mitigating channel distortions in wireless orthogonal frequency division multiplexing communication systems," August 1997; now with the Univ. of Texas at Austin (Associate Professor).
9. Z. Wang, "Multirate Transceivers for Wireless Block Transmissions and Multicarrier CDMA Irrespective of Multipath Channels," December 1998.
10. Y. Lin, "Globally Convergent Constant-Modulus Blind Equalization of Redundant Block Transmissions," January 1999; now with Capital One, Richmond Virginia.
11. W. Tang, "Redundant Filterbank Precoders and Decision-Feedback Equalizers for Block Transmissions," January 1999; now with Hughes Network Systems, MD.
12. A. Kambanellas, "All-Digital Modulo Pre-Equalization of Nonlinear Communication Channels," February 1999; now with Telecom, Cyprus.
13. P. Anghel, "Generalized Multicarrier and Code Division Multiple Access in Wireless Multipath Channels," March 1999.
14. Y. Liao, "Turbo-Decoding of Zero-Padded OFDM Transmissions," April 2001.
15. L. Yang, "Multi-Stage Block-Spreading for Impulse Radio Multiple Access through ISI channels," January 2002.
16. N. Bapat, "Turbo-Decoding of Unitary Precoded and Coded OFDM," December 2002.
17. B. Lu, "Block Differential Encoding for Rapidly Fading Channels," December 2002.
18. A. Ribeiro, "Distributed Quantization-Estimation for Wireless Sensor Networks," August 2005.
19. T. Wang, "Wireless Cooperative Communications and Networking: Performance and Protocols," January 2006.
20. S. Farahmand, "Low-Complexity Synchronization and Demodulation Algorithms for Ultra-Wideband Impulse Radios," May 2006.
21. I. D. Schizas, "Distributed Estimation using Wireless Sensor Networks," February 2007.
22. G. Mateos, "Distributed Adaptive Estimation and Tracking using Ad Hoc Wireless Sensor Networks," July 2009.
23. J.-A. Bazerque, "Distributed Sensing and Resource Allocation for Cognitive Radio Networks," August 2009. (Won the university-wide best M.Sc. Thesis Award for 2009.)

24. H. Zhu, “Distributed Kalman Filtering, Demodulation, and Decoding Using Consensus and Exploiting Sparsity,” September 2009.
25. N. Gatsis, “Utility-Based Power Control for Cooperative Dynamic Spectrum Access Networks,” July 2010.
26. N. Jain, “Joint Link Learning and Cognitive Radio Sensing,” May 2012.
27. B. Baingana, “Embedding Graphs under Centrality Constraints,” May 2013.
28. P. A. Traganitis, “Large-scale clustering using Random Sketching and Validation,” *Dept. of ECE, University of Minnesota*, July 2015.
29. D. K. Berberidis, “Online Censoring for Large-Scale Regressions with Application to Streaming Big Data,” *Dept. of ECE, University of Minnesota*, July 2015.
30. T. Chen, “Resource Allocation for Green Cloud Networks under Uncertainty: Stochastic, Robust and Big Data-driven Approaches,” *Dept. of ECE, University of Minnesota*, June 2016.
31. G. V. Karanikolas, “Multikernel-based Nonlinear Functional Connectivity Brain Models,” *Dept. of ECE, University of Minnesota*, August 2016.

➤ **Undergraduate Theses supervised**

1. A. Pressuti, “Analysis and synthesis of speech signals,” December 1990.
2. C. Malek, “A programming aid for chaotic and nonlinear system analysis,” May 1991.
3. D. Dinh, “A voice-activated appliance controller system design,” May 1991.
4. S. Pan, “Implementation and testing of human vocal tract estimation model,” May 1993.
5. E. Byrne “Hardware design of a DSP platform for high fidelity audio,” May 1993.
6. X. Wu “Use of a load plate under a dynamic test condition,” August 1993.
7. R. Mozeleski, “Digital processing of an audio signal for passive monitoring of hospital patients’ heart signal,” May 1994.
8. A. Redfern “Time-varying models of speech,” May 1995.
9. B. Allen, “Using wavelets for forecasting 1/f type behavior,” May 1995 (Applied Math student).
10. R. W. Heath Jr., “Blind blur identification and perfect image restoration,” May 1996. ¹⁰
11. A. Kambanellas, “Pre-equalization of OFDM systems,” April 1998.
12. A. Pitsillides, “Multicarrier Wide-band CDMA Systems,” May 1999.

¹⁰Received the William L. Everitt Student Award for Excellence; won the first prize in the Undergraduate Thesis Symposium (oral presentation), University of Virginia, 1996.

➤ **Postdoctoral Researchers supervised**

1. Daniele Angelosante, 2009-2011; now with ABB, Switzerland (**Research Engineer**).
2. Xiaodong Cai, 2001-2004; now with the Univ. of Miami (**Professor**).
3. Alfonso Cano, 2007-2011; now with Broadcom, CA (**Research Engineer**).
4. Jia Chen, 2017-present
5. Emiliano Dall' Anese, 2011-2014; now with NREL: Ntl. Renewable Energy Lab, Denver, CO (**Research Engineer**).
6. David Declercq; 1995-1997; now with the Univ. of Cergy, France (**Professor**).
7. Siavash Ghavami, 2015-2016.
8. Vasileios Kekatos, 2008-2014; now with Virginia Tech., (**Assistant Professor**).
9. Seung-Jun Kim, 2008-2013; now with the Univ. of Maryland Baltimore County (**Asst. Professor**).
10. Geert Leus, 2000-2002; now with Delft Univ. of Tech., Netherlands (**Professor and IEEE Fellow**).
11. Bertrand Muquet, 1999-2001; now with Motorola, France (**Research Engineer**).
12. Athanasios Nikolakopoulos, 2017-present
13. Daniel Romero, 2015-2016; now with University of Agder, Norway, (**Associate Professor**).
14. Pooya Rezaei, 2015-2016; now with OATI (**Software Engineer**).
15. Anna Scaglione, 1999-2001; now with the Arizona State Univ.; formerly with Univ. of California, Davis; and with Cornell Univ. (**Professor and IEEE Fellow**).
16. Konstantinos Slavakis, 2012-2015, UMN (**Research Assoc. Prof.**); now with SUNY Buffalo (**Associate Professor**)
17. Yingwei Yao, 2002-2004; now with the Univ. of Illinois at Chicago (**Associate Professor**).
18. Xin Wang, 2005-2007; now with Florida Atlantic Univ., USA; and with Fudan Univ., P.R. China (**Professor**).
19. Yunlong Wang, 2015-2016; now with IMS Health Data Analytics (**Software Engineer**).

