Distributed Network Structure Estimation Using Consensus Methods

Sai Zhang
Arizona State University

Cihan Tepedelenlioglu
Arizona State University

Andreas Spanias
Arizona State University

Mahesh Banavar
Clarkson University

SYNTHESIS LECTURES ON COMMUNICATIONS #13

MORGAN & CLAYPOOL PUBLISHERS

ABSTRACT

The area of detection and estimation in a distributed wireless sensor network (WSN) has several applications, including military surveillance, sustainability, health monitoring, and Internet of Things (IoT). Compared with a wired centralized sensor network, a distributed WSN has many advantages including scalability and robustness to sensor node failures. In this book, we address the problem of estimating the structure of distributed WSNs. First, we provide a literature review in: (a) graph theory; (b) network area estimation; and (c) existing consensus algorithms, including average consensus and max consensus. Second, a distributed algorithm for counting the total number of nodes in a wireless sensor network with noisy communication channels is introduced. Then, a distributed network degree distribution estimation (DNDD) algorithm is described. The DNDD algorithm is based on average consensus and in-network empirical mass function estimation. Finally, a fully distributed algorithm for estimating the center and the coverage region of a wireless sensor network is described. The algorithms introduced are appropriate for most connected distributed networks. The performance of the algorithms is analyzed theoretically, and simulations are performed and presented to validate the theoretical results. In this book, we also describe how the introduced algorithms can be used to learn global data information and the global data region.

KEYWORDS

wireless sensor networks, diffusion adaptation, node counting, Internet-of-Things (IoT)

Bibliography

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, A survey on sensor networks, *IEEE Communications Magazine*, 40, 2002. DOI: 10.1109/mcom.2002.1024422. 1

[2] J. A. Stankovic, Wireless sensor networks, *Computer*, 41(10), pp. 92–95, October 2008. DOI: 10.1109/mc.2008.441.

[3] C.-Y. Chong and S. P. Kumar, Sensor networks: Evolution, opportunities, and challenges, *Proc. of the IEEE*, 91(8), pp. 1247–1256, August 2003. DOI: 10.1109/jproc.2003.814918.

[4] D. Culler, D. Estrin, and M. Srivastava, Overview of sensor networks, *Computer*, 37(8), pp. 41–49, August 2004. DOI: 10.1109/mc.2004.93. 1

[5] Wikipedia, Wireless sensor network—Wikipedia, the free encyclopedia, 2014. `https://en.wikipedia.org/wiki/Wireless_sensor_network` 1

[6] J. Yick, B. Mukherjee, and G. Dipak, Wireless sensor network survey, *Computer Networks*, 52, pp. 2292–2330, August 2008. DOI: 10.1016/j.comnet.2008.04.002. 1, 2, 5

[7] M. Goldenbaum, S. Stanczak, and M. Kaliszan, On function computation via wireless sensor multiple-access channels, *Wireless Communications and Networking Conference*, pp. 1–6, April 2009. DOI: 10.1109/wcnc.2009.4917843. 1, 4, 11, 15

[8] F. Cattivelli and A. Sayed, Diffusion LMS strategies for distributed estimation, *IEEE Transactions on Signal Processing*, 58, pp. 1035–1048, 2010. DOI: 10.1109/tsp.2009.2033729. 1, 4, 43, 45

[9] O. Younis and S. Fahmy, Distributed clustering in ad-hoc sensor networks: A hybrid, energy-efficient approach, *IEEE INFOCOM*, 1, p. 640, March 2004. DOI: 10.1109/infcom.2004.1354534.

[10] A. G. Dimakis, S. Kar, J. M. F. Moura, M. G. Rabbat, and A. Scaglione, Gossip algorithms for distributed signal processing, *Proc. of the IEEE*, 98(11), pp. 1847–1864, November 2010. DOI: 10.1109/jproc.2010.2052531.

[11] J. F. Chamberland and V. V. Veeravalli, Decentralized detection in sensor networks, *IEEE Transactions on Signal Processing*, 51(2), pp. 407–416, February 2003. DOI: 10.1109/tsp.2002.806982. 1

[12] R. K. Shakya, Y. N. Singh, and N. K. Verma, A novel spatial correlation model for wireless sensor network applications, *9th International Conference on Wireless and Optical Communications Networks (WOCN)*, pp. 1–6, September 2012. DOI: 10.1109/wocn.2012.6335549. 1, 56

[13] R. W. Santucci, M. K. Banavar, A. Spanias, and C. Tepedelenlioglu, Design of limiting amplifier models for nonlinear amplify-and-forward distributed estimation, *18th International Conference on Digital Signal Processing (DSP)*, pp. 1–6, July 2013. DOI: 10.1109/icdsp.2013.6622749. 1, 4

[14] R. W. Santucci, M. K. Banavar, A. Spanias, and C. Tepedelenlioglu, Nonlinear amplify and forward distributed estimation over non-identical channels, *IEEE Transactions on Vehicular Technologies*, 64(11), pp. 5390–5395, November 2015. DOI: 10.1109/tvt.2014.2381094. 4

[15] M. Krämer, S. Bader, and B. Oelmann, Implementing wireless sensor network applications using hierarchical finite state machines, *10th IEEE International Conference on Networking, Sensing and Control (ICNSC)*, pp. 124–129, April 2013. DOI: 10.1109/icnsc.2013.6548723.

[16] K. Ghosal, T. Anand, V. Chaturvedi, and B. Amrutur, A power-scalable RF CMOS receiver for 2.4 GHz wireless sensor network applications, *19th IEEE International Conference on Electronics, Circuits, and Systems (ICECS)*, pp. 161–164, December 2012. DOI: 10.1109/icecs.2012.6463775.

