Tree-Based Approaches for Improving Energy Efficiency and Life Time of Wireless Sensor Networks (WSN): A Survey and Future Scope for Research

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Abstract Wireless Sensor Networks (WSN) are characterized by highly application-specific nature, stringent resource constraints, self-organizing, spatio-temporal traffic, and large dynamic topology with several contradicting design goals. Of these design goals, network life time and energy efficiency are considered as of paramount importance. Many research works from the past have dedicated themselves in extending the network life time and achieving energy efficiency of WSN through various techniques, including that of the application of Tree as a data structure. This article attempts to present a detailed survey of the existing research works with the application of different variants of Trees. Further, the paper tries to analyze the performance implications of application of variants of trees, advantages, and disadvantages. The paper mentions possible feasibility of the application of Red Black Trees (RBL) in WSN and the potentials for future research while giving algorithmic comparison of RBL with other tree data structures.

Keywords Wireless sensor network · Tree-based approaches · Red black tree · Network life time · Energy efficiency

1 Introduction

A wireless sensor network is constituted of large number of sensor nodes deployed randomly around phenomenon of interest Some important applications of WSN are: home automation, industrial applications, monitoring applications for environment, traffic, & wildlife, health care applications, defence applications involving security & surveillance, and some special research applications like study of sand bar formations

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or related to oceanography, etc. Due to these wide varying applications WSN are evolving as a new paradigm for information processing [1, 2]. Although WSN are similar to Adhoc Networks, there are number of fine differences. Some important differences between WSN and Adhoc network are: the number of sensor nodes in a sensor network will be large, densely deployed, prone to variety of frequent failures, the topology of a sensor network changes very frequently, and have stringent constraints for various resources. In this regard, a novel architecture & design of WSN, its protocol stack, layer-wise open issues have been discussed in detail, along with description of some of the existing WSN specific protocols as solutions to some of the open issues, in [1]. The need for self-organization and some solutions for the same have been presented elaborately in [3]. Thus, with the above general background about WSN, the motivation of this paper is to attempt to present a detailed survey of the various existing works which proposed application of Tree as a data structures and Chain concept from discrete mathematics for achieving energy efficiency and extended the network life time. Further, the organization of this paper is as follows: Sect. 2 presents the detailed literature survey of research works, the implications of application of tree data structures on the overall performance of WSN is analyzed in Sect. 3 and Sect. 3.4 identifies the potentials for application of Red Black Trees, and the paper will be concluded in Sect. 4 mentioning the scope for future research using Red Black trees.

2 Literature Survey

Wendi et al. have proposed a work involving clustering for energy-efficient communication resulting in seven times efficiency in energy [4]. Huang et al. proposed an energy-efficient routing scheme for WSN based on clustering with the use of minimum spanning trees degree constrained (CMST-DC) [5]. Z. Han et al. proposed an efficient routing by constructing routing tree (GSTEB) and mention about achieving increase in life time anywhere in between 100 and 300% depending on various scenarios while comparing with PEDAP [6]. Weighted Spanning Tree variant of LEACH (WST-LEACH) was proposed in [7] and authors claim that it performs better than LEACH. Geographic and Energy Aware Routing (GEAR) algorithm is proposed in [8]. Krishnamachari et al. [9] have discussed in detail about the influence of source-destination placement, communication network density, and the energy costs on each other. Boulis [10] proposed distributed estimation algorithm to explore energy-accuracy subspace for subclass of periodical data collection problems and presents results with five-fold improvement in energy efficiency. Yu et al. [11] explores energy-latency trade off to a great deal. Tan and Korpeoglu [12] proposed a new work consisting of two new algorithms, with power efficiency as their major design goals, called as "Power Efficient Data gathering and Aggregation Protocol (PEDAP)". These two algorithms were relying on the usage of near-optimal minimum spanning trees. A near-optimal chain-based protocol with energy-efficient as its primary design goal, called Power-Efficient Gathering in Sensor Information Systems (PEGASIS), was proposed by [13]. Kulik et al. [14] proposed Sensor Protocols for Information via Negotiation (SPIN) family of protocols, claiming 75% energy efficiency but incur lot meta-data usage. He et al. [15] proposed a research work by using feedback between sensor nodes, and reported 30–50% energy efficiency when compared to non-feedback based fixed scenarios but incurs 2 byte extra overhead for each packet for dealing with feedback. Tabassum et al. [16] proposed a work which is energy-aware version of periodical data collection. Further the same authors present two more improved works in [17, 18] which are based on 'chain' concept and claim to achieve 15–30% extended network life time and 90–95% energy efficiency. Du et al. [19] also present a similar chain-based improved algorithm for data gathering, called 'Chain Oriented SEnsor Network' (COSEN). Heuristics based aggregation tree construction for data gathering had been discussed in detail (called EADAT) in [20]. Kalpakis et al. [21] attempted to propose a novel solution for extending life time of network for data gathering purposes. Another work intending to extend the life time of network for data aggregation is presented by Hong and Prasanna [22]. Sadagopan et al. [23] focused on maximizing the data collected than so far considered parameters. However, Ordonez et al. [24] presented a more interesting work concerning the same maximization of data collection but amidst of energy constraints while providing flexibility to choose trade-off depending upon the design requirements. Another research work intending to extend the life time of the network for data aggregation was presented by Xue et al. [25]. Kim et al. [26] proposed an idea of construction of trees for the purpose of data collection, which was termed by authors as Tree-Based Clustering (TBC). Parthasarathy and Karthickeyan [27] presented a research work to improve the life time of the network for data aggregation purposes. The approach of this work involved both trees and cluster concepts as well. Salam and Ferdous [28] present a detailed survey of Tree-based data aggregation works for WSN in detail. Dreef et al. [29] focused on the application of Tree as a data structure to achieve improved security. Hussain et al. [30] proposed a work for hierarchical clusters operating in distributed fashion.