PAST, CURRENT, AND PENDING RESEARCH FUNDING

➤ **Summary figures: \$10,605,193 (as PI); \$4,861,537 (as co-PI); Total amount: \$15,466,730**

- | | Past |
|--|-------------|
| PA1. <i>Harry Diamond Labs</i> (\$35,000), “Optical Triple Correlators,” October 1988 - November 1989. | |
| PA2. <i>Univ. of Virginia: Dean’s Research Initiation Grant</i> , (\$9,000 no overhead), “Adaptive algorithms for neural networks,” October 1989-September 1990. | |

- PA3. *Harry Diamond Labs* (\$40,000), “Signal and image detection and classification using higher-order statistics,” October 1989 - July 1990.
- PA4. *Army Research Labs* (\$50,000), “Channel equalization and array processing using higher-order correlations,” November 1989 - October 1990.
- PA5. *Army Research Labs* (\$91,000), “Research in higher-order spectral analysis,” January 1991 - December 1991.
- PA6. *Dept. of Pediatrics, Health Sciences Center, Univ. of Virginia*, (\$15,000), “Signal processing architectures for neonatal heart rate variability tests,” January 1992-December 1992.
- PA7. *Army Research Labs* (\$45,000), “Canceling platform noise and detection of helicopter acoustic signals,” January 1992 - December 1993.
- PA8. *Office of Naval Research*, (\$20,000), “Intl. Workshop on Higher-Order Statistics,” (November 1992 - August 1993; ONR/Math. Div. N00014-93-1-0065.
- PA9. *Army Research Office*, (\$7,000), “Intl. Workshop on Higher-Order Statistics,” May 1993 - September 1993; DAAH04-93-G-0180.
- PA10. *National Science Foundation*, (\$90,000), “Optimal multiresolution analysis in statistical signal processing,” July 1992 - July 1995; NSF/MIPS - Research Initiation Award.
- PA11. *Office of Naval Research*, (\$179,000), “Polyspectral algorithms for optimal processing of cyclostationary acoustic signals,” July 1993 - October 1995; ONR Grant No. N00014-93-1-0485.
- PA12. *Army Research Office*, (\$10,000), “8th Intl. Workshop on Statistical Signal and Array Processing,” May 1, 1996 - April 30, 1997; ARO Grant No. DAAH04-96-1-0171.
- PA13. *Office of Naval Research*, (\$10,000), “8th Intl. Workshop on Statistical Signal and Array Processing,” May 1, 1996 - April 30, 1997; ONR Grant No. N00014-96-1-0725.
- PA14. *Harbor Branch, Oceanographic Inst., Inc.*, (\$20,000), “Propagation modeling, characterization, and equalization of underwater acoustic channels,” December 1, 1996 - November 30, 1997.
- PA15. *National Science Foundation (CISE/MIPS)*, (\$171,242), “Estimation and equalization of time-varying channels,” July 1995 - May 1999; NSF Grant No. MIP 9424305.
- PA16. *Office of Naval Research (AASERT)*, (\$191,614), “Applications of cyclostationarity in communications and signal analysis,” May 1, 1995 - September 30, 1998; ONR Grant No. N00014-95-1-0908.
- PA17. *Office of Naval Research*, (\$296,347), “Parametric modeling of nonstationary signals and identification of nonlinear time-varying channels,” October 1995 - October 1999 ONR Grant No. N00014-93-1-0485.
- PA18. *DURIP/ONR*, (\$145,429), “Instrumentation for Research in Wireless Communications,” 1997-1998; co-PI with Dr. H. Liu (PI).
- PA19. *Office of Naval Research*, (\$60,000), “PARAFAC Space-Time Processing for Circular Ring Arrays,” May 1999 - December 1999; ONR Grant No. N00014-99-1-0693; PI with co-PI N. Sidiropoulos.

- PA20. *Army Research Lab*, (\$25,000), “Multipath mitigation in frequency-hopping systems,” April 1999 - May 2001; DOD Grant no. ARL-7850-98.
- PA21. *Army Research Office*, (\$297,346), “Algorithm Development and Experimental Evaluation of Blind Equalizers for Rapidly Varying Channels with Antenna Arrays,” April 1998 - May 2001; ARO Grant no. DAAG55-98-1-0336.
- PA22. *National Science Foundation - CISE/CNRS (Communications and Networking)*, (\$255,000), “Design of User Codes and Low-Complexity CDMA Receivers for MUI Elimination in Unknown Multipath,” July 1, 1998 - June 30, 2001; NSF CCR grant no. 9805350.
- PA23. *General Dynamics, MN*, (\$25,000), “Frequency-Hopped Generalized Multi-Carrier Transceivers for Multi-User Communications,” October 1, 2001 - May 31, 2002.
- PA24. *National Science Foundation - Electrical and Communications Systems Div.* (\$925,000), “Mobile Communications and Networking: Low Power and Low Complexity Transceivers for Wireless Multimedia Transmissions,” September 1, 1999 - August 31, 2002; NSF Wireless Initiative grant no. 9979443; PI with 4 co-PIs: S. Alouini, M. Kaveh, J. Kieffer, and A. Tewfik.
- PA25. *ARL Collaborative Technology Alliance*, (\$250,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2001 - September 2002; PI with N. Sidiropoulos co-PI.
- PA26. *ETRI, Korea*, (\$50,000), “Space-Time-Frequency Coding for MIMO OFDM,” May 1, 2002 - March 31, 2003.
- PA27. *ARL Collaborative Technology Alliance*, (\$350,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2002 - September 2003; PI.
- PA28. *National Science Foundation - CISE/SPS (Signal Processing)*, (\$350,000), “Chip-interleaved Block-Spread Code Division Multiple Access,” May 1, 2001 - April 30, 2004; NSF SPS grant no. 0105612.
- PA29. *ARL Collaborative Technology Alliance*, (\$344,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2003 - September 2004; PI.
- PA30. *ETRI, Korea*, (\$100,000), “Multicarrier MIMO Communications for High-Speed Mobile Cellular Access,” May 1, 2005 - December 31, 2006.
- PA31. *ARL Collaborative Technology Alliance*, (\$344,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2004 - September 2005; PI.
- PA32. *ARL Collaborative Technology Alliance*, (\$325,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2005 - September 2006; PI.
- PA33. *ARL Collaborative Technology Alliance*, (\$300,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2006 - September 2007; PI.
- PA34. *ARL Collaborative Technology Alliance*, (\$280,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2007 - September 2008; PI.
- PA35. *National Science Foundation - FMF Regular*, (\$450,906) “Waveform Diversity for Wireless Communications,” August 1, 2005 - July 30, 2008; co-PI with M. Zoltowski, Purdue Univ.; Giannakis’ part 71K/yr.