[17] U. Pesovic, Z. Jovanovic, S. Randjic, and D. Markovic, Benchmarking performance and energy efficiency of microprocessors for wireless sensor network applications, *Proc. of the 35th International Convention MIPRO*, pp. 743–747, May 2012. 1

[18] R. Zeng and C. Tepedelenlioglu, Multiple device-to-device users overlaying cellular networks, *IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, March 2017. DOI: 10.1109/wcnc.2017.7925800. 1

[19] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, Wireless sensor networks: A survey, *Computer Networks*, 38, pp. 393–422, 2002. DOI: 10.1002/9780470515181. 1

[20] S. Zhang, C. Tepedelenlioglu, M. Banavar, and A. Spanias, Max consensus in sensor networks: Non-linear bounded transmission and additive noise, *IEEE Sensors Journal*, 16, pp. 9089–9098, December 2016. DOI: 10.1109/jsen.2016.2612642. 5, 15, 16, 17

[21] R. Saber and R. Murray, Consensus protocols for networks of dynamic agents, *Proc. of the American Control Conference*, pp. 951–956, June 2003. DOI: 10.1109/acc.2003.1239709. 1, 11

[22] T. Arampatzis, J. Lygeros, and S. Manesis, A survey of applications of wireless sensors and wireless sensor networks, *Proc. of the IEEE International Symposium on, Mediterrean Conference on Control and Automation Intelligent Control*, pp. 719–724, June 2005. DOI: 10.1109/.2005.1467103. 1

[23] U. Prathap, P. D. Shenoy, K. R. Venugopal, and L. M. Patnaik, Wireless sensor networks applications and routing protocols: Survey and research challenges, *International Symposium on Cloud and Services Computing*, pp. 49–56, December 2012. DOI: 10.1109/iscos.2012.21. 2, 5

[24] U. Shanthamallu, A. Spanias, C. Tepedelenlioglu, and M. Stanley, A brief survey of machine learning methods and their sensor and IoT applications, *Proc. 8th International Conference on Information, Intelligence, Systems and Applications (IEEE IISA)*, August 2017. 1, 3, 5, 56

[25] C. Meesookho, S. Narayanan, and C. S. Raghavendra, Collaborative classification applications in sensor networks, *Sensor Array and Multichannel Signal Processing Workshop Proceedings*, pp. 370–374, August 2002. DOI: 10.1109/sam.2002.1191063. 1, 5

[26] D. Li, K. D. Wong, Y. H. Hu, and A. M. Sayeed, Detection, classification, and tracking of targets, *IEEE Signal Processing Magazine*, 19(2), pp. 17–29, March 2002. DOI: 10.1109/79.985674. 1

[27] M. Hammoudeh, F. Al-Fayez, H. Lloyd, R. Newman, B. Adebisi, A. Bounceur, and A. Abuarqoub, A wireless sensor network border monitoring system: Deployment issues and routing protocols, *IEEE Sensors Journal*, 17(8), pp. 2572–2582, April 2017. DOI: 10.1109/jsen.2017.2672501. 1, 2, 6

[28] E. Felemban, Advanced border intrusion detection and surveillance using wireless sensor network technology, *International Journal of Communications, Network and System Sciences*, 6, pp. 251–259, May 2013. DOI: 10.4236/ijcns.2013.65028. 2, 5, 6

[29] M. K. Banavar, J. J. Zhang, B. Chakraborty, H. Kwone, Y. Li, H. Jiang, A. Spanias, C. Tepedelenlioglu, C. Chakrabartie, and A. Papandreou-Suppappola, An overview of recent advances on distributed and agile sensing algorithms and implementation, *Digital Signal Processing*, 39, pp. 1–14, April 2015. DOI: 10.1016/j.dsp.2015.01.001. 2, 5

[30] S. Peter and P. Langendörfer, Tool-supported methodology for component-based design of wireless sensor network applications, *IEEE 36th Annual Computer Software and Applications Conference Workshops*, pp. 526–531, July 2012. DOI: 10.1109/compsacw.2012.98.

[31] H. Braun, C. Tepedelenlioglu, A. Spanias, and M. Banavar, *Signal Processing for Solar Array Monitoring, Fault Detection, and Optimization, Synthe-*

sis Lectures on Power Electronics, Morgan & Claypool Publishers, 2012. DOI: 10.2200/S00425ED1V01Y201206PEL004. 2

[32] M. Castillo-Effer, D. H. Quintela, W. Moreno, R. Jordan, and W. Westhoff, Wireless sensor networks for flash-flood alerting, *Proc. of the 5th IEEE International Caracas Conference on Devices, Circuits and Systems*, 1, pp. 142–146, November 2004. DOI: 10.1109/iccdcs.2004.1393370. 2

[33] G. Werner-Allen, K. Lorincz, M. Ruiz, O. Marcillo, J. Johnson, J. Lees, and M. Welsh, Deploying a wireless sensor network on an active volcano, *IEEE Internet Computing*, 10(2), pp. 18–25, March 2006. DOI: 10.1109/mic.2006.26.

[34] K. Lorincz, D. J. Malan, T. R. F. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland, M. Welsh, and S. Moulton, Sensor networks for emergency response: Challenges and opportunities, *IEEE Pervasive Computing*, 3(4), pp. 16–23, October 2004. DOI: 10.1109/mprv.2004.18. 2, 5

[35] M. K. Banavar, C. Tepedelenlioglu, and A. Spanias, Distributed snr estimation with power constrained signaling over gaussian multiple-access channels, *IEEE Transactions on Signal Processing*, 60, pp. 3289–3294, February 2012. DOI: 10.1109/tsp.2012.2188524. 2, 5

[36] N. Kovvali, M. Banavar, and A. Spanias, *An Introduction to Kalman Filtering with MATLAB Examples*, Synthesis Lectures on Signal Processing, Morgan & Claypool Publishers, 2013. DOI: 10.2200/s00534ed1v01y201309spr012. 2, 5

[37] Y. Zhou and S. Maskell, RB^2-PF : A novel filter-based monocular visual odometry algorithm, *20th International Conference on Information Fusion*, IEEE, pp. 1–8, July 2017. DOI: 10.23919/icif.2017.8009745.

