

**Consensus-based Time Synchronization Algorithms for Wireless Sensor Networks with Topological Optimization Strategies for Performance Improvement**

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**Consensus-based Time Synchronization Algorithms for Wireless Sensor Networks with Topological Optimization Strategies for Performance Improvement**

*Report submitted in partial fulfillment of the requirements of the degree of*

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*in*

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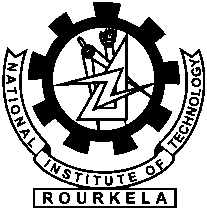
*by*

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*based on research carried out under the supervision of*

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This is to certify that the work presented in the dissertation entitled *Consensus-based Time Synchronization Algorithms for Wireless Sensor Networks with Topological Optimization Strategies for Performance Improvement* submitted by *Niranjan Panigrahi*, Roll Number 511CS110, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of *Doctor of Philosophy* in *Computer Science and Engineering*. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Pabitra Mohan Khilar

# Dedication

*Dedicated to My Family...*

# Declaration of Originality

I, *Niranjan Panigrahi*, Roll Number *511CS110* hereby declare that this dissertation entitled *Consensus-based Time Synchronization Algorithms for Wireless Sensor Networks with Topological Optimization Strategies for Performance Improvement* presents my original work carried out as a doctoral student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections

``Bibliography''. I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

NIT Rourkela *Niranjan Panigrahi*

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# Abstract

Wireless Sensor Networks (WSNs) have received considerable attention in recent years because of its broad area of applications. In the same breadth, it also faces many challenges. Time synchronization is one of those fundamental challenges faced by WSN being a distributed system. It is a service by which all nodes in the network will share a common notion of time. It is a prerequisite for correctness of other protocols and services like security, localization and tracking protocols. Several approaches have been proposed in the last decade for time synchronization in WSNs. The well-known methods are based on synchronizing to a reference (root) node's time by considering a hierarchical backbone for the network. However, this approach seems to be not purely distributed, higher accumulated synchronization error for the farthest node from the root and subjected to the root node failure problem. Recently, consensus based approaches are gaining popularity due its computational lightness, robustness, and distributed nature.

In this thesis, average consensus-based time synchronization algorithms are proposed, aiming to improve the performance metrics like number of iterations for convergence, total synchronization error, local synchronization error, message complexity, and scalability. Further, to cope up with energy constraint environment, Genetic algorithm based topological optimization strategies are proposed to minimize energy consumption and to accelerate the consensus convergence of the existing consensus-based time synchronization algorithms. All algorithms are analyzed mathematically and validated through simulation in MATLAB based PROWLER simulator.

Firstly, a distributed Selective Average Time Synchronization (SATS) algorithm is proposed based on average consensus theory. The algorithm is purely distributed (runs at each node), and each node exploits a selective averaging with the neighboring node having maximum clock difference. To identify the neighboring node with maximum clock difference, every node broadcasts a synchronization initiation message to the neighboring nodes at its local oscillation period and waits for a random interval to get the synchronization acknowledgment messages. After receiving acknowledgment messages, a node estimates relative clock value and sends an averaging message to the selected node. The iteration continues until all nodes reach an acceptable synchronization error bound. The optimal convergence of the proposed SATS algorithm is analyzed and validated through simulation and compared with some state-of-the-art, average consensus based time synchronization algorithms.

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Furthermore, it is observed that most of the consensus-based time synchronization algorithms are one-hop in nature, i.e., the algorithms iterate by averaging with one-hop neighbors' clock value. In a sparse network with a lower average degree of connectivity, these algorithms show poor performance. In order to have better convergence on the sparse network, a multi-hop SATS algorithm is proposed. The basic principle of multi-hop SATS algorithm remains same as that of SATS algorithm, i.e., performing selective averaging with the neighboring node, having maximum clock difference. But, in this case, the search for neighboring node goes beyond one hop. The major challenge lies in multi-hop search is the end-to-end delay which increases with the increase in hop count. So, to search a multi-hop neighboring node with maximum clock difference and with minimum and bounded end-to-end delay, a distributed, constraint-based dynamic programming approach is proposed for multi-hop SATS algorithm. The performance of the proposed multi-hop SATS algorithm is compared with some one-hop consensus time synchronization algorithms. Simulation results show notable improvement in terms of convergence speed, total synchronization error within a restricted hop count. The trade-off with the increase in number of hops is also studied.