- PA36. *Army Research Office*, (\$272,000), “Energy-Efficient Protocols and Cross-Layer Designs for Wireless Sensor Networks,” June 1, 2005 - May 31, 2008 (sole PI).
- PA37. *National Science Foundation - Medium ITR Grant*, (\$1,599,980) “Multi-Robot Emergency Response,” September 1, 2003 - August 31, 2008; co-PI with 5 co-PIs; Giannakis’ part 70K/yr; multi-institutional proposal: UMN (lead), UPenn, and Caltech.
- PA38. *National Science Foundation - MRI*, (\$500,000) “Development of Miniature Search/Rescue Robots,” September 1, 2004 - August 31, 2008; co-PI with 5 co-PIs; Giannakis’ part 50K/yr; multi-institutional proposal: UMN (lead), Berea College.
- PA39. *ARL Collaborative Technology Alliance*, (\$275,000), “Precoding, Space-Time Coding, and Turbo-Decoding in FH Communications,” October 1, 2008 - September 30, 2010; PI.
- PA40. *National Science Foundation - ECCS Regular*, (\$300,000) “A Stochastic Framework for Robust Wireless Networking,” Sept. 1, 2008 - August 31, 2011 (sole PI).
- PA41. *National Science Foundation - CCF Regular*, (\$300,000) “Theoretical Foundations for Wireless Communication Networks,” Sept. 1, 2008 - Aug. 31, 2011 (sole PI).
- PA42. *National Science Foundation - CISE CCF*, (\$100,000) “CIF: Exploiting Sparsity for Dimensionality Reduction,” Sept. 1, 2010 - Aug. 31, 2011 (sole PI).
- PA43. *European Commission, CORDIS - Marie Curie Fellowship*, (\$81,871) “Distributed Estimation in Sensor Networks,” March 1, 2009 - Feb. 28, 2011 (co-PI with K. Berberidis, Greece).
- PA44. *Qatar National Research Fund*, (\$1,100,000) “Spectrum Cartography for Cognitive Radio Sensing,” Oct. 1, 2010 - Sept. 30, 2013 (PI with 3 co-PIs; Giannakis’ part 120K/yr; multi-institutional proposal: UMN (lead), Texas A&M, Qatar; and Qatar Univ.).
- PA45. *National Science Foundation - ECCS Regular*, (\$391,707) “IHCS: Sparsity-Aware RF Cartography for Cognitive Networks,” June 1, 2010 - May 31, 2013 (sole PI).
- PA46. *Australian Research Council*, (\$520,000) “Cross-layer design in wireless communication systems with channel uncertainty,” Oct. 1, 2010 - Sept. 30, 2013 (PI with 3 co-PIs; Giannakis’ part 60K/yr.).
- PA47. *National Science Foundation - CISE/CCF and ENG/ECCS*, (\$50,000) “Workshop on Control, Computing and Signal Processing for Future Power Systems,” November 1, 2013 - October 31, 2014 (co-PI with S. Dhople (Minnesota PI) and S. Low (Caltech)).
- PA48. *Institute of Renewable Energy and the Environment (IREE)*, (\$375,000) “Big Data and Control of Renewable Energy Sources in Microgrids,” December 1, 2012 - November 30, 2015 (PI with 2 additional co-PIs from Minnesota; no overhead; Giannakis’ part 65K/yr for 3 years.).
- Current**
- CU1. *AirForce - MURI* (with U. of Pennsylvania; UofMn sub-award \$1,350,000 co-PI with S. Roumeliotis (PI)); “CHASE: Control of Heterogeneous Autonomous Sensors for Situational Awareness,” Sept. 1, 2010 - Aug. 31, 2015; Giannakis’ part 120K/yr.
- CU2. *National Science Foundation - ECCS*, (\$416,340) “Modeling, Monitoring, and Optimization of Cognitive Networks,” May 1, 2012 - April 30, 2015; no-cost extension to April 2016 (sole PI).