[38] Y. Wang, Y. Sheng, J. Wang, and W. Zhang, Optimal collision-free robot trajectory generation based on time series prediction of human motion, *IEEE Robotics and Automation Letters*, 3(1), pp. 226–233, January 2018. DOI: 10.1109/lra.2017.2737486. 2, 5

[39] M. Usman, V. Muthukkumarasamy, X. W. Wu, and S. Khanum, Securing mobile agent based wireless sensor network applications on middleware, *International Symposium on Communications and Information Technologies (ISCIT)*, pp. 707–712, October 2012. DOI: 10.1109/iscit.2012.6380993. 2

[40] A. Simonetto, T. Keviczky, and D. V. Dimarogonas, Distributed solution for a maximum variance unfolding problem with sensor and robotic network applications, *50th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, pp. 63–70, October 2012. DOI: 10.1109/allerton.2012.6483200. 2, 5

[41] X. Zhang, C. Tepedelenlioglu, M. Banavar, and A. Spanias, *Node Localization in Wireless Sensor Networks, Synthesis Lectures on Communications*, Morgan & Claypool Publishers, 2016. DOI: 10.2200/s00742ed1v01y201611com012.

[42] X. Zhang, M. Banavar, C. Tepedelenlioglu, and A. Spanias, Maximum likelihood localization in the presence of channel uncertainties, November 2016, US Patent. https://www.google.com/patents/US9507011?hl=zh-CN#backward-citations 2, 5

[43] J. Lee, M. Stanley, A. Spanias, and C. Tepedelenlioglu, Integrating machine learning in embedded sensor systems for internet-of-things applications, *IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*, pp. 290–294, Limassol, December 2016. DOI: 10.1109/isspit.2016.7886051. 2

[44] C. Tepedelenlioglu, M. K. Banavar, and A. Spanias, On the asymptotic efficiency of distributed estimation systems with constant modulus signals over multiple-access channels, *IEEE Transactions on Information Theory*, 57(10), pp. 7125–7130, October 2011. DOI: 10.1109/tit.2011.2165806. 2, 5

[45] X. Zhang, C. Tepedelenlioglu, M. K. Banavar, and A. Spanias, Distributed location detection in wireless sensor networks, *Asilomar Conference on Signals, Systems and Computers*, pp. 428–432, November 2013. DOI: 10.1109/acssc.2013.6810312.

[46] X. Zhang, M. K. Banavar, M. Willerton, A. Manikas, C. Tepedelenlioglu, A. Spanias, T. Thornton, E. Yeatman, and A. G. Constantinides, Performance comparison of localization techniques for sequential WSN discovery, *Sensor Signal Processing for Defence (SSPD)*, pp. 1–5, September 2012. DOI: 10.1049/ic.2012.0120. 6, 7

[47] J. Foutz, A. Spanias, and M. Banavar, *Narrowband Direction of Arrival Estimation for Antenna Arrays, Synthesis Lectures on Antennas*, Morgan & Claypool Publishers, 2008. DOI: 10.2200/s00118ed1v01y200805ant008. 2, 5

[48] Y. H. Nam, Z. Halm, Y. J. Chee, and K. S. Park, Development of remote diagnosis system integrating digital telemetry for medicine, *Proc. of the 20th Annual International Conference of the IEEE*, pp. 1170–1173, October 1998. DOI: 10.1109/iembs.1998.747079. 2, 5

[49] D. Shao, Y. Yang, C. Liu, F. Tsow, H. Yu, and N. Tao, Noncontact monitoring breathing pattern, exhalation flow rate and pulse transit time, *IEEE Transactions on Biomedical Engineering*, 61(11), pp. 2760–2767, November 2014. DOI: 10.1109/tbme.2014.2327024.

[50] T. Gao, D. Greenspan, M. Welsh, R. R. Juang, and A. Alm, Vital signs monitoring and patient tracking over a wireless network, *IEEE Engineering in Medicine and Biology 27th Annual Conference*, pp. 102–105, January 2005. DOI: 10.1109/iembs.2005.1616352.

[51] M. Mathew, N. Weng, and L. J. Vespa, Quality-of-information modeling and adapting for delay-sensitive sensor network applications, *IEEE 31st International Performance Computing and Communications Conference (IPCCC)*, pp. 471–477, December 2012. DOI: 10.1109/pccc.2012.6407659.

[52] G. Fortino, R. Giannantonio, R. Gravina, P. Kuryloski, and R. Jafari, Enabling effective programming and flexible management of efficient body sensor network applications, *IEEE Transactions on Human-machine Systems*, 43(1), pp. 115–133, January 2013. DOI: 10.1109/tsmcc.2012.2215852. 2

[53] D. Shao, Y. Yang, F. Tsow, C. Liu, and N. Tao, Non-contact simultaneous photoplethysmogram and ballistocardiogram video recording towards real-time blood pressure and abnormal heart rhythm monitoring, *12th IEEE International Conference on Automatic Face Gesture Recognition (FG)*, pp. 273–277, May 2017. DOI: 10.1109/fg.2017.42. 2

[54] D. Shao, F. Tsow, C. Liu, Y. Yang, and N. Tao, Simultaneous monitoring of ballistocardiogram and photoplethysmogram using a camera, *IEEE Transactions on Biomedical Engineering*, 64(5), pp. 1003–1010, May 2017. DOI: 10.1109/tbme.2016.2585109.

[55] C. R. Baker, K. Armijo, S. Belka, M. Benhabib, V. Bhargava, N. Burkhart, A. D. Minassians, G. Dervisoglu, L. Gutnik, M. B. Haick, C. Ho, M. Koplow, J. Mangold, S. Robinson, M. Rosa, M. Schwartz, C. Sims, H. Stoffregen, A. Waterbury, E. S. Leland, T. Pering, and P. K. Wright, Wireless sensor networks for home health care, *Advanced Information Networking and Applications Workshops, (AINAW), 21st International Conference on*, 2, pp. 832–837, May 2007. DOI: 10.1109/AINAW.2007.376. 2, 5

[56] S. Rao, D. Ramirez, H. Braun, J. Lee, C. Tepedelenlioglu, E. Kyriakides, D. Srinivasan, J. Frye, S. Koizumi, Y. Morimoto, and A. Spanias, An 18 kw solar array research facility for fault detection experiments, *18th Mediterranean Electrotechnical Conference (MELECON)*, pp. 1–5, Limassol, April 2016. DOI: 10.1109/melcon.2016.7495369. 3, 5

[57] S. Rao, S. Katoch, A. Spanias, C. Tepedelenlioglu, R. Ayyanar, H. Braun, J. Lee, U. Shanthamallu, M. Banavar, and D. Srinivasan, A cyber-physical system approach for photovoltaic array monitoring and control, *Proc. 8th International Conference on Information, Intelligence, Systems and Applications (IEEE IISA)*, Larnaca, August 2017.