The well-known consensus-based time synchronization algorithms are ``all node based'', i.e., every node iterates the algorithm to reach the synchronized state. This increases the overall message complexity and consumption of energy. Further, congestion in the network increases due to extensive synchronization message exchanges and induces the delay in the network. The delay induced in the message exchange is the main source of synchronization error and slows down the convergence speed to the synchronized (consensus) state. Hence, it is desirable that a subset of sensors along with a reasonable number of neighboring sensors should be selected in such a way that the resultant logical topology will accelerate the consensus algorithm with optimal message complexity and minimizes energy consumption. This problem is formulated as topological optimization problem which is claimed to be NP-complete in nature. Therefore, Genetic Algorithm (GA) based approaches are used to tackle this problem. Considering dense network topology, a single objective GA-based approach is proposed and considering sparse topology, a multi-objective Random Weighted GA based approach is proposed. Using the proposed topological optimization strategy, significant improvements are observed for consensus-based time synchronization algorithms in terms of average number of messages exchanged, energy consumption, and average mean square synchronization error.

###### Keywords: Wireless Sensor Network, Consensus Time Synchronization, Distributed Constraint Dynamic Programming, Topological Optimization, Genetic Algorithm, Random Weighted Genetic Algorithm

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# Bibliography

* + 1. B. Sundararaman, U. Buy, and A. D. Kshemkalyani, ``Clock synchronization for wireless sensor networks: a survey,'' *Ad Hoc Networks*, vol. 3, no. 3, pp. 281 – 323, 2005.
    2. D. L. Mills, ``Internet time synchronization: the network time protocol,'' *IEEE Transactions on Communications*, vol. 39, no. 10, pp. 1482–1493, Oct 1991.
    3. M. D. Lemmon, J. Ganguly, and L. Xia, ``Model-based clock synchronization in networks with drifting clocks,'' in *Proc. of Pacific Rim International Symposium on Dependable Computing*, 2000, pp. 177–184.
    4. K. lae Noh, E. Serpedin, and K. Qaraqe, ``A new approach for time synchronization in wireless sensor networks: Pairwise broadcast synchronization,'' *IEEE Transactions on Wireless Communications*, vol. 7, no. 9, pp. 3318–3322, Sept 2008.
    5. W. Sun, ``On clock synchronization in wireless networks using parameter estimation and consensus techniques,'' Ph.D. dissertation, Chalmers University of Technology, 2013.
    6. P. Kartaschoff, ``Synchronization in digital communications networks,'' *Proceedings of the IEEE*, vol. 79, no. 7, pp. 1019–1028, Jul 1991.
    7. I. K. Rhee, J. Lee, J. Kim, E. Serpedin, and Y. C. Wu, ``Clock synchronization in wireless sensor networks: An overview,'' *Sensors*, vol. 9, no. 1, p. 56, 2009. [Online]. Available: <http://www.mdpi.com/1424-8220/9/1/56>
    8. S. Youn, ``A comparison of clock synchronization in wireless sensor networks,'' *International Journal of Distributed Sensor Networks*, vol. 2013, no. 1, p. 10, 2013.
    9. A. R. Swain and R. Hansdah, ``A model for the classification and survey of clock synchronization protocols in wsns,'' *Ad Hoc Networks*, vol. 27, pp. 219 – 241, 2015. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1570870514002960>
    10. F. Sivrikaya and B. Yener, ``Time synchronization in sensor networks: a survey,'' *IEEE Network*, vol. 18, no. 4, pp. 45–50, July 2004.
    11. ``Microcontroller clock–rc oscillator, crystal or resonator,'' <http://www.hosonic.com/quartz> crystal clock oscillator.htm.
    12. J. Lichtenauer, J. Shen, M. Valstar, and M. Pantic, ``Cost-effective solution to synchronised audio-visual data capture using multiple sensors,'' *Image and Vision Computing*, vol. 29, no. 10, pp. 666 – 680, 2011. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0262885611000618>
    13. ``Tmotesky data sheet,'' [www.eecs.harvard.edu/](http://www.eecs.harvard.edu/) konrad/projects/tmote-sky-datasheet.pdf.
    14. Zheng and A. Jamalipour, *Wireless sensor network: A Networking Perspective*. Willey Publication, 2009.
    15. N. M. Freris, S. R. Graham, and P. R. Kumar, ``Fundamental limits on synchronizing clocks over networks,'' *IEEE Transactions On Automatic Control*, vol. 56, no. 6, pp. 1352–1364, June 2011.