3 Analysis of Implications of Application of Tree Data Structures on Overall Performance of WSN

It may be observed from the literature survey presented in Sect. 2 that, most of the existing works have considered mainly spanning-tree variant as a data structure, with one or two applying general tree approaches. Also, few works were based on chain concept.

3.1 Disadvantages of Minimum Spanning Trees (MST) and Binary Search Trees (MST)

Main advantage of MST and BST variants of trees is that they are easy and simple to implement. But, at the same time, they have several disadvantages. In case of minimum spanning trees, they have varying path lengths along with many instances being applicable. Most frequently followed algorithms for constructing minimum spanning tree have been shown to run with complexity of $O(m \log n)$ where 'm' is the number of edges in the resultant spanning tree and 'n' is the number of nodes. Any other variants of binary trees are also having varying depths and operational costs (time complexity) depending upon the circumstances. For example, simple binary search tree may often show the performances for best case as $O(\log n)$ and for worst-case can degrade to $O(n)$ when it becomes unbalanced, where 'n' is the number of nodes in the tree. Thus, the time taken to perform operations is less if the height of the search tree is small; but if its height is large, their performance may be no better than with a linked list.

3.2 Disadvantages of Self-balancing Variants of Trees

Now let us consider the case of self-balanced tree variants those could be considered for application in WSN. AVL trees are a kind of self-balancing trees. But they are good only if lookups dominate the insert/delete operations. In the case of frequent insert/delete operations, even though its depth is at most ~1.44 * lg(n + 2), AVL tree performance will be slower requiring as many as $\Theta(\log n)$ rotations to maintain balance in an n-node tree. Further, AVL trees impose rigid balance on the tree structure leading to slow and costly operations.

3.3 Reasons for Worst-Case Performance of MST, BST, and Self-balancing Variants of Trees When Applied in WSN

But, all the above-discussed variants of tree data structure are not well suited for application in WSN. Major reasons for such infeasibility come from two aspects. First aspect of such infeasibility is that most often applied tree variants in the existing works are going to demonstrate the worst performance in case of frequent insert, delete and lookups in trees with arbitrarily longer depths. Second aspect of such infeasibility stems from some important unique features of WSN like highly dynamic topologies with very large number of sensor nodes. This unique nature may also imply that the length of path/depth/number of levels in WSN with respect to Sink/Base station/Gateway may be a serious concern. Added to these limitations, spatio-temporal nature of traffic in WSN also expects that path discovery and maintenance activities, which are local to a particular part of the WSN at any time, should be attempted in an efficient way in order to achieve the overall better performance and specifically the energy efficiency and extended network life time.

3.4 Red Black Trees (RBL): Feasibility and Potentials for Application in WSN

At first, let us glance through the properties of Red Black Trees(RBL). Red Black Trees are a variant of self-balancing trees. The nodes in RBL are differentiated as red and black nodes. Further, every path in RBL from root to leaf has same number of black links. In RBL at most one red link in-a-row or path from root to leaf is permissible. Height of tree in case of RBL is less than 2 log $(n + 1)$. Additionally, following are the advantages of RBL trees:

- Red-black trees perform insert, delete, and lookup with the Best- and Worst-case complexity guaranteed to be always $O(\log(n))$.
- Particularly useful when inserts and/or deletes are relatively frequent.
- Relatively low constants in a wide variety of scenarios.
- All the advantages of binary search trees are also available.

The only disadvantage is that they are comparatively difficult to be implemented. More details on these Red Black Trees can be found in from references like [31]. The brief summary of implementation costs in case of various tree variants has been described in [31] and repeated in Table 1 for convenient reference.

With the above-mentioned advantages of RBL trees, the potentials for being applied in WSN are very high. With this motivation, the authors of this paper have been progressing in their research work, with a hope, to design algorithm(s) for

Table 1 Summary of implementation costs of various data structures [31]

	Worst case scenario			Average case scenario		
Approach	Search	Insert	Delete	Search	Insert	Delete
Sorted array	log N	N	N	log N	N	N
Unsorted list	N	1	1	N	1	1
Hashing	N	1	N	1^a	1^a	1^a
Binary search tree	N	N	N	log N^b	log N^b	log N^b
Randomized binary search tree	log N^c	log N^c	log N^c	log N	log N	log N
Splay tree	log N^d	log N^d	log N^d	log N^d	log N^d	log N^d
Red-Black tree	log N	log N	log N	log N	log N	log N

Legend [a]based on random hash map for all keys; N^b number of nodes ever inserted; [c]probabilistic guarantee; [d]amortized guarantee applying RBL trees exploiting the previously mentioned properties of WSN and to take the benefit of advantages of RBL tree specifically to improve the energy efficiency and extend the network lifetime. Authors are hoping to publish the outcomes of the same in their future research publications.

4 Conclusions

WSN have found widespread application in different domains. The WSN are also characterized by peculiar features and conflicting design goals making them different from other types of networks. Various techniques like application of data structures etc. have been considered in the earlier research works to improve the overall performance and specifically energy efficiency and network life time. In this regard, this article made an attempt to present, as far as possible, a detailed survey of existing research works which applied tree data structures for improving the energy efficiency and extending the network life time of WSN. Further, an analysis of implications of applying different types of tree data structures on the overall performance and specifically towards the energy efficiency and network life time was also presented. Also, this article presented a brief discussion on the possible potentials for application of Red Black Tree as data structures for improving energy efficiency and network life time while comparing the same with other variants of trees with a hope to establish the feasibility of application of Red Black Trees as a data structure in WSN.

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