[58] A. Spanias, Solar energy management as an internet of things (IoT) applications, *Proc. 8th International Conference on Information, Intelligence, Systems and Applications (IEEE IISA)*, Larnaca, August 2017. 3

[59] H. Braun, S. Buddha, V. Krishnan, C. Tepedelenlioglu, A. Spanias, M. Banavar, and D. Srinivansan, Topology reconfiguration for optimization of photovoltaic array output, *Elsevier Sustainable Energy, Grids and Networks*, 6, pp. 58–69, June 2016. DOI: 10.1016/j.segan.2016.01.003. 3, 5, 6

[60] N. A. Lynch, *Distributed Algorithms*, Morgan Kaufmann, 1997. 3

[61] R. Olfati-Saber, J. A. Fax, and R. M. Murray, Consensus and cooperation in networked multi-agent systems, *IEEE Signal Processing Magazine*, 95(1), 2007. DOI: 10.1109/jproc.2006.887293. 3, 4, 11

[62] J. Baillieul and P. J. Antsaklis, Control and communication challenges in networked real-time systems, *Proc. of the IEEE*, 95(1), pp. 9–28, January 2007. DOI: 10.1109/jproc.2006.887290. 3

[63] W. Ren, R. W. Beard, and E. M. Atkins, A survey of consensus problems in multi-agent coordination, *Proc. of the American Control Conference*, 3, pp. 1859–1864, June 2005. DOI: 10.1109/acc.2005.1470239.

[64] S. Kar and J. Moura, Distributed consensus algorithms in sensor networks with imperfect communication: Link failures and channel noise, *IEEE Transactions on Signal Processing*, 57(1), pp. 355–369, January 2009. DOI: 10.1109/tsp.2008.2007111. 3, 4, 12, 13, 21, 24, 31, 33

[65] S. Kar and J. M. F. Moura, Sensor networks with random links: Topology design for distributed consensus, *IEEE Transactions on Signal Processing*, 56(7), pp. 3315–3326, July 2008. DOI: 10.1109/tsp.2008.920143. 3

[66] R. Olfati-Saber and R. Murray, Consensus problems in networks of agents with switching topology and time-delays, *IEEE Transactions on Automatic Control*, 49(9), pp. 1520–1533, September 2004. DOI: 10.1109/tac.2004.834113. 3, 4, 9, 11, 14

[67] L. Xiao, S. Boyd, and S. Kim, Distributed average consensus with least-mean-square deviation, *Journal of Parallel and Distributed Computing*, 67, pp. 33–46, 2007. DOI: 10.1016/j.jpdc.2006.08.010. 3, 12, 16

[68] R. Santucci, M. Banavar, C. Tepedelenlioglu, and A. Spanias, Energy-efficient distributed estimation by utilizing a nonlinear amplifier, *IEEE Transactions on Circuits and Systems I: Regular Papers*, pp. 302–311, January 2014. DOI: 10.1109/tcsi.2013.2268354. 1, 3, 4

[69] L. Xiao and S. Boyd, Fast linear iterations for distributed averaging, *Proc. 42nd IEEE Conference on Decision and Control*, 5, pp. 4997–5002, December 2003. DOI: 10.1109/cdc.2003.1272421. 4, 5, 11, 12, 16, 21

[70] J. Lee, C. Tepedelenlioglu, M. K. Banavar, and A. Spanias, Nonlinear diffusion adaptation with bounded transmission over distributed networks, *IEEE ICC*, pp. 6707–6711, London, June 2015. DOI: 10.1109/icc.2015.7249394. 3, 42

[71] A. Papachristodoulou, A. Jadbabaie, and U. Munz, Effects of delay in multi-agent consensus and oscillator synchronization, *IEEE Transactions on Automatic Control*, 55(6), pp. 1471–1477, 2010. DOI: 10.1109/tac.2010.2044274. 4, 11

[72] R. Olfati-Saber, Flocking for multi-agent dynamic systems: Algorithms and theory, *IEEE Transaction on Automatic Control*, 51(3), pp. 401–420, March 2006. DOI: 10.1109/tac.2005.864190. 4

[73] R. Olfati-Saber and R. M. Murray, Distributed cooperative control of multiple vehicle formations using structural potential functions, *IFAC Proceedings Volumes, 15th IFAC World Congress*, 35(1), pp. 495–500, 2002. http://www.sciencedirect.com/science/article/pii/S1474667015386651 DOI: 10.3182/20020721-6-es-1901.00244. 4

[74] R. Olfati-Saber and R. M. Murray, Graph rigidity and distributed formation stabilization of multi-vehicle systems, *Proc. of the 41st IEEE Conference on Decision and Control*, 3, pp. 2965–2971, December 2002. DOI: 10.1109/cdc.2002.1184307. 4

[75] L. Xiao, S. Boyd, and S. Lall, A scheme for robust distributed sensor fusion based on average consensus, *Fourth International Symposium on Information Processing in Sensor Networks*, pp. 63–70, April 2005. DOI: 10.1109/ipsn.2005.1440896. 4, 5, 11

[76] K. C. Chang, C. Y. Chong, and Y. Bar-Shalom, Distributed estimation in distributed sensor networks, *Large-scale Stochastic Systems Detection, Estimation, Stability and Control*, S. G. Tzafestas and K. Watanabe, Eds., ch. 2, pp. 23–71, Marcel Dekker, 1992. 4

[77] D. Zhao, Z. An, and Y. Xu, Time synchronization in wireless sensor networks using max and average consensus protocol, *International Journal of Distributed Sensor Networks*, February 2013. DOI: 10.1155/2013/192128. 4, 11