    16. D. Djenouri, ``R4sync: Relative referenceless receiver/receiver time synchronization in wireless sensor networks,'' *IEEE Signal Processing Letters*, vol. 19, no. 4, pp. 175–178, April 2012.
    17. M. K. Maggs, S. G. Keefe, and D. V. Thiel, ``Consensus clock synchronization for wireless sensor networks,'' *IEEE Sensors Journal*, vol. 12, no. 6, pp. 2269–2277, June 2012.
    18. L. Schenato and F. Fiorentin, ``Average timesynch: A consensus-based protocol for clock synchronization in wireless sensor networks,'' *Automatica*, vol. 47, pp. 1878–1886, July 2011.
    19. J. He, P. Cheng, L. Shi, and J. Chen, ``Time synchronization in wsns: A maximum value based consensus approach,'' in *Proc. of 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC)*, 12-15 Dec 2011, pp. 7882–7887.
    20. J. Elson, L. Girod, and D. Estrin, ``Fine-grained network time synchronization using reference broadcasts,'' in *Proc. of 5th USENIX Symposium on Operating System Design and Implementation (OSDI'02)*, Dec 2002, pp. 147–163.
    21. S. Ganeriwal, R. Kumar, and M. Srivastava, ``Timing-sync protocol for sensor networks,'' in *Proc. of 1st ACM conference on embedded networked sensor systems*, 2003, pp. 138–149.
    22. J.Wu, L.Jiao, and R.Ding, ``Average time synchronization in wireless sensor networks using pairwise messages,'' *Computer Communications*, vol. 35, pp. 221–233, Jan 2012.
    23. Q. Li and D. Rus, ``Global clock synchronization in sensor networks,'' *IEEE Transactions on Computers*, vol. 55, no. 2, pp. 214– 226, Feb. 2006.
    24. L. Schenato and G. Gamba, ``A distributed consensus protocol for clock synchronization in wireless sensor network,'' in *Proc. of 46th IEEE Conference on Decision and Control*, 12-14 Dec. 2007, pp. 2289–2294.
    25. J. Chen, M. Yu, L. H. Dou, and M. G. Gan, ``A fast averaging synchronization algorithm for clock oscillators in nonlinear dynamical network with arbitrary time-delays,'' *Acta Automatica Sinica*, vol. 36, no. 6, pp. 873–880, June 2010.
    26. M. Franceschelli, A. Giua, and C. Seatzu, ``Distributed averaging in sensor networks based on broadcast gossip algorithms,'' *IEEE Sensors Journal*, vol. 11, no. 3, pp. 808–817, March 2011.
    27. T. Aysal, M. Yildiz, A. Sarwate, and A. Scaglione, ``Broadcast gossip algorithms for consensus,'' *IEEE Transactions on Signal Processing*, vol. 57, no. 7, pp. 2748–2761, July 2009.
    28. R. O. Saber and R. M. Murray, ``Consensus problems in networks of agents with switching topology and time-delays,'' *IEEE Transactions on Automatic Control*, vol. 49, no. 9, pp. 1520–1533, Sept 2004.
    29. C. Asensio-Marco and B. Beferull-Lozano, ``Network topology optimization for accelerating consensus algorithms under power constraints,'' in *Proc. of IEEE 8th International Conference on Distributed Computing in Sensor Systems*, May 2012, pp. 224–229.
    30. *Prowler Simulator*, [www.isis.vanderbilt.edu/projects/nest/prowler.](http://www.isis.vanderbilt.edu/projects/nest/prowler)
    31. M. Singhal and N. Shivaratri, *Advanced concepts in Opeating System*. TMH Publication, 2007.
    32. L. Lamport, ``Time, clocks, and the ordering of events in a distributed system,'' *Commun. ACM*, vol. 21, no. 7, pp. 558–565, Jul. 1978. [Online]. Available: <http://doi.acm.org/10.1145/359545.359563>
    33. C. Fidge, ``Logical time in distributed computing systems,'' *Computer*, vol. 24, no. 8, pp. 28–33, Aug 1991.
    34. F. Cristian, ``Probabilistic clock synchronization,'' *Distributed Computing*, vol. 3, no. 3, pp. 146–158, 1989. [Online]. Available: <http://dx.doi.org/10.1007/BF01784024>
    35. K. Arvind, ``Probabilistic clock synchronization in distributed systems,'' *IEEE Transactions on Parallel and Distributed Systems*, vol. 5, no. 5, pp. 474–487, 1994.
    36. M. Mock, R. Frings, E. Nett, and S. Trikaliotis, ``Continuous clock synchronization in wireless real-time applications,'' in *Proc. of 19th IEEE Symposium on Reliable Distributed Systems*, 2000, pp. 125–132.
    37. S.Ping, ``Delay measurement time synchronization for wireless sensor networks,'' 2003.
    38. K. Römer, ``Time synchronization in ad hoc networks,'' in *Proc. of 2nd ACM International Symposium on Mobile Ad Hoc Networking & Computing*, ser. MobiHoc '01. ACM, 2001, pp. 173–182. [Online].