- CU3. *Greek Research Council - Thales Program*, (\$790,848) “Secure Wireless Nonlinear Communications at the Physical Layer,” Jan. 1, 2012 - Dec. 31, 2015; total of 12 co-PIs; Giannakis’ part 32K.
- CU4. *Greek Research Council - Thales Program*, (\$790,848) “Energy-efficient Designs of Communication Networks,” Jan. 1, 2012 - Dec. 31, 2015; total of 12 co-PIs; Giannakis’ part 24K.
- CU5. *National Science Foundation - EARS Program*, (\$499,379) “Spectral Tweets: A Community Paradigm for Spatio-temporal Cognitive Sensing and Access,” Sept. 1, 2012 - Aug. 31, 2015 (co-PI with J. Haupt, and N. Sidiropoulos (PI); Giannakis’ part 60K/yr for 3 years).
- CU6. *National Institutes of Health - Joint NIH-NSF-DMS Program on Computational Biology*, (\$1,840,214) “High-Dimensional Sparse Structural Equation Modeling for Inference of Gene Networks and Optimized Chemical Genomics,” September 1, 2012 - August 31, 2017 (co-PI with Chad Meyers (Minnesota), and two co-PIs from U. of Miami; PI: X. Cai; Minnesota part \$896,461; Giannakis’ part 95K/yr for 5 years.).
- CU7. *National Science Foundation - EARS Program*, (\$1,200,000) “Comprehensive Network State Inference for Policy-Cognizant Spectrum Access,” Sept. 1, 2013 - Aug. 31, 2017 (PI with S.-J. Kim, S. Kelley from Minnesota, and R. Baxley (GTRI); Giannakis’ part 775K/yr for 4 years).
- CU8. *National Renewable Laboratory (NREL)*, (\$100,000) “Optimal Inverter Dispatch: Facilitating High PV Penetration with Optimization and Grid Informatics,” October 1, 2014 - September 30, 2016 (co-PI with S. Dhople (PI)); plus \$300K for B. Johnson (NREL).
- CU9. *National Science Foundation - CISE/CCF and ENG/ECCS*, (\$254,786) “From Communication to Power Networks: Adaptive Energy Management for Power Systems with Renewables,” September 1, 2014 - August 31, 2017 (PI); plus \$172,000 to U. Texas at San Antonio (N. Gatsis) (co-PI).
- CU10. *National Science Foundation - CCF/CyberSEES*, (\$649,147) “Tenable Power Distribution Networks,” September 1, 2014 - August 31, 2017 (PI with S. Dhople co-PI); plus \$550,000 to U. of Michigan (G. Mihailidis) and GWU (X. Chen).
- CU11. *National Science Foundation & AFOSR: EAGER-DynamicData Program*, (\$300,000) “Censor, Sketch, and Validate to Learn from Dynamic and Large-Sale Data,” Jan. 1, 2015 - Dec. 31, 2016 (sole PI).
- CU12. *Army Research Office*, (\$450,000) “Comprehensive Tactical Network State Inference from Incomplete Data,” June 1, 2015 - May 31, 2018.
- CU13. *National Science Foundation - ENG CCSS*, (\$410,230) “Smart-Grid Powered Green Communications in Heterogeneous Networks,” May 1, 2015 - April 30, 2018 (co-PI with X. Wang (PI), FAU); Giannakis part \$231,230 for 3 yrs.
- CU14. *National Science Foundation, ECCS-EPCN*, (\$300,000) “Stochastic Power Control and Learning for Energy Grids,” September 1, 2015 - August 31, 2018 (PI with V. Kekatos as co-PI).
- CU15. *National Science Foundation - CIF*, (\$100,000) “Parallel Online Learning for Big Data and Dynamic Networks,” September 1, 2015 - August 31, 2016 (PI).
- Pending**
- PE1. *National Science Foundation - ENGR CCSS*, (\$400,000) “Learn-and-Adapt to Manage Dynamic Cyber-Physical Networks,” May 1, 2017 - April 30, 2020 (PI).

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- [P11] G. B. Giannakis and X. Luo, “Blind Synchronization and Demodulation,” **US Patent no. 7,864,880 B2**, issued January 4, 2011.
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- [P21] G. B. Giannakis, and S. Zhou, “Space-Time Coded Transmissions within a Wireless Communication Network,” **Korean Patent no. 10-0870557**, issued November 27, 2008.
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APPENDIX B



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APPENDIX C

A Highly Accurate Blind Frequency-Offset Synchronization for OFDM Communications

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ABSTRACT

We address the problem of carrier frequency offset (CFO) synchronization in Orthogonal Frequency Division Multiplexing (OFDM) communications systems in the context of frequency-selective fading channels. We consider the case where the transmitted symbols have constant modulus, i.e., Phase-Shift-Keying (PSK) constellations. A novel blind CFO synchronization algorithm is developed. The new algorithm is shown to greatly outperform a recently published blind technique that exploits the fact that practical OFDM systems are not fully loaded, i.e., the number of modulated sub-carriers is smaller than the size of the FFT block. Further, the proposed algorithm is consistent even when the system is fully loaded. Finally, the proposed CFO estimator is obtained via a one-dimensional search, the same as with the existing VSC-based estimator, but achieves a substantial gains in performance (10 dB SNR or one order of magnitude in CFO MSE).

1 INTRODUCTION

The presence of carrier frequency offset (CFO) causes loss of orthogonality between the sub-carriers in an OFDM scheme, and leads to increased bit-error-rate. Consequently, there has been considerable work in the area of CFO estimation. A number of pilot-assisted CFO synchronization techniques are available in the literature. Blind CFO synchronization is attractive because it saves bandwidth, i.e., no training pilots are required. A blind CFO estimator was recently proposed in [2] (see also [3] for more details); this estimator, de-

signed to work with dispersive channels, exploits the fact that practical OFDM systems are not fully loaded, i.e., the number of information-bearing sub-carriers is smaller than the size of the FFT block.

Here, we consider the case where the transmitted symbols have constant-modulus. Judicious use of this side information leads to a simple CFO estimator which significantly outperforms the estimators in [2, 3].

2 SIGNAL MODEL

OFDM modulation consists of N (usually a power of 2) sub-carriers, equi-spaced at a separation of $\Delta f = B/N$, where B is the total system bandwidth. All sub-carriers are mutually orthogonal over a time interval of length $T = 1/\Delta f$. Each sub-carrier is modulated independently with symbols having constant modulus, i.e., PSK constellations. Each OFDM block is preceded by a cyclic prefix whose duration is longer than the delay spread of the propagation channel, so that inter-block interference can be eliminated at the receiver, without affecting the orthogonality of the sub-carriers. Practical OFDM systems are in general not fully loaded in order to avoid aliasing. In this case, some of the sub-carriers at the edges of the OFDM block are not modulated; these sub-carriers are referred to as virtual sub-carriers. Their number is dictated by system design requirements and is, in general, about 10% of N . Let $\mathcal{N} = \{-N/2+1, \dots, N/2\}$ denote the entire set of sub-carriers; also let $\mathcal{N}_a = \{-(N_a-1)/2, \dots, (N_a-1)/2\}$ denote the N_a -element set of active or modulated sub-carriers ($N_a < N$ and N_a is odd), and let $\mathcal{N}_v = \mathcal{N} - \mathcal{N}_a$

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denote the set of $N_v = N - N_a$ virtual sub-carriers¹.