[78] S. Dasarathan, C. Tepedelenlioglu, M. Banavar, and A. Spanias, Non-linear distributed average consensus using bounded transmissions, *IEEE Transactions on Signal Processing*, 61, pp. 6000–6009, December 2013. DOI: 10.1109/tsp.2013.2282912. 4, 12, 13, 14, 16, 21, 24, 31

[79] S. Dasarathan, C. Tepedelenlioglu, M. Banavar, and A. Spanias, Robust consensus in the presence of impulsive channel noise, *IEEE Transactions on Signal Processing*, 63, pp. 2118–2129, March 2015. DOI: 10.1109/tsp.2015.2408564. 4, 13

[80] F. Iutzeler, P. Ciblat, and J. Jakubowicz, Analysis of max-consensus algorithms in wireless channels, *IEEE Transactions on Signal Processing*, 60, pp. 6103–6107, November 2012. DOI: 10.1109/tsp.2012.2211593. 4, 14, 43, 45

[81] A. Tahbaz-Salehi and A. Jadbabaie, A one-parameter family of distributed consensus algorithms with boundary: From shortest paths to mean hitting times, *45th*

IEEE Conference on Decision and Control, pp. 4664–4669, December 2006. DOI: 10.1109/cdc.2006.377308. 15, 42

[82] B. Nejad, S. Attia, and J. Raisch, Max-consensus in a max-plus algebraic setting: The case of fixed communication topologies, *International Symposium on Information, Communication and Automation Technologies*, pp. 1–7, October 2009. DOI: 10.1109/icat.2009.5348437. 14, 15, 43

[83] G. Shi and K. H. Johansson, Convergence of distributed averaging and maximizing algorithms Part II: State-dependent graphs, *American Control Conference*, pp. 6859–6864, June 2013. DOI: 10.1109/acc.2013.6580916. 15

[84] S. Giannini, A. Petitti, D. D. Paola, and A. Rizzo, Asynchronous max-consensus protocol with time delays: Convergence results and applications, *IEEE Transactions on Circuits and Systems I: Regular Papers*, 63, pp. 256–264, January 2016. DOI: 10.1109/tcsi.2015.2512721. 4, 14

[85] S. Zhang, C. Tepedelenlioglu, M. Banavar, and A. Spanias, Max-consensus using the soft maximum, *Asilomar Conference on Signals, Systems and Computers*, pp. 433–437, November 2013. DOI: 10.1109/acssc.2013.6810313. 5, 15, 17

[86] S. Vu, C. T. Gao, W. P. Deshmukh, and L. Yingshu, Distributed energy-efficient scheduling approach for k-coverage in wireless sensor networks, *IEEE Military Communications Conference*, pp. 1–7, October 2006. DOI: 10.1109/milcom.2006.302146. 5, 6, 39

[87] J. A. Deri and J. Moura, Graph sampling: Estimation of degree distributions, *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 6501–6505, May 2013. DOI: 10.1109/icassp.2013.6638918. 6, 7

[88] D. Rojković, T. Crnić, and I. Cavrak, Agent-based topology control for wireless sensor network applications, *Proc. of the 35th International Convention MIPRO*, pp. 277–282, May 2012. 5, 6

[89] O. Serrat, *Social Network Analysis*, Singapore, Springer Singapore, pp. 39–43, 2017. DOI: 10.1007/978-981-10-0983-9_9. 5

[90] D. W. Hearn and J. Vijay, Efficient algorithms for the (weighted) minimum circle problem, *Operations Research*, 30, pp. 777–795, July 1982. DOI: 10.1287/opre.30.4.777. 6, 39

[91] Z. Yu, J. Teng, X. Li, and D. Xuan, On wireless network coverage in bounded areas, *INFOCOM, Proceedings IEEE*, pp. 1195–1203, July 2013. DOI: 10.1109/infcom.2013.6566911. 6, 39

[92] Z. Sun, P. Wang, M. Vuran, M. Al-Rodhaan, A. Al-Dhelaan, and I. Akyildiz, Bordersense: Border patrol through advanced wireless sensor networks, *Ad Hoc Networks*, 9, pp. 468–477, May 2011. DOI: 10.1016/j.adhoc.2010.09.008. 6

[93] N. M. M. de Abreu, Old and new results on algebraic connectivity of graphs, *Linear Algebra and its Applications*, 423, pp. 53–73, May 2007. DOI: 10.1016/j.laa.2006.08.017. 9, 17

[94] S. Lu and Z. Wang, Accelerated algorithms for eigen-value decomposition with application to spectral clustering, *49th Asilomar Conference on Signals, Systems and Computers*, pp. 355–359, November 2015. DOI: 10.1109/acssc.2015.7421146. 10, 17, 56

[95] P. D. Lorenzo and S. Barbarossa, Distributed estimation and control of algebraic connectivity over random graphs, *IEEE Transactions on Signal Processing*, 62(21), pp. 5615–5628, November 2014. DOI: 10.1109/tsp.2014.2355778. 10, 17

[96] A. Nedic, A. Ozdaglar, and P. A. Parrilo, Constrained consensus and optimization in multi-agent networks, *IEEE Transactions on Automatic Control*, 55(4), pp. 922–938, April 2010. DOI: 10.1109/tac.2010.2041686. 11

[97] D. P. Spanos and R. M. Murray, Distributed sensor fusion using dynamic consensus, *IFAC World Congress*, pp. 1–6, July 2005. 11

[98] D. Scherber and H. Papadopoulos, Locally constructed algorithms for distributed computations in ad-hoc networks, *3rd International Symposium on Information Processing in Sensor Networks*, pp. 11–19, June 2004. DOI: 10.1145/984622.984625. 11

[99] L. Schenato and G. Gamba, A distributed consensus protocol for clock synchronization in wireless sensor network, *46th IEEE Conference on Decision and Control*, pp. 2289–2294, December 2007. DOI: 10.1109/cdc.2007.4434671. 11

[100] S. Kar, J. M. F. Moura, and K. Ramanan, Distributed parameter estimation in sensor networks: Nonlinear observation models and imperfect communication, *IEEE Transactions on Information Theory*, 58(6), pp. 3575–3605, June 2012. DOI: 10.1109/tit.2012.2191450. 11

[101] I. D. Schizas, G. B. Giannakis, S. I. Roumeliotis, and A. Ribeiro, Consensus in ad hoc wsns with noisy links—Part II: Distributed estimation and smoothing of random signals, *IEEE Transactions on Signal Processing*, 56(4), pp. 1650–1666, April 2008. DOI: 10.1109/TSP.2007.908943.