Available: <http://doi.acm.org/10.1145/501436.501440>

* + 1. S. PalChaudhuri, A. Saha, and D. B. Johnson, ``Probabilistic clock synchronization service in sensor networks,'' *IEEE Transactions on Networking*, vol. 2, no. 2, pp. 177–189, 2003.
    2. W. Su and I. F. Akyildiz, ``Time-diffusion synchronization protocol for wireless sensor networks,''

*IEEE/ACM Trans. Netw.*, vol. 13, no. 2, pp. 384–397, Apr. 2005. [Online]. Available: http:

//dx.doi.org/10.1109/TNET.2004.842228

* + 1. M. L. Sichitiu and C. Veerarittiphan, ``Simple, accurate time synchronization for wireless sensor networks,'' in *Proc. of Wireless Communications and Networking, WCNC*, vol. 2, March 2003, pp. 1266–1273.
    2. K. L. Noh, Y. C. Wu, K. Qaraqe, and B. Suter, ``Extension of pairwise broadcasting clock synchronization for multi-cluster sensor networks,'' *EURASIP J. Adv. Signal Process*, vol. 2008, pp. 71:1–71:10, Jan. 2008.
    3. K. Cheng, K. S. Lui, Y. C. Wu, and V. Tam, ``A distributed multihop time synchronization protocol for wireless sensor networks using pairwise broadcast synchronization,'' *IEEE Transaction on wireless communications*, vol. 8, no. 4, pp. 1764–1772, April 2009.
    4. M. Maróti, B. Kusy, G. Simon, and A. Lédeczi, ``The flooding time synchronization protocol,'' in *Proc. of 2nd International Conference on Embedded Networked Sensor Systems*, ser. SenSys '04, 2004, pp. 39–49. [Online]. Available: <http://doi.acm.org/10.1145/1031495.1031501>
    5. G. Qi, P. Song, K. Li, and C. Chen, ``One improved time synchronization based on ant colony optimization and tpsn mechanism,'' in *Proc. of International Conference on Networking, Sensing and Control (ICNSC), 2010*, April 2010, pp. 223–227.
    6. L. Liu, Y. Xiao, and J. Zhang, ``A bio-inspired time synchronization algorithm for wireless sensor networks,'' in *Proc. of 2nd International Conference on Computer Engineering and Technology (ICCET),*, vol. 4, April 2010, pp. V4–306–V4–311.
    7. Y. P. Tian, ``Lsts: A new time synchronization protocol for networks with random communication delays,'' in *Proc. of 54th IEEE Conference on Decision and Control (CDC)*, Dec 2015, pp. 7404–7409.
    8. J. S. Kim, J. Lee, E. Serpedin, and K. Qaraqe, ``A robust clock synchronization algorithm for wireless sensor networks,'' in *Proc. of IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, May 2011, pp. 3512–3515.
    9. J. Li and A. Nehorai, ``Joint sequential target estimation and clock synchronization in wireless sensor networks,'' *IEEE Transactions on Signal and Information Processing over Networks*, vol. 1, no. 2, pp. 74–88, June 2015.
    10. Q. Liu, X. Liu, J. L. Zhou, G. Zhou, G. Jin, Q. Sun, and M. Xi, ``Adasynch: A general adaptive clock synchronization scheme based on kalman filter for wsns,'' *Wireless Personal Communications*, vol. 63, no. 1, pp. 217–239, 2012. [Online]. Available: <http://dx.doi.org/10.1007/s11277-010-0116-3>
    11. X. Li, M. Xi, Y. Cao, and J. Yuan, ``A general clock synchronization method based on kalman filter model in wireless sensor networks,'' in *Proc. of 2nd International Conference on Consumer Electronics, Communications and Networks (CECNet)*, April 2012, pp. 2277–2280.
    12. B. R. Hamilton, X. Ma, Q. Zhao, and J. Xu, ``Aces: Adaptive clock estimation and synchronization using kalman filtering,'' in *Proc. of 14th ACM International Conference on Mobile Computing and Networking*, ser. MobiCom '08, 2008, pp. 152–162. [Online]. Available: <http://doi.acm.org/10.1145/1409944.1409963>
    13. L. Ma, H. Zhu, G. Nallamothu, B. Ryu, and Z. Zhang, ``Impact of linear regression on time synchronization accuracy and energy consumption for wireless sensor networks,'' in *Proc. of IEEE Military Communications Conference*, Nov 2008, pp. 1–7.
    14. K. Huang and D. Lee, ``Consensus-based peer-to-peer control architecture for multiuser haptic interaction over the internet,'' *IEEE Transactions on Robotics*, vol. 29, no. 2, pp. 417–431, April 2013.
    15. Z. Wang, M. M. Hayat, M. Rahnamay-Naeini, Y. Mostofi, and J. E. Pezoa, ``Consensus-based estimation protocol for decentralized dynamic load balancing over partially connected networks,'' in *Proc. of 50th IEEE Conference on Decision and Control and European Control Conference*, Dec 2011, pp. 4572–4579.
    16. J. Zhou, *First International Conference on Complex Science, Shanghai, China, February 23-25, 2009*, ser. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering. Springer Berlin Heidelberg, 2009. [Online]. Available: https://books.google.co.in/books?id=9ScGkMmyp8QC
    17. J. Wu, L. Zhang, Y. Bai, and Y. Sun, ``Cluster-based consensus time synchronization for wireless sensor networks,'' *IEEE Sensors Journal*, vol. 15, no. 3, pp. 1404–1413, March 2015.
    18. D. Djenouri, N. Merabtine, F. Z. Mekahlia, and M. Doudou, ``Fast distributed multi-hop relative time synchronization protocol and estimators for wireless sensor networks,'' *Ad Hoc Netw.*, vol. 11, no. 8, pp. 2329–2344, Nov. 2013. [Online]. Available: <http://dx.doi.org/10.1016/j.adhoc.2013.06.001>
    19. J. He, P. Cheng, L. Shi, J. Chen, and Y. Sun, ``Time synchronization in wsns: A maximum-value-based consensus approach,'' *IEEE Transactions on Automatic Control*, vol. 59, no. 3, pp. 660–675, March 2014.
    20. J. He, J. Chen, P. Cheng, and X. Cao, ``Secure time synchronization in wireless sensor networks: A maximum consensus-based approach,'' *IEEE Transactions on Parallel and Distributed Systems*, vol. 25, no. 4, pp. 1055–1065, April 2014.
    21. J. He, P. Cheng, J. Chen, L. Shi, and R. Lu, ``Time synchronization for random mobile sensor networks,''