At the receiver, the output of the matched filter is sampled with period $T_s = T/N$. After discarding the cyclic prefix, the complex envelope of the baseband received signal in an OFDM block can be described as

$$x(k) = e^{j2\pi k\xi_o/N} \sum_{n \in \mathcal{N}_a} H_n s_n e^{j2\pi kn/N} + v(k) \quad (1)$$

with $k = 0, \dots, N - 1$, where $\{s_n\}$ is a constant-modulus data sequence, $|s_n| = 1, \forall n$; ξ_o (a real number, $|\xi_o| < N/2$) is the CFO normalized to $1/T$, H_n is the complex channel response at the n th subcarrier frequency

$$H_n = \sum_{l=0}^L h_l e^{-j2\pi ln/N}. \quad (2)$$

Here, $\{h_l\}$ are the coefficients of the $L+1$ -tap channel, and $v(k)$ is additive noise which is assumed to be zero-mean, uncorrelated, circularly symmetric and Gaussian with variance $\sigma_v^2 = E\{|v(k)|^2\}$.

Since $\{s_n\}$ is a constant-modulus sequence, $H_n s_n$ in eq. (1) may be rewritten as $H_n s_n = |H_n| e^{j\theta_n}$ where θ_n is the angle of $H_n s_n$, $|\theta_n| \leq \pi$. It is worth noting that the N_a unknown parameters, $\{|H_n|\}$ in (1), are parameterized by only $(L+1)$ complex parameters which are the channel coefficients $\{h_l\}$. This property is the core of the proposed algorithm.

3 FREQUENCY-OFFSET ESTIMATION

We consider the parameters $\{|H_n|\}$ and $\{\theta_n\}$ as unknown deterministic parameters. Since the additive noise is white, circularly symmetric and Gaussian, the ML estimates of ξ_o , $|\mathbf{H}| = \{|H_n|, n \in \mathcal{N}_a\}$ and $\boldsymbol{\theta} = \{\theta_n, n \in \mathcal{N}_a\}$ are obtained by minimizing the L_2 norm:

$$J(\xi, |\mathbf{H}|, \boldsymbol{\theta}) = \sum_{k=0}^{N-1} \left| x(k) - e^{j2\pi k\xi/N} \sum_{n \in \mathcal{N}_a} |H_n| e^{j\theta_n} e^{j2\pi kn/N} \right|^2 \quad (3)$$

¹The assumptions that N is even and N_a is odd are not critical.

The criterion in eq. (3) can be rewritten as²

$$J(\xi, |\mathbf{H}|, \boldsymbol{\theta}) = \sum_{k=0}^{N-1} |x(k)|^2 + N \sum_{n \in \mathcal{N}_a} |H_n|^2 - 2N \mathcal{R} \left[\sum_{n \in \mathcal{N}_a} |H_n| X(n + \xi) e^{-j\theta_n} \right] \quad (4)$$

where $\mathcal{R}[z]$ denotes the real part of a complex variable z ($\mathcal{I}[z]$ denotes the imaginary part), and $X(f)$ is the discrete-Fourier transform of $\{x(k)\}$ at frequency f/N

$$X(f) = \frac{1}{N} \sum_{k=0}^{N-1} x(k) e^{-j2\pi kf/N}.$$

Setting $\partial J / \partial \theta_n = 0$, and assuming that $|H_n| \neq 0$ ³, the ML estimate $\hat{\theta}_n$, satisfies

$$\mathcal{I} \left[X(n + \xi) e^{-j\hat{\theta}_n} \right] = 0, \quad n \in \mathcal{N}_a \quad (5)$$

which implies

$$\hat{\theta}_n = \arg\{X(n + \xi)\} \quad (6)$$

where $\arg\{z\}$ denotes the argument of a complex variable z . Substituting $\hat{\theta}_n$ into eq. (4), the criterion to minimize becomes

$$J(\xi, |\mathbf{H}|) = \frac{1}{N} \sum_{k=0}^{N-1} |x(k)|^2 + \sum_{n \in \mathcal{N}_a} |H_n|^2 - 2 \sum_{n \in \mathcal{N}_a} |H_n| |X(n + \xi)| \quad (7)$$

$$= J_{VSC}(\xi) + J_A(\xi, |\mathbf{H}|) \quad (8)$$

$$J_{VSC}(\xi) = \sum_{n \in \mathcal{N}_a} |X(n + \xi)|^2 \quad (8)$$

$$J_A(\xi, |\mathbf{H}|) = \sum_{n \in \mathcal{N}_a} (|X(n + \xi)| - |H_n|)^2 \quad (9)$$

²If m is an integer, we have that $\sum_{k=0}^{N-1} e^{j2\pi km/N} = N\delta(m)$, where $\delta(m) = 1$ if $m = 0 \bmod N$, and $\delta(m) = 0$ otherwise.

³if $|H_n| = 0$, θ_n becomes non-identifiable. A channel with $L+1$ taps can have at most L zeros that coincide with the sub-carriers; clearly $N_a > L$ ensures that $H_n \neq 0, \forall n \in \mathcal{N}_a$. With $N_a > L$, all the H_n 's cannot be zero; hence having $H_n = 0$ for some $n \in \mathcal{N}_a$ will not affect the final CFO estimator.

where we have used Parseval's theorem,

$$(1/N) \sum_{k=0}^{N-1} |x(k)|^2 = \sum_{n \in \mathcal{N}} |X(n + \xi)|^2, \quad \xi \in \mathcal{R}, \quad (10)$$

and the fact that $H_n s_n = 0$ for $n \notin \mathcal{N}_a$. The linear relations in eq. (2) should be taken into account in the minimization of the above criterion.

