Chapter 7

Conclusion and Future Work

This chapter highlights major contributions of the research. Next, some of the opportunities for future work are presented.

7.1 Summary of Contributions

The main components and contributions of research presented in the thesis are summarized below:


The versatile applications of WSN require protocols that: are energy efficient; avoid collisions; are scalable; are adaptive to changes in traffic, network conditions, and network densities. However, with the emerging WSN applications like Internet of Things (Jayavardhana et al.), conventional performance metrics like fairness, latency, throughput, bandwidth utilization, and reliable data delivery become equally important. SOFLEE offers multiple needs of modern WSN applications like: energy efficiency; fair media access; reliable data delivery; low data latency; adaptation to dynamic traffic patterns of application; robustness; scalability; and simplicity. In doing so, it also respects the severe energy and memory constraints of sensor nodes. A comparative analysis of SOFLEE with FlexiTP (Lee, Datta, and Oliver), SOTP (Wang et al.), EEFF (Tao et al.), and D-MAC (Lu, Krishnamachari, and Raghavendra) shows that SOFLEE is up to 39 % more energy efficient; has up to 34 % more network lifetime; has 3 % more...
goodput; has up to 35% less latency; and receives up to 21% more data at MS compared to FlexiTP (Lee, Datta, and Oliver). Experimental results agree with those obtained from simulations. SOFLEE achieves its noteworthy features as discussed below:

- Energy efficiency by: (i) using TDMA based MAC that combines routing information during time slot allocation for uninterrupted data forwarding; (ii) techniques for hop by hop congestion control.
- Fairness by using TDMA with slot allocation by Master Station (MS).
- Reliable data delivery by: (i) using TDMA for media access to minimize transceiver interference and assure a communication path; (ii) node deciding to participate in routing only if it is located towards MS; has sufficient energy; less traffic load; and good communication link quality.
- Reduced data latency by: (i) strategic back off (to avoid collision during slot requests) and backward scheduling (nodes far from MS are given an early slot position in data transfer frame); (ii) spatial reuse (MS allocates same slot to nodes that are outside the interference range of each other).
- SOFLEE adapts to dynamic traffic pattern by providing flexibility in data transmission wherein non-holder of a slot can use the slot when holder does not have data to send. Thus, node can transmit data as soon as the channel is available to achieve high channel utilization; lower data latency; and adapt to application traffic pattern.
- Robustness by local repair techniques to recover from node and link failures.
- Scalability by: (i) multihop network architecture; (ii) distributing transit traffic along multihop path towards MS; (iii) spatial reuse.

Publications related to simulation and experimentation work embodied in Chapter 3:


The key design problems of hierarchical clustering in WSN are: (i) suitable selection of cluster heads; (ii) cluster organization; (iii) energy efficient and reliable intra cluster communication; (iv) routing data packets to MS; (iv) avoiding hot spots problem. LEFUCMA is designed and optimized to solve all the problems of hierarchical clustering and offer maximum communication performance with minimum energy expenditure. A comparative analysis of LEFUCMA with UHEED (Enver et al.), EADUC (Jiguo et al., “An Energy Aware Distributed Unequal Clustering Protocol for Wireless Sensor Networks”), COCA (Li et al., “COCA: Constructing Optimal Clustering Architecture to Maximize Sensor Network Lifetime”), and EAUCF (Bagci and Yazici) shows that, LEFUCMA is up to 56 % more energy efficient; has up to 78 % more network lifetime; has 28 % more goodput; receives up to 56 % more data at MS; and has up to 30 % more throughput compared to EAUCF. LEFUCMA achieves its noteworthy features as discussed below:

- Selection of cluster head to ensure energy efficiency and transmission reliability by: fuzzy based cluster head selection algorithm that selects cluster heads that are, (i) near the MS (to ensure minimum energy for transmission to MS); (ii) having more residual energy (to balance energy consumption of the network), number of neighbour (to ensure minimum energy for intra
cluster communication), and packet reception rate (to ensure transmission reliability).

- Energy efficient cluster organization by: fuzzy based algorithm to decide number of cluster heads in a given area based on node density and distance of cluster from MS.

- Energy efficient intra cluster communication by use of TDMA which rules out intra cluster collision.

- Energy efficient routing of data packets to MS by selecting next hop cluster head considering: (i) its residual energy (to evenly distribute energy consumption among cluster heads); (ii) distance from MS and from current cluster head (represents energy required for communication); (iii) number of cluster members (represents intra cluster traffic); and (iv) number of descendant nodes (represents inter cluster traffic).

- Avoiding hot spots problem by partitioning nodes into clusters of unequal size, with clusters closer to MS having smaller sizes than those farther away from MS.