*IEEE Transactions on Vehicular Technology*, vol. 63, no. 8, pp. 3935–3946, Oct 2014.

* + 1. J. He, P. Cheng, L. Shi, and J. Chen, ``Sats: Secure average-consensus-based time synchronization in wireless sensor networks,'' *IEEE Transactions on Signal Processing*, vol. 61, no. 24, pp. 6387–6400, Dec 2013.
    2. B. J. Choi, H. Liang, X. Shen, and W. Zhuang, ``Dcs: Distributed asynchronous clock synchronization in delay tolerant networkd,'' *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 3, pp. 491–504, March 2012.
    3. G. Zhou, T. He, S. Krishnamurthy, and J. A. Stankovic, ``Models and solutions for radio irregularity in wireless sensor networks,'' *ACM Trans. Sen. Netw.*, vol. 2, no. 2, pp. 221–262, May 2006. [Online].

Available: <http://doi.acm.org/10.1145/1149283.1149287>

* + 1. D. Ustebay, B. N. Oreshkin, M. J. Coates, and M. G. Rabbat, ``Greedy gossip with eavesdropping,''

*IEEE Transactions on Signal Processing*, vol. 58, no. 7, pp. 3765–3776, July 2010.

* + 1. G. Xiong and S. Kishore, ``Analysis of distributed consensus time synchronization with gaussian delay over wireless sensor networks,'' *EURASIP Journal on Wireless Communications and Networking*, vol. 2009, 2009.
    2. L. Yong and G. Lixin, ``On the placement of clock reference nodes for time synchronization in sensor networks,'' rio.ecs.umass.edu, Tech. Rep.
    3. S. Boyd and L. Vandenberghe, *Convex Optimization*. New York, NY, USA: Cambridge University Press, 2004.
    4. J. Liu, A. S. Morse, B. D. O. Anderson, and C. Yu, ``Contractions for consensus processes,'' in *Proc. of 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC)*, Orlando, FL, USA, Dec. 12-15 2011, pp. 1974–1979.
    5. A. Nedic and D. Bertsekas, ``Incremental sub-gradient methods for non differentiable optimization,''

*SIAM Journal on Optimization.*, vol. 12, no. 1, pp. 109–138, 2001.