[102] V. Saligrama, M. Alanyali, and O. Savas, Distributed detection in sensor networks with packet losses and finite capacity links, *IEEE Transactions on Signal Processing*, 54(11), pp. 4118–4132, November 2006. DOI: 10.1109/tsp.2006.880227. 11

[103] M. Bawa, H. Garcia-Molina, A. Gionis, and R. Motwani, Estimating aggregates on a peer-to-peer network, Stanford Info Lab, Technical Report 2003–24, April 2003. http://ilpubs.stanford.edu:8090/586/ 11, 17, 18

[104] S. Sundaram and C. N. Hadjicostis, Distributed function calculation via linear iterative strategies in the presence of malicious agents, *IEEE Transactions on Automatic Control*, 56(7), pp. 1495–1508, July 2011. DOI: 10.1109/tac.2010.2088690. 11

[105] A. Jadbabaie, J. Lin, and A. Morse, Coordination of groups of mobile autonomous agents using nearest neighbor rules, *IEEE Transactions on Automatic Control*, 48, pp. 988–1001, June 2003. DOI: 10.1109/cdc.2002.1184304. 11

[106] X. Li, C. Tepedelenlioglu, and H. Şenol, Channel estimation for residual self-interference in full-duplex amplify-and-forward two-way relays, *IEEE Transactions on Wireless Communications*, 16(8), pp. 4970–4983, August 2017. DOI: 10.1109/twc.2017.2704123. 12

[107] J. Cortes, Distributed algorithms for reaching consensus on general functions, *Automatica*, 44(3), pp. 401–420, 2008. DOI: 10.1016/j.automatica.2007.07.022. 14, 15

[108] D. Bauso, L. Giarre, and R. Pesenti, Nonlinear protocols for optimal distributed consensus in networks of dynamic agents, *System and Control Letters*, 55(11), pp. 918–928, June 2006. DOI: 10.1016/j.sysconle.2006.06.005. 15

[109] S. Zhang, S. C. Liew, and P. P. Lam, Hot topic: Physical-layer network coding, *Proc. of the 12th Annual International Conference on Mobile Computing and Networking*, pp. 358–365, September 2006. DOI: 10.1145/1161089.1161129. 16

[110] J. Sykora, Hierarchical network transfer function and doubly-greedy half-duplex stage scheduling for WPNC networks, *IEEE Communications Letters*, 19(6), pp. 1029–1032, June 2015. DOI: 10.1109/lcomm.2015.2417874. 16

[111] A. Ganesh, A. Kermarrec, E. Merrer, and L. Massoulie, Peer counting and sampling in overlay networks based on random walks, *Distributed Computing*, 20, pp. 267–278, January 2007. DOI: 10.1007/s00446-007-0027-z. 16, 17, 18

[112] J. Sykora, Distributed consensus estimator of hierarchical network transfer function in WPNC networks, *COST IRACON*, pp. 1–4, October 2016. 16, 17

[113] X. Zhang, The Laplacian eigenvalues of graphs: A survey, *arXiv:1111.2897v1 [math.CO]*, pp. 1–35, November 2011. 17

[114] P. Yang, F. R. A., G. G. J., K. Jynch, S. Srinivasa, and R. Sukthankar, Decentralized estimation and control of graph connectivity for mobile sensor networks, *Automatica*, 46(2), pp. 390–396, February 2010. DOI: 10.1016/j.automatica.2009.11.012. 17

[115] W. Y. Chen, Y. Song, H. Bai, C. J. Lin, and E. Y. Chang, Parallel spectral clustering in distributed systems, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 33(3), pp. 568–586, March 2011. DOI: 10.1109/tpami.2010.88. 17

[116] M. Talistu, T. S. Moh, and M. Moh, Gossip-based spectral clustering of distributed data streams, *International Conference on High Performance Computing Simulation (HPCS)*, pp. 325–333, July 2015. DOI: 10.1109/hpcsim.2015.7237058. 17

[117] R. Zeng and C. Tepedelenlioglu, Underlay cognitive multiuser diversity with random number of secondary users, *IEEE Transactions on Wireless Communications*, 13(10), pp. 5571–5581, October 2014. DOI: 10.1109/twc.2014.2340868. 17

[118] R. Zeng and C. Tepedelenlioglu, Fundamental BER performance trade-off in cooperative cognitive radio systems with random number of secondary users, *50th Asilomar Conference on Signals, Systems and Computers*, pp. 889–893, November 2016. DOI: 10.1109/acssc.2016.7869177.

[119] R. Zeng and C. Tepedelenlioglu, Fundamental performance trade-offs in cooperative cognitive radio systems, *IEEE Transactions on Cognitive Communications and Networking*, 3(2), pp. 169–179, June 2017. DOI: 10.1109/tccn.2017.2701814. 17

[120] B. Ribeiro and D. Towsley, Estimating and sampling graphs with multidimensional random walks, *Proc. of the 10th Annual Conference on Internet Measurement*, pp. 390–403, November 2010. DOI: 10.1145/1879141.1879192. 18

[121] C. Gkantsidis, M. Mihail, and A. Saberi, Random walks in peer-to-peer networks: Algorithms and evaluation, *Performance Evaluation*, 63, pp. 241–263, March 2006. DOI: 10.1016/j.peva.2005.01.002. 18

[122] R. Ali, S. Lor, and M. Rio, Two algorithms for network size estimation for master/slave ad hoc networks, *arXiv:0908*, 56, October 2009. DOI: 10.1109/ants.2009.5409896.