Publication details related to work embodied in Chapter 4:


FAMACROW is another protocol designed to solve the problems of hierarchical clustering with minimal energy expenditure. A comparative analysis of FAMACROW with UCR [Guihai et al.], ULCA [Zhao and Wang], EAUCF
(Bagci and Yazici), and IFUC (Song et al.) shows that FAMACROW is up to 41 % more energy efficient, has up to 63 % more network lifetime; has 14 % more goodput; receives up to 95 % more data at MS and has up to 15 % more throughput compared to IFUC. FAMACROW achieves its noteworthy features as discussed below:

- Selection of cluster head to ensure energy efficiency and transmission reliability by fuzzy based cluster head selection algorithm that selects cluster heads having: more residual energy (to balance energy consumption of the network); more number of neighbour (to ensure minimum energy for intra cluster communication); and good quality of communication link with neighbour (to ensure transmission reliability).

- Energy efficient intra cluster communication by use of TDMA which rules out intra cluster collision.

- Energy efficient and reliable routing of data packets to MS by use of ACO based inter cluster routing that selects relay cluster head based on: (i) its distance from current cluster head and that from MS (for energy efficient inter cluster communication); (ii) residual energy (for energy distribution across the network); (iii) queue length (for congestion control) and packet reception rate (for reliable communication).

- Avoiding hot spots problem by partitioning nodes into clusters of unequal size, with clusters closer to MS having smaller sizes than those farther away from MS.

Publication details related to work embodied in Chapter 5:


Fuzzy Cross (FUCR) is cross layer decision making and information sharing architecture that assists the protocols to achieve energy efficiency, communication reliability, and low data latency. Following are the salient features of FUCR:

- Extends cross layering mechanism to physical, data link, network, and application layer to collect vital information of the node.
- The vital information collected is used by fuzzy agent to run fuzzy logic and suggest changes in parameters for protocols running at different layers.
- Protocol at each layer uses its local information, neighbourhood information, and information from fuzzy agent to achieve energy efficiency, communication reliability, and low data latency.
- Is a simple, generic, extensible, flexible, portable, stable architecture compatible with existing layered architecture like OSI (Zimmermann).
- It supports WSN and ad hoc networks working with existing and futuristic layered and cross layered protocols.

A comparative analysis of FUCR; ZigBee with integrated ADAPT (Mario et al.); and standard ZigBee (ZigBee-Alliance) without any modifications shows that FUCR is up to 12% energy efficient; has up to 19% less data latency; and has up to 12% more delivery ratio for a single hop network compared to ADAPT. Similar trend is seen for multihop network and for a wide range of operating conditions. Preliminary experimental results agree with those obtained from simulations.

Publication related to simulation work embodied in Chapter 6.
7.2 Directions for Future Work

In the course of this research and on consideration of the presented results, several prospects for future work and some issues that may be subject for further study are evident. A few of the directions for future work are discussed below:

1. The next important step is implementing all the proposed protocols and the architecture in a sensor network operating system like TinyOS (Levis) to further evaluate their performance in a real world operating system framework.

2. The proposed protocols can be experimented with real world applications like: (i) ”Low Frequency Array Agro Project” (Baggio) that requires periodic measurements and (ii) ”A line in the Sand” (Arora et al.) that requires event detection. Experiment will reflect to what extent the proposed protocols are suitable to the variety of hardware technologies available in the market. It will also check whether they are able to meet the various requirements of sensor network application (both periodic and event detection).

3. An energy efficient and simple clock synchronization technique that can be easily interlaced with the proposed protocol operations can be developed. Similarly an appropriate data aggregation technique can also be developed.

4. Implementing LEFUCMA and FAMACROW on a testbed of nodes will help to demonstrate their real world feasibility, verify their simulations results and increase confidence in existing work.

5. Experimentation of FUCR is limited to finding the average energy consumed in the network. More experiments can be performed to include the parameters tested in simulations.
6. SOFLEE can be implemented with FUCR and the intuition is that SOFLEE with FUCR will show better performance compared to SOFLEE without FUCR. For example, FUCR variable PRE can be used as one of the parameters for parenthood willingness condition of SOFLEE; BOT can be used for collision avoidance during slot requests; and TXP can be used to set transmission power to transmit SCHEDULE_MESSAGE to the neighbouring node.

7.3 Epilogue

Nevertheless, independent of the direction of sensor network research, it can be concluded from the research presented in the thesis that: with low cost, resource constrained nodes; and unreliable transmission media, cross layering will help WSN protocol developers to get closer to the goal of “anytime and anywhere” communication among and between, users and objects around them.