* + 1. *Matrix Reference Manual*, [http://www.ee.ic.ac.uk/hp/staff/dmb/matrix.](http://www.ee.ic.ac.uk/hp/staff/dmb/matrix)
    2. G. Chartrand and O. R. Oellermann, *Applied and algorithmic graph theory*. McGraw-Hill, 1993.
    3. J. Wang, S. Zhang, D. Gao, and Y. Wang, ``Two-hop time synchronization protocol for sensor networks,'' *EURASIP Journal on Wireless Communications and Networking*, vol. 2014, no. 1, pp. 1–10, 2014. [Online]. Available: <http://dx.doi.org/10.1186/1687-1499-2014-39>
    4. T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algorithms*, 3rd ed. MIT Press and McGraw-Hill, 2009.
    5. J. K. Antonio, G. M. Huang, and W. K. Tsai, ``A fast distributed shortest path algorithm for a class of hierarchically clustered data networks,'' *IEEE Transactions on Computers*, vol. 41, no. 6, pp. 710–724, Jun 1992.
    6. S. Manfredi, ``A theoretical analysis of multi-hop consensus algorithms for wireless networks: Trade off among reliability, responsiveness and delay tolerance,'' *Ad Hoc Networks*, vol. 13, Part A, pp. 234 – 244, 2014. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1570870511001004>
    7. T. Ratnaparkhe, S. Natekar, S. Chandan, and V. P. Sadaphal, ``Selection of time synchronizing nodes in wireless sensor network,'' in *Proc. of Communication Systems and Networks (COMSNETS)*, Jan 2010, pp. 1–8.
    8. Y. Zou and K. Chakrabarty, ``A distributed coverage and connectivity-centric technique for selecting active nodes in wireless sensor networks,'' *IEEE Transactions on Computers*, vol. 54, no. 8, pp. 978–991, Aug 2005.
    9. H. Zhou, T. Liang, C. Xu, and J. Xie, ``Multiobjective coverage control strategy for energy-efficient wireless sensor networks,'' *International Journal of Distributed Sensor Networks*, vol. 2012, pp. 1–10, 2012.
    10. Y. K. Park, M. G. Lee, K. K. Jung, J. J. Yoo, S. H. Lee, and H. S. Kim, ``Optimum sensor nodes deployment using fuzzy c-means algorithm,'' in *Proc. of International Symposium on Computer Science and Society (ISCCS)*, July 2011, pp. 389–392.
    11. J. Ryu, J. Yu, E. Noel, and K. W. Tang, ``Borel cayley graph-based topology control for consensus protocol in wireless sensor networks,'' *ISRN Sensor Networks*, vol. 2013, pp. 1–15, 2013.
    12. S. Chu, P. Wei, X. Zhong, X. Wang, and Y. Zhou, ``Deployment of a connected reinforced backbone network with a limited number of backbone nodes,'' *IEEE Transactions on Mobile Computing*, vol. 12, no. 6, pp. 1188–1200, June 2013.
    13. J. He, S. Ji, Y. Pan, and Z. Cai, ``Approximation algorithms for load-balanced virtual backbone construction in wireless sensor networks,'' *Theoretical Computer Science*, vol. 507, no. 0, pp. 2–16, 2013.
    14. J. He, S. Ji, M. Yan, Y. Pan, and Y. Li, ``Genetic-algorithm-based construction of load-balanced cdss in wireless sensor networks,'' in *Proc. of MILITARY COMMUNICATIONS CONFERENCE*, Nov 2011, pp. 667–672.
    15. D. Manohari and G. S. A. Mala, ``An evolutionary algorithmic approach to construct connected dominating set in manets,'' in *Proc. of International Conference on Software Engineering and Mobile Application Modelling and Development (ICSEMA)*, Dec 2012, pp. 1–6.
    16. F. Nawab, K. Jamshaid, B. Shihada, and P. H. Ho, ``Fair packet scheduling in wireless mesh networks,''

*Ad Hoc Networks*, vol. 13, Part B, no. 0, pp. 414 – 427, 2014.

* + 1. A. Konak, D. W. Coit, and A. E. Smith, ``Multi-objective optimization using genetic algorithms: A tutorial,'' *Reliability Engineering and System Safety*, vol. 91, no. 9, pp. 992 – 1007, 2006, special Issue

- Genetic Algorithms and Reliability.