[123] D. Kostoulas, D. Psaltoulis, I. Gupta, K. Birman, and A. Demers, Active and passive techniques for group size estimation in large-scale and dynamic distributed systems, *Journal of Systems and Software*, 80, pp. 1639–1658, October 2007. DOI: 10.1016/j.jss.2007.01.014.

[124] K. Horowitz and D. Malkhi, Estimating network size from local information, *Information Processing Letters*, 88, pp. 237–243, December 2003. DOI: 10.1016/j.ipl.2003.08.011.

[125] S. Peng, S. Li, X. Liao, Y. Peng, and N. Xiao, Estimation of a population size in large-scale wireless sensor networks, *Journal of Computer Science and Technology*, 24, pp. 987–997, September 2009. DOI: 10.1007/s11390-009-9273-9. 18

[126] D. Saha and P. S. Das, Nabanita, *A Digital-Geometric Approach for Computing Area Coverage in Wireless Sensor Networks*, Lecture Notes in Computer Science, book series, Springer International Publishing Switzerland, 2014. DOI: 10.1007/978-3-319-04483-5_15. 18, 19

[127] E. Le Merrer, A.-M. Kermarrec, and L. Massoulie, Peer to peer size estimation in large and dynamic networks: A comparative study, *15th IEEE International Symposium on High Performance Distributed Computing*, pp. 7–17, 2006. DOI: 10.1109/hpdc.2006.1652131. 18

[128] D. Kostoulas, D. Psaltoulis, I. Gupta, K. Birman, and K. Demers, Decentralized schemes for size estimation in large and dynamic groups, *4th IEEE International Symposium on Network Computing and Applications*, pp. 41–48, July 2005. DOI: 10.1109/nca.2005.15. 18

[129] G. S. Manku, M. Bawa, and P. Raghavan, Symphony: Distributed hashing in a small world, *USITS'03 Proceedings of the 4th Conference on USENIX Symposium on Internet Technologies and Systems*, 2003. 18

[130] D. Varagnolo, G. Pillonetto, and L. Schenato, Distributed cardinality estimation in anonymous networks, *IEEE Transaction on Automatic Control*, 59(3), pp. 645–659, March 2014. DOI: 10.1109/tac.2013.2287113. 18

[131] D. Varagnolo, G. Pillonetto, and L. Schenato, Distributed statistical estimation of number of nodes in networks, *49th IEEE Conference on Decision and Control*, pp. 1498–1503, December 2010. DOI: 10.1109/cdc.2010.5717355. 18

[132] S. Kamath, D. Manjunath, and R. Mazumdar, On distributed function computation in structure-free random wireless networks, *IEEE Transactions on Information Theory*, 60(1), pp. 432–442, January 2014. DOI: 10.1109/tit.2013.2293214.

[133] H. Terelius, D. Varagnolo, and K. H. Johansson, Distributed size estimation of dynamic anonymous networks, *51st IEEE Conference on Decision and Control*, pp. 5221–5227, December 2012. DOI: 10.1109/cdc.2012.6425912. 18

[134] I. Shames, T. Charalambous, C. N. Hadjicostis, and M. Johansson, Distributed network size estimation and average degree estimation and control in networks isomorphic to directed graphs, *50th Annual Allerton Conference*, pp. 1885–1892, October 2012. DOI: 10.1109/allerton.2012.6483452. 18

[135] M. Jelasity and A. Montresor, Epidemic-style proactive aggregation in large overlay networks, *Proc. of the 24th International Conference on Distributed Computing Systems*, pp. 102–109, 2004. DOI: 10.1109/icdcs.2004.1281573. 18

[136] S. Zhang, *Consensus Algorithms and Distributed Structure Estimation in Wireless Sensor Networks*, Ph.D. Dissertation, Arizona State University, May 2017. 18, 39, 41

[137] S. Kundu and N. Das, In-network area estimation and localization in wireless sensor networks, *The 7th IEEE International Workshop on Heterogeneous, Multi-hop, Wireless and Mobile Networks*, pp. 431–435, 2012. DOI: 10.1109/glocomw.2012.6477611. 18, 19

[138] S. Li, H. Fan, and Y. Wang, Finding the smallest ellipse containing a point set based on genetic algorithms, *IEEE International Symposium on Knowledge Acquisition and Modeling Workshop*, pp. 693–696, December 2008. DOI: 10.1109/kamw.2008.4810584. 18, 19

[139] B. Greenstein, E. Kohler, D. Culler, and D. Estrin, Distributed techniques for area computation in sensor networks, *29th Annual IEEE International Conference on Local Computer Networks*, pp. 1–9, November 2004. DOI: 10.1109/lcn.2004.45. 18

[140] S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004. DOI: 10.1017/cbo9780511804441. 18, 19, 41

[141] S. Zhang, C. Tepedelenlioglu, M. Banavar, and A. Spanias, Distributed node counting in wireless sensor networks in the presence of communication noise, *IEEE Sensors Journal*, 17, pp. 1175–1186, February 2017. DOI: 10.1109/jsen.2016.2640943. 21, 23, 25

[142] S. Zhang, C. Tepedelenlioglu, M. Banavar, and A. Spanias, Distributed node counting in wireless sensor networks, *49th Asilomar Conference on Signals Systems and Computers*, November 2015. DOI: 10.1109/acssc.2015.7421147. 25

[143] S. Zhang, C. Tepedelenlioglu, J. Lee, H. Braun, and A. Spanias, Cramer-Rao bounds for distributed system size estimation using consensus algorithms, *Sensor Signal Processing for Defence*, pp. 1–5, Edinburgh, September 2016. DOI: 10.1109/sspd.2016.7590591. 21

[144] C. Bettstetter, On the minimum node degree and connectivity of a wireless multihop network, *Proc. of the 3rd ACM International Symposium on Mobile ad hoc Networking and Computing*, pp. 80–91, 2002. DOI: 10.1145/513800.513811. 29

[145] C. Bettstetter, J. Klinglmayr, and S. Lettner, On the degree distribution of k-connected random networks, *Proc. IEEE International Conference on Communications (ICC)*, pp. 1–6, May 2010. DOI: 10.1109/icc.2010.5502272. 29

