A survey on Bandwidth resource Allocation and Scheduling in wireless sensor networks

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Abstract

Bandwidth resource allocation and scheduling has posed a challenging problem in wireless sensor networks. This paper provides a survey on the current state-of-the-art researches in this important area. Bandwidth reservation is considered in terms of time slot allocation in a pure TDMA or TDMA/CSMA based networks. We first overview different approaches for time slot allocation in a star network topology, and then elaborate the problem of time slot allocation and scheduling in a multihop wireless communication network in the presence of interference. Since the problem in multihop wireless network is proved to be NP-complete, most of the exiting solutions use different heuristics to resolve this problem. We address some of these heuristics and algorithms and their impact in wireless sensor networks. Finally, we provide some of the advantages, limitations and possible extensions in the context of IEEE 802.15.4 communications protocol which is being widely used for wireless sensor networks.

1. Introduction

Traditionally the problem of bandwidth allocation has been considered in wired network and cellular network with various multiplexing approaches such as FDMA, CDMA and TDMA. These multiplexing approaches have also been studied for Wireless Sensor Networks (WSNs). However, due to energy and cost limitations most of the real-world implementations of WSN consider carrier sense multiple access (CSMA) and TDMA based schemes. Hence we limit our survey to TDMA and its variations along with CSMA.

In this survey, we first consider bandwidth allocation and scheduling approaches in a start topology. These approaches are presented with their advantages and limitations and possible direction for further research. Then we move on from the simple star topology to more general multi-hop mesh and cluster tree network topology. Each topology has its own set of problems with an additional cost of interference due to neighboring 1-hop and 2-hop neighbors.

The rest of the paper is organized as follows. Section 2 describes existing medium access control (MAC) layer solutions for time slot allocation in a star topology. These MAC protocols mainly deal with the collision free period of IEEE 802.15.4 specification. Section 3 describes the time slot scheduling and interference related problems in multihop mesh networks. It presents various near optimal solutions for mesh and cluster tree based multi hop communication with different heuristics used for their solution. Conclusions are given in Section 4.

2. Bandwidth allocation and resource reservation in a star topology

Network topology is an important issue in WSNs. The topology has a significant impact on the interference and hence the bandwidth allocation in WSNs. A WSN with a good topology that is designed for the pertinent application will help to increase the bandwidth utilization. This requires a good model for describing various aspects of the spatial interference, routing and resource allocation.

Wireless sensor networks typically rely on three different topologies: star, cluster tree and mesh. Among them the star topology has the least complexity in terms of Bandwidth Allocation and Scheduling (BAS), since all the neighbors are within one hop distance. In contrast, the multi-hop wireless communication gives rise to NP complete problems for time slot allocation and scheduling.

Here we show various strategies for TDMA/CSMA MAC algorithms in a star network concerning only BAS. Usually a star topology will have a coordinator device and multiple end devices. All the neighbors are within one hop distance and can listen to everyone within the network. Such a network does not face the
problems of hidden node, exposed or slot shortage problem which would be explained in Section 3. We will make following assumption about the topology. A coordinator device has more energy capability than the end devices. A coordinator is also responsible for collecting packets from the end devices. An end device can only communicate with other end device via the coordinator, that is direct end to end communication between the end devices is not allowed. In the following, we first overview some general mechanisms for BAS proposed in the literatures, and then discuss recent approaches particularly targeted to 802.15.4 specification [6] for WSNs, as there has been a growing popularity and a variety of implementations of this protocol in recent years.

2.1 General Mechanisms for BAS

In [4], a BAS scheme is proposed in a network environment in which various traffic classes such as hard and soft traffic depending on the timing guarantees are considered. This reservation based MAC protocol is directed towards applications such as rescue and disaster discovery and tackling moving objects which demand end-to-end guarantees as the timely delivery of data is the most important requirements of such applications. The protocol is designed to flexibly assign bandwidth to the sensor nodes and update the assignments as necessary based on variable (traffic adaptive) application demands.

A star topology is considered where the coordinator node or the cluster head is in charge of the traffic adaptive slot allocation algorithm used to create the transmission schedule for scheduled access in each TDMA frame. The protocol uses a CDMA mechanism for inter cluster communication. However we will limit our discussion only to the application specific slot reservation model. The scheduled access period is used by the sensor nodes according to the reserved bandwidth using the allocated TDMA slots. The reservation request is calculated by the end devices depending on its queue size. If the transmit queue size is less then the predefined request threshold than the node make a request of the queue size otherwise the request would be limited to limit a prevent node from making to many requests, thus maintaining fairness in prioritized access mechanism. The end device makes this request along with the priority of the application which demands bandwidth reservation. Upon receiving a bandwidth reservation requests, the coordinator creates a global map of the bandwidth requests and compares it with the available bandwidth to reserve slots depending on the application priority. A heuristic based algorithm for time slot assignment depending on hard and soft bounds is used to allocate the requested bandwidth of all high priority applications by manipulating the low priority request. However the algorithm maintains fairness by setting high and low bounds for low priority application where the low bound requests are rejected before affecting the higher bound requests. The scheme is as follows.