Notice that J_{VSC} is equivalent to the cost function used in an existing blind CFO estimator [2], which exploits the virtual sub-carriers (\mathcal{N}_v). The extra term J_A exploits the constant-modulus property of the transmitted symbols. As for J_{VSC} , minimizing J_A alone provides a consistent estimate of the CFO. Of course, J_{VSC} (respectively J_A) is a valid criterion only if the system is not fully loaded (respectively the constant-modulus property is satisfied). There are however some identifiability conditions associated with each criterion. These are discussed in Subsection 3.3. Also note that the development so far does not really require the constant-modulus assumption; in the general case, H_n in the preceding equations would be replaced by $H_n s_n$.

In the sequel, we first study the case of non-dispersive channels, for which $L = 0$, and then the more general and interesting case of dispersive channels, i.e., $L > 0$, the case for which OFDM is designed.

3.1 Non-Dispersive Channels

In this case, $H_n = h_o, \forall n \in \mathcal{N}_a$. Using eq. (7), the ML estimator of ξ_o is obtained by minimizing the following L_1 -type norm:

$$\hat{\xi}_o = \arg \max_{\xi} \sum_{n \in \mathcal{N}_a} |X(n + \xi)|. \quad (11)$$

Note that the VSC-based estimator is equivalently obtained by maximizing the L_2 -norm of the same vector as above. Indeed, using Parseval's theorem, we have that

$$\arg \min_{\xi} J_{VSC}(\xi) = \arg \max_{\xi} \sum_{n \in \mathcal{N}_a} |X(n + \xi)|^2$$

3.2 Dispersive Channels

First, we note that J_{VSC} is not a function of $|\mathbf{H}|$. Therefore, only J_A needs to be considered in the mini-

mization of J with respect to $|\mathbf{H}|$. This should be carried out under the constraint

$$|H_n|^2 = \sum_{l,p=0}^L h_l h_p^* e^{-j2\pi(l-p)n/N} \quad (12)$$

which follows from (2). Constraint (12) states that $|H_n|^2, n \in \mathcal{N}_a$, are quadratic forms of the $(L + 1)$ channel coefficients.

We modify J_A as follows

$$J'_A(\xi, |\mathbf{H}|) = \sum_{n \in \mathcal{N}_a} (|X(n + \xi)|^2 - |H_n|^2)^2. \quad (13)$$

The motivation for using this modified criterion is given next. Since our goal is to estimate the CFO by using a one-dimensional optimization procedure, we need to eliminate the $|H_n|$'s from the criterion in eq. (9). Towards this objective, we use $|H_n|^2$ instead of $|H_n|$ since the former can be re-parameterized as follows:

$$|H_n|^2 = \mathbf{c}_n^T \boldsymbol{\lambda}$$

where

$$\begin{aligned} \mathbf{c}_n &= [1, \sqrt{2} \cos(2\pi n/N), \dots, \sqrt{2} \cos(2\pi nL/N), \\ &\quad \sqrt{2} \sin(2\pi n/N), \dots, \sqrt{2} \sin(2\pi nL/N)]^T \\ \boldsymbol{\lambda} &= [g_0, \sqrt{2}\mathcal{R}[g_1], \dots, \sqrt{2}\mathcal{R}[g_L], \\ &\quad \sqrt{2}\mathcal{I}[g_1], \dots, \sqrt{2}\mathcal{I}[g_L]]^T \\ g_i &= \sum_{l=0}^{L-i} h_l^* h_{l+i}. \end{aligned}$$

The sequence $\{|H_n|^2\}$ is then described by linear combinations of the $(2L + 1)$ elements of the parameter vector $\boldsymbol{\lambda}$. Note that both \mathbf{c}_n and $\boldsymbol{\lambda}$ are real-valued vectors. The cost function J'_A is no longer the ML cost, but it does lead to a consistent estimate of ξ_o .

By assumption we have that $\mathbf{c}_n^T \boldsymbol{\lambda} \neq 0, \forall n \in \mathcal{N}_a$; further, from the definition of \mathbf{c} , we have that

$$\mathbf{C}_2 := \sum_{n \in \mathcal{N}_a} \mathbf{c}_n \mathbf{c}_n^T.$$

Setting $\partial J'_A / \partial \boldsymbol{\lambda} = 0$ yields the following closed-form estimator

$$\hat{\boldsymbol{\lambda}} = \mathbf{C}_2^\dagger \sum_{n \in \mathcal{N}_a} |X(n + \xi)|^2 \mathbf{c}_n, \quad (14)$$

where \dagger denotes the pseudo-inverse. Substituting $|\widehat{H}_n|^2 = \mathbf{c}_n^T \hat{\boldsymbol{\lambda}}$ into eqs. (7)-(9), we obtain the following criterion

$$J(\xi) = J_{VSC}(\xi) + J_{CM}(\xi) \quad (15)$$

$$J_{VSC}(\xi) = \sum_{n \in \mathcal{N}_v} |X(n + \xi)|^2 \quad (16)$$

$$J_{CM}(\xi) = \sum_{n \in \mathcal{N}_a} \left(|X(n + \xi)| - \sqrt{Y(n; \xi)} \right)^2 \quad (17)$$

where

$$Y(n; \xi) = \mathbf{c}_n^T \mathbf{C}_2^\dagger \sum_{n \in \mathcal{N}_a} |X(n + \xi)|^2 \mathbf{c}_n. \quad (18)$$

In the above criterion, J_{CM} exploits the constant modulus property of the symbol constellations. Using Parseval's theorem, eqn. (10), the two criteria can be merged together; after dropping constant terms, the pseudo-ML estimator of the CFO is obtained as

$$\hat{\xi}_o = \arg \min_{\xi} \sum_{n \in \mathcal{N}_a} \left(Y(n; \xi) - 2|X(n + \xi)|\sqrt{Y(n; \xi)} \right) \quad (19)$$

where recall that $X(f)$ is the discrete Fourier transform of $x(k)$ in (1) at frequency f/N , and $Y(n; \xi)$ is defined in (18). We refer to the estimator minimizing J_{VSC} as the VSC-based estimator, which is equivalent to the estimator in [2] for a specific choice of \mathcal{N}_v . We refer to our estimator in eq. (19) as the VSC&CM-based estimator.