* + 1. T. Murata and H. Ishibuchi, ``Moga: multi-objective genetic algorithms,'' in *Proc. of IEEE International Conference on Evolutionary Computation*, vol. 1, Nov 1995, pp. 289–294.
    2. J. Yu, N. Wang, G. Wang, and D. Yu, ``Connected dominating sets in wireless ad hoc and sensor networks
       - a comprehensive survey,'' *Computer Communications*, vol. 36, no. 2, pp. 121 – 134, 2013.
    3. A. Potluri and A. Singh, ``Metaheuristic algorithms for computing capacitated dominating set with uniform and variable capacities,'' *Swarm and Evolutionary Computation*, vol. 13, pp. 22 – 33, 2013.
    4. A. Mahapatro and P. M. Khilar, ``Detection and diagnosis of node failure in wireless sensor networks: A multiobjective optimization approach,'' *Swarm and Evolutionary Computation*, vol. 13, pp. 74 – 84, 2013.
    5. S. H. Lee and L. Choi, ``Chaining clock synchronization: an energy-efficient clock synchronization scheme for wireless sensor networks,'' in *Proc. of 10th International Symposium on Pervasive Systems, Algorithms, and Networks(ISPAN'09)*, 2009, pp. 171–177.
    6. M. Mock, R. Frings, E. Nett, and S. Trikaliotis, ``Continuous clock synchronization in wireless real-time application,'' in *Proc. of 19th IEEE Symposium on Reliable Distributed Systems (SRDS-00)*, Oct. 2000, pp. 125–133.
    7. S. Ahmed, F. Xiao, and T. Chen, ``Asynchronous consensus-based time synchronisation in wireless sensor networks using unreliable communication links,'' *IET Control Theory Applications*, vol. 8, no. 12, pp. 1083–1090, August 2014.
    8. C. Li, Y. Wang, and M. Hurfin, ``Clock synchronization in mobile ad hoc networks based on an iterative approximate byzantine consensus protocol,'' in *Proc. of IEEE 28th International Conference on Advanced Information Networking and Applications*, May 2014, pp. 210–217.
    9. H. Cheng, S. Yang, and J. Cao, ``Dynamic genetic algorithms for the dynamic load balanced clustering problem in mobile ad hoc networks,'' *Expert Systems with Applications*, vol. 40, pp. 1381 – 1392, 2013.
    10. S. Manfredi, ``Design of a multi-hop dynamic consensus algorithm over wireless sensor networks,'' *Control Engineering Practice*, vol. 21, no. 4, pp. 381 – 394, 2013. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0967066112002559>
    11. N. Panigrahi and P. M. Khilar, ``Optimal consensus-based clock synchronisation algorithm in wireless sensor network by selective averaging,'' *IET Wireless Sensor Systems*, vol. 5, no. 3, pp. 166–174, 2015.
    12. ——, ``Optimal topological balancing strategy for performance optimisation of consensus-based clock synchronisation protocols in wireless sensor networks: a genetic algorithm-based approach,'' *IET Wireless Sensor Systems*, vol. 4, no. 4, pp. 213–222, 2014.
    13. C. Kahraman, *Computational Intelligence Systems in Industrial Engineering: With Recent Theory and Applications*, ser. Atlantis Computational Intelligence Systems. Atlantis Press, 2012. [Online].