[146] M. Newman, The structure and function of complex networks, *SIAM Review*, 45(2), pp. 167–256, January 2003. DOI: 10.1137/s003614450342480. 29, 32

[147] S. Zhang, J. Lee, C. Tepedelenlioglu, and A. Spanias, Distributed estimation of the degree distribution in wireless sensor networks, *IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, December 2016. DOI: 10.1109/glocom.2016.7841740. 29, 34

[148] S. Zhang, C. Tepedelenlioglu, and A. Spanias, Distributed center and coverage region estimation in wireless sensor networks using diffusion adaptation, *Asilomar Conference on Signals, Systems and Computers*, 2017 (accepted). 39

[149] S. Zhang, C. Tepedelenlioglu, and A. Spanias, Distributed network center and size estimation, *IEEE Sensors Journal*, 2017 (submitted). 39

[150] G. Montavon, G. B. Orr, and K. R. Muller, *Neural Networks: Tricks of the Trade*, Lecture Notes in Computer Science, book series, Springer Berlin Heidelberg, 2012. DOI: 10.1007/978-3-642-35289-8. 41

[151] J. Chen and A. H. Sayed, Diffusion adaptation strategies for distributed optimization and learning over networks, *IEEE Transactions on Signal Processing*, 60, pp. 4289–4305, August 2012. DOI: 10.1109/tsp.2012.2198470. 42, 43, 45

[152] A. Nemirovski, A. Juditsky, G. Lan, and A. Shapiro, Robust stochastic approximation approach to stochastic programming, *SIAM Journal of Optimization*, 19(4), pp. 1574–1609, January 2009. DOI: 10.1137/070704277. 45

[153] M. Xiang, L. Sun, and L. Li, Survey on the connectivity and coverage in wireless sensor networks, *7th International Conference on Wireless Communications, Networking and Mobile Computing*, pp. 1–4, September 2011. DOI: 10.1109/wicom.2011.6040351. 56

[154] G. Zhi-yan and W. Jian-zhen, Research on coverage and connectivity for heterogeneous wireless sensor network, *7th International Conference on Computer Science Education (ICCSE)*, pp. 1239–1242, July 2012. DOI: 10.1109/iccse.2012.6295289.

[155] W. Qihua, G. Ge, C. Lijie, and X. Xufeng, Voronoi coverage algorithm based on connectivity for wireless sensor networks, *34th Chinese Control Conference (CCC)*, pp. 7833–7837, July 2015. DOI: 10.1109/chicc.2015.7260884. 56

[156] Y. Zhou, A. Ortega, D. Wang, and S. Lee, Node clustering for data collection in wireless sensor networks using graph-transform and compressive sampling, *12th International Conference on Signal Processing (ICSP)*, pp. 2251–2256, October 2014. DOI: 10.1109/icosp.2014.7015395. 56

[157] R. Bhatt and R. Datta, Utilizing graph sampling and connected dominating set for backbone construction in wireless multimedia sensor networks, *20th National Conference on Communications (NCC)*, pp. 1–6, February 2014. DOI: 10.1109/ncc.2014.6811362.

[158] H. Zheng, F. Yang, X. Tian, X. Gan, X. Wang, and S. Xiao, Data gathering with compressive sensing in wireless sensor networks: A random walk based approach, *IEEE Transactions on Parallel and Distributed Systems*, 26(1), pp. 35–44, January 2015. DOI: 10.1109/tpds.2014.2308212. 56

[159] J. Zhou, L. Chen, C. L. P. Chen, Y. Wang, and H. X. Li, Uncertain data clustering in distributed peer-to-peer networks, *IEEE Transactions on Neural Networks and Learning Systems*, PP(99), pp. 1–15, 2017. DOI: 10.1109/tnnls.2017.2677093. 56

[160] J. Qin, W. Fu, H. Gao, and W. X. Zheng, Distributed k-means algorithm and fuzzy c-means algorithm for sensor networks based on multiagent consensus theory, *IEEE Transactions on Cybernetics*, 47(3), pp. 772–783, March 2017. DOI: 10.1109/tcyb.2016.2526683. 56

[161] M. A. Alsheikh, S. Lin, D. Niyato, and H. P. Tan, Machine learning in wireless sensor networks: Algorithms, strategies, and applications, *IEEE Communications Surveys Tutorials*, 16(4), pp. 1996–2018, 2014. DOI: 10.1109/comst.2014.2320099. 56

[162] T. Shafaat, A. Ghodsi, and S. Haridi, *A Practical Approach to Network Size Estimation for Structured Overlays*, Lecture Notes in Computer Science, book series (LNCS, volume 5343), 2008. DOI: 10.1007/978-3-540-92157-8_7.

[163] A. Forster and A. Murphy, *Machine Learning Across the WSN Layers* InTech, 2011. DOI: 10.5772/10516.

[164] Y. Zhang, N. Meratnia, and P. Havinga, Outlier detection techniques for wireless sensor networks: A survey, *IEEE Communications Surveys Tutorials*, 12(2), pp. 159–170, 2010. DOI: 10.1109/surv.2010.021510.00088.

[165] A. Wisler, V. Berisha, A. Spanias, and A. Hero, Direct estimation of density functionals using a polynomial basis, *IEEE Transactions on Signal Processing*, 66(3), pp. 558–572, 2017. DOI: 10.1109/TSP.2017.2775587.

[166] V. Berisha, A. Wisler, A. O. Hero, and A. Spanias, Empirically estimable classification bounds based on a nonparametric divergence measure, *IEEE Transactions on Signal Processing*, 64(3), pp. 580–591, February 2016. DOI: 10.1109/tsp.2015.2477805.

[167] A. Forster and A. L. Murphy, Clique: Role-free clustering with q-learning for wireless sensor networks, *29th IEEE International Conference on Distributed Computing Systems*, pp. 441–449, June 2009. DOI: 10.1109/icdcs.2009.43.

[168] M. Mihaylov, K. Tuyls, and A. Nowé, *Decentralized Learning in Wireless Sensor Networks*, pp. 60–73, Berlin, Heidelberg, Springer Berlin Heidelberg, 2010. DOI: 10.1007/978-3-642-11814-2_4. 56