We have, therefore, shown that the constant-modulus property can be exploited in blindly estimating ξ_o without increasing the dimension of the optimization procedure. Indeed, the VSC&CM-based estimator is obtained by a one-dimensional search, the same as with the existing VSC-based estimator. The computation of the criterion in eq. (19) is obviously more demanding than that of J_{VSC} . However, as we see next, the performance improvement of the VSC&CM-based estimator over the VSC-based estimator is more than one order of magnitude (i.e., more than 10dB!) provided $N_a \gg L$ (typically $N_a > 2L$), which is usually the case.

If the system is fully loaded, then $N_a = N$, and the VSC-based estimator fails. Our estimator, which in this case should be referred to as the CM-based estimator,

continues to perform well. Furthermore, in this case, $\mathbf{C}_2 = N\mathbf{I}$ where \mathbf{I} is the $N \times N$ identity matrix, and hence no matrix inversion is required. However, in this case, the CFO can be unambiguously estimated only in the interval $[-0.5, 0.5)$.

3.3 Identifiability

We consider the noise-free case, i.e., $v(k) = 0, \forall k$. The entire frequency acquisition range is $[-N/2, N/2)$. Let $\xi_o = m + \nu_o$ where m is an integer and $\nu_o \in [0, 1)$ is a fraction of the sub-carrier spacing. The estimator based solely on the CM property cannot determine m ; only ν_o can be estimated. To see this, consider the fully loaded scenario. We have that (in the noise-free case)

$$J'_A(\nu_o + m, |\mathbf{H}|) = J'_A(\nu_o, |\mathbf{H}'|) = 0$$

where \mathbf{H}' is the frequency response of the modified channel $\{h'_i = h_i \exp(-j2\pi m/N)\}$.

On the other hand, the VSC-based estimator is unambiguous in the entire acquisition range provided that $N_a > L$ and none of the L channel zeros occurs at the edges of the modulated frequency band [4, 5], i.e.,

$$H_{-(N_a-1)/2} \neq 0 \text{ and } H_{(N_a-1)/2} \neq 0$$

The first condition is always satisfied in practice. The second condition may not hold true for certain channels. Although the probability that this occurs is zero if we assume that the channel coefficients are continuous-valued random variables, small values of H_k at $k = -(N_a - 1)/2$ and/or $k = (N_a - 1)/2$ would have detrimental effects in the presence of noise.

To overcome this identifiability problem (and also to improve performance), two approaches have been proposed in the literature. One approach is based on inserting zero pilots in the OFDM block. A judicious placement of these pilots can guarantee an ambiguity-free estimator using a single OFDM block [4, 5]. When multiple blocks can be used to estimate the CFO, a pilot hopping technique was proposed in [6]. Another approach is based on exploiting space diversity wherein the frequency responses of the channels at the different diversity branches are less likely to all vanish at the edges of the modulated frequency band [7]. All of these techniques could be easily incorporated in our method.

4 EXTENSION TO MULTIPLE BLOCKS

In the case where multiple OFDM blocks could be used to estimate the CFO, the estimation accuracy can be further improved as follows. We assume that the CFO remains constant during these blocks.

4.1 Time-Invariant Channel

In this case, the channel coefficients do not vary across the blocks. Let M denote the number of blocks. The received signal at the m th block is then

$$x_m(k) = e^{j2\pi k\xi_o/N} \sum_{n \in \mathcal{N}_a} H_n s_{m,n} e^{j2\pi kn/N} + v_m(k)$$

where $m = 1, \dots, M$, $s_{m,n}$ is the symbol transmitted on the n th subcarrier during the m th block. Using the same reasoning as above, our estimator is obtained by minimizing

$$\sum_{n \in \mathcal{N}_a} \left[Z(n; \xi) - 2 \left(\frac{1}{M} \sum_{m=1}^M |X_m(n + \xi)| \right) \sqrt{Z(n; \xi)} \right] \quad (20)$$

where $X_m(f)$ is the discrete Fourier transform of $x_m(k)$ at frequency f/N , and

$$Z(n; \xi) = \mathbf{c}_n^T \mathbf{C}_2^\dagger \sum_{n \in \mathcal{N}_a} \left(\frac{1}{M} \sum_{m=1}^M |X_m(n + \xi)|^2 \right) \mathbf{c}_n.$$

4.2 Time-Variant Channel

In this case, the channel coefficients vary across the blocks. We consider the quasi-static scenario where the channel is invariant during each block but is different from one block to another. The received signal at the m th block is in then described as

$$x_m(k) = e^{j2\pi k\xi_o/N} \sum_{n \in \mathcal{N}_a} H_{m,n} s_{m,n} e^{j2\pi kn/N} + v_m(k)$$

where $H_{m,n}$ is the frequency response of the channel at the m th block. Our estimator turns out to be

$$\hat{\xi}_o = \arg \min_{\xi} \sum_{m=1}^M J_m(\xi)$$

$$J_m(\xi) = \sum_{n \in \mathcal{N}_a} \left(Y_m(n; \xi) - 2|X_m(n + \xi)| \sqrt{Y_m(n; \xi)} \right)$$

where $Y_m(n; \xi)$ is defined as in (18) with $X(f)$ replaced by $X_m(f)$. Thus, the new cost function is the

average of the cost functions corresponding to individual blocks. Note that this cost function is different from that in eq. (20).

5 PERFORMANCE ANALYSIS

Here, we compare our estimator with the estimator of [2, 3] using Monte-Carlo simulations. Only one OFDM block is used. We consider a total of $N = 64$ sub-carriers where only $N_a = 49$ sub-carriers are used, i.e., the number of virtual sub-carriers is $N_v = 15$. The transmitted symbols are drawn from equiprobable 8-PSK constellations. The channel coefficients are generated using an uncorrelated Rayleigh scattering model with exponential power delay profile, i.e., $E\{h_i^* h_j\} = \exp(-\beta i) \delta(i - j)$, with $\beta = 1/5$. The CFO is generated randomly between -2 and 2. Both the channel coefficients and the CFO are generated randomly for each Monte-Carlo run. The signal-to-noise ratio (SNR) is defined as $SNR = 10 \log_{10}(N_a \sum_{i=0}^L E\{|h_i|^2\} / \sigma_v^2)$ where σ_v^2 is the variance of the additive noise. Mean-square error (MSE) was estimated empirically from 200 Monte-Carlo runs.