Available: https://books.google.co.in/books?id=RZZGIp7VGCIC

* + 1. G. Werner-Allen, G. Tewari, A. Patel, M. Welsh, and R. Nagpal, ``Firefly-inspired sensor network synchronicity with realistic radio effects,'' in *Proc. of 3rd International Conference on Embedded Networked Sensor Systems*, ser. SenSys '05, 2005, pp. 142–153. [Online]. Available: <http://doi.acm.org/10.1145/1098918.1098934>
    2. P. Sommer and R. Wattenhofer, ``Gradient clock synchronization in wireless sensor networks,'' in *Proc. of International Conference on Information Processing in Sensor Networks*, April 2009, pp. 37–48.
    3. F. Fagnani and S. Zampieri, ``Randomized consensus algorithms over large scale networks,'' *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 4, pp. 634–649, May 2008.
    4. A. Marco, R. Casas, J. L. S. Ramos, V. Coarasa, A. Asensio, and M. S. Obaidat, ``Synchronization of multihop wireless sensor networks at the application layer,'' *IEEE Wireless Communications*, vol. 18, no. 1, pp. 82–88, February 2011.
    5. J. Liu, Z. Zhou, Z. Peng, J. H. Cui, M. Zuba, and L. Fiondella, ``Mobi-sync: Efficient time synchronization for mobile underwater sensor networks,'' *IEEE Transactions on Parallel and Distributed Systems*, vol. 24, no. 2, pp. 406–416, Feb 2013.
    6. L. Paladina, A. Biundo, M. Scarpa, and A. Puliafito, ``Self organizing maps for synchronization in wireless sensor networks,'' in *Proc. of Conference on New Technologies, Mobility and Security*, Nov 2008, pp. 1–6.
    7. I. Shames and A. N. Bishop, ``Relative clock synchronization in wireless networks,'' *IEEE Communications Letters*, vol. 14, no. 4, pp. 348–350, April 2010.
    8. L. M. He, ``Time synchronization based on spanning tree for wireless sensor networks,'' in *Proc. of 4th International Conference on Wireless Communications, Networking and Mobile Computing*, Oct 2008, pp. 1–4.
    9. B. M. Sadler, ``Local and broadcast clock synchronization in a sensor node,'' *IEEE Signal Processing Letters*, vol. 13, no. 1, pp. 9–12, Jan 2006.
    10. Y. Wang, J. Huang, L. Yang, and Y. Xue, ``Toa-based joint synchronization and source localization with random errors in sensor positions and sensor clock biases,'' *Ad Hoc Netw.*, vol. 27, no. C, pp. 99–111, Apr. 2015. [Online]. Available: <http://dx.doi.org/10.1016/j.adhoc.2014.12.001>
    11. K. L. Noh, Q. M. Chaudhari, E. Serpedin, and B. W. Suter, ``Novel clock phase offset and skew estimation using two-way timing message exchanges for wireless sensor networks,'' *IEEE Transactions on Communications*, vol. 55, no. 4, pp. 766–777, April 2007.
    12. M. Leng and Y. C. Wu, ``On clock synchronization algorithms for wireless sensor networks under unknown delay,'' *IEEE Transactions on Vehicular Technology*, vol. 59, no. 1, pp. 182–190, Jan 2010.
    13. P.-H. Huang, M. Desai, X. Qiu, and B. Krishnamachari, ``On the multihop performance of synchronization mechanisms in high propagation delay networks,'' *IEEE Transactions on Computers*, vol. 58, no. 5, pp. 577–590, 2009.
    14. A. R. Swain and R. C. Hansdah, ``An energy efficient and fault-tolerant clock synchronization protocol for wireless sensor networks,'' in *Proc. of 2nd International Conference on COMmunication Systems and NETworks (COMSNETS 2010)*, Jan 2010, pp. 1–10.
    15. N. Panigrahi and P. M. Khilar, ``An evolutionary based topological optimization strategy for consensus based clock synchronization protocols in wireless sensor network,'' *Swarm and Evolutionary Computation*, vol. 22, pp. 66 – 85, 2015. [Online]. Available: <http://www.sciencedirect.com/science/> article/pii/S2210650215000164
    16. M. Akhlaq and T. R. Sheltami, ``Rtsp: An accurate and energy-efficient protocol for clock synchronization in wsns,'' *IEEE Transactions on Instrumentation and Measurement*, vol. 62, no. 3, pp. 578–589, March 2013.
    17. S. Ganguly, N. Sahoo, and D. Das, ``Multi-objective planning of electrical distribution systems using dynamic programming,'' *International Journal of Electrical Power and Energy Systems*, vol. 46, pp. 65
        - 78, 2013. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0142061512005935>
    18. J. Wu, S. Ren, Y. Jiang, and L. Song, ``Qos-aware multihop routing in wireless sensor networks with power control using demodulation-and-forward protocol,'' *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, no. 1, pp. 1–9, 2012.
    19. Y. Wang, M. Z. Bocus, and J. P. Coon, ``Dynamic programming for route selection in multihop fixed gain amplify-and-forward relay networks,'' *IEEE Communications Letters*, vol. 17, no. 5, pp. 932–935, May 2013.
    20. J. Zhang, X. Jia, and G. Xing, ``Real-time data aggregation in contention-based wireless sensor networks,'' *ACM Trans. Sen. Netw.*, vol. 7, no. 1, pp. 2:1–2:25, Aug. 2010.
    21. J. He, H. Li, J. Chen, and P. Cheng, ``Study of consensus-based time synchronization in wireless sensor networks,'' *ISA Transactions*, vol. 53, no. 2, pp. 347 – 357, 2014. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0019057813001900>
    22. F. Wang, X. Wu, Y. Pang, C. Yu, Y. Hu, and X. Liu, ``A time synchronization method of wireless sensor networks based on the simulated annealing algorithm,'' in *Proc. of 26th Chinese Control and Decision Conference (CCDC)*, May 2014, pp. 870–87