5.1 Performance versus L and the SNR

Figure 1 displays MSE vs. SNR for a seven-tap channel, i.e., $L = 6$. Figure 2 displays MSE vs. channel length, L , for fixed $SNR = 15dB$. The performance of the proposed estimator is significantly better than that of the estimators in [2, 3]. Figure 1 indicates a 10 dB improvement, and Figure 2 indicates an order of magnitude improvement in the variance of the CFO estimator.

5.2 Unknown Channel Order

Here, we set the actual channel order to $L = 6$ and analyze the MSE when the assumed channel order varies from 0 to 25. The results are depicted in Figure 3. It is seen that our estimator still performs well if the assumed channel order is (slightly) larger than the actual channel order. This implies that in practice, if L is unknown, one only needs to use a reasonable upper limit on the possible values of L .

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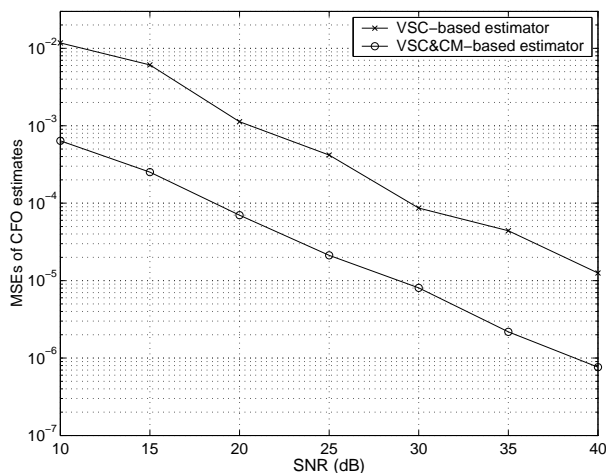


Figure 1: MSE of CFO estimators vs. SNR; $L = 6$.

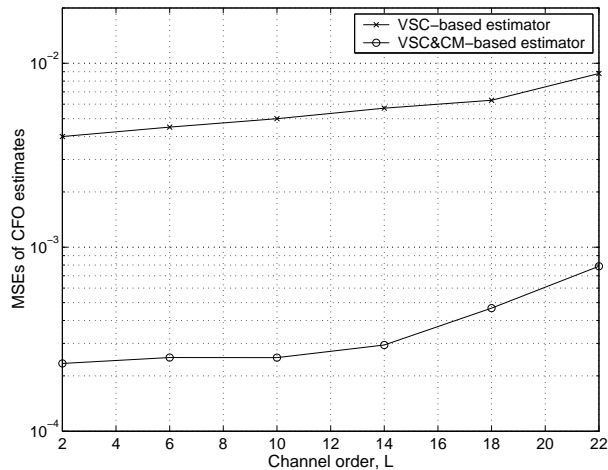


Figure 2: MSE of CFO estimators vs. channel order L .

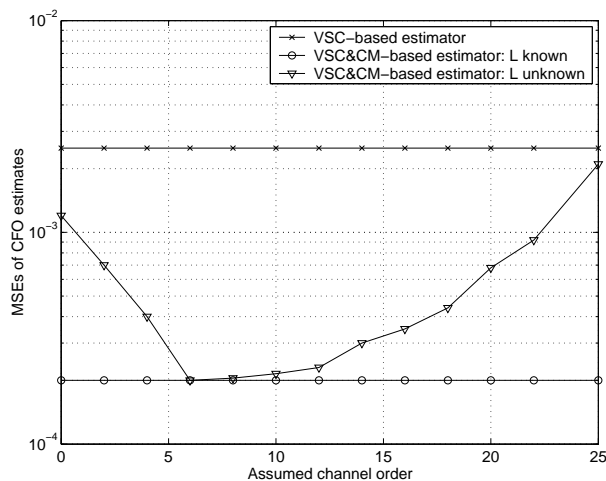


Figure 3: MSE of CFO estimators vs. assumed channel order; the actual channel order is 6.

APPENDIX D

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Profile

Mounir Ghogho has received the M.S. degree in 1993 and the PhD degree in 1997 from the National Polytechnic Institute of Toulouse, France. He was an EPSRC Research Fellow with the University of Strathclyde (Scotland), from Sept 1997 to Nov 2001. Since Dec 2001, he has been a faculty member with the school of Electronic and Electrical Engineering at the University of Leeds (England), where he is currently a Professor. He was awarded the UK Royal Academy of Engineering Research Fellowship in September 2000. He is a recipient of the 2013 IBM Faculty Award. He is currently an associate editor of the Signal Processing Magazine. He served as an Associate Editor of the IEEE Signal Processing Letters from 2001 to 2004, the IEEE Transactions on Signal Processing from 2005 to 2008, and the Elsevier Digital Signal Processing journal from 2011 to 2012. He served as a member of the IEEE Signal Processing Society SPCOM Technical Committee from 2005 to 2010, a member of IEEE Signal Processing Society SPTM Technical Committee from 2006 to 2011, and is currently a member of the IEEE Signal Processing Society SAM Technical Committee. He was the General Chair of the European Signal Processing conference Eusipco2013 and the IEEE workshop on Signal Processing for Advanced Wireless Communications SPAWC'2010, the technical co-chair of the MIMO symposium of IWCMC 2007 and IWCMC 2008, and a technical area co-chair of Eusipco 2008, Eusipco 2009 and ISCCSP'05. He has published over 260 journal and conference papers in the areas of signal processing and wireless communication. He held invited scientist/professor positions at Telecom Paris-Tech (France), NII (Japan), BUPT (China), University Carlos 3rd of Madrid (Spain), ENSICA (Toulouse), Darmstadt Technical University (Germany), and Minnesota University (USA).



Research interests



- Modeling of wireless networks using stochastic geometry
- Massive MIMO, device-to-device and drone communication for 5G
- Physical layer security in wireless communication
- Sparse signal processing for radar
- Distributed signal processing for wireless sensor networks
- Machine learning and its applications (renewable energy, driving behavior, urban pollution monitoring, etc.)
- Geolocalization


Research groups and institutes

- Institute of Robotics, Autonomous Systems and Sensing


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