Let N be the total number of slots into pre-defined soft and hard bounds as follows,
\[ N = N_{HPA} + N_{MPA(\text{hard bound})} + N_{MPA(\text{soft bound})} + N_{LPA(\text{hard bound})} + N_{LPA(\text{soft bound})} \]

where HPA, MPA and LPA represents high, Medium and low priority applications. If all N requests can be satisfied with the available bandwidth the scheme reserves the time slots without changing any soft bound requests.

In case the requested higher priority traffic is less than \( N_{HPA} \) then the scheme reserves the remaining traffic for the medium priority traffic (i.e. bandwidth reclamation) else assign some of the soft bound tasks first from lower priority traffic and then from the medium priority traffic for the high priority traffic. If the demand for the higher priority traffic still cannot be satisfied than no more reservation are made for the remaining high priority time slot requests.

This approach is useful in WSN which deals with different data traffics. While this algorithm does not consider issues such as bandwidth utilization, optimal bandwidth allocation, it is still useful for classifying application types and reserving bandwidth providing application flexibility and fairness.

Implicit earliest deadline first (EDF) for WSN is a robust MAC layer deterministic protocol which provides predictable temporal behavior as well as better throughput in a star based network. Implicit EDF is based on a distributed scheme for reserving the time slots in a TDMA based frame where every device node is responsible for BAS, which is quite unique with respect to other protocols in which the coordinator is responsible for BAS, thus avoiding a single point of failure. This protocol does not require clock synchronization and also provides bandwidth reclamation. As the name suggests the protocol makes use of EDF scheduling algorithm for scheduling the requested time slots.

This algorithm considers a message M as the basic scheduling entity. Each message is associated with its length, period and a priority index. All the messages are scheduled according to EDF where the dynamic priority of every message depends on its deadline. The message with smallest absolute deadline is scheduled before the others. The priority of message is used to break the tie for messages having same absolute deadline, thus implicitly avoiding collision in the wireless network. This protocol makes use of packet trains where every packet train is the instance of the
periodic message within the schedule. A packet train is similar to an instance of a job in a task set scheduled using EDF. The packet train is ordered in non-decreasing order of time when it is scheduled. The robustness property is supported by making use of budget and recovery mechanisms. A budget is assigned to every packet train which is equal to the remaining transmission time required by the packet train. This is the default budget which depends on the message length. In the case that a packet train finishes before the budget exhaustion, the remaining amount of budget is forwarded to another node with the next packet train. The next node in the schedule reclaims this budget by forwarding an aperiodic message. Recovery uses carrier sense to identify node failures. Robust Implicit EDF maintains a state transition within each node to keep an account of the transmission, reception and recovery states. It maintains a conflict free schedule in presence of node failures and packet losses without a centralized scheduler and has no single point of failure. The protocol is appropriate for WSN applications with periodic traffic with intermittent aperiodic events. However it does not consider the effect on response time due to bursty traffic. In the case of bursty traffic the algorithm will have to drop any access requests exceeding the assigned budget. Otherwise, it would lead to increase in response time of lower priority messages. The guaranteed time slot (GTS) scheduling algorithm (GSA) algorithm which follows tries to resolve this problem.

2.2 IEEE 802.15.4 related approaches

i-GAME: An implicit GTS Allocation Mechanism in IEEE 802.15.4 for Time-Sensitive WSNs presented in [9] suggests an alternate algorithm, different from the IEEE 802.15.4 based method for assigning GTS to the nodes in a star based beacon mode operation. According to the specification of IEEE 802.15.4, the coordinator assigns the requested GTS slots depending on the availability of the bandwidth following a First Come First Served (FCFS) schedule. Since, this method of bandwidth allocation reserves the GTS slots purely on the basis of device requests it could lead to a significant wastage of the available bandwidth in Contention Free Period (CFP) of IEEE 802.15.4 superframe. The implicit GTS allocation mechanism (i-GAME) takes into account the traffic specifications and the delay requirements of the flow. This approach enables the use of a GTS by multiple nodes, while all their (delay, bandwidth) requirements are still satisfied. This algorithm relies on the fact that if the bandwidth requested by individual node per beacon interval is less than the available capacity of a unit GTS, then allocating a unit GTS to a single node or a round robin based allocation to different nodes leads to wastage of the available bandwidth. An effective strategy for allocation of bandwidth should be dependent on requested traffic and the service capability of GTS within a super frame. This idea leads to using a network calculus based approach for sharing a GTS slot among different nodes such that available bandwidth is effectively utilized at the same time maintaining the deadline guarantees. Let \( \alpha(t) = b + r.t \) denote the incoming arrival traffic of the node in a star network. It has been shown that the service curve offered by a GTS allocation of \( n \) time slots is approximated by a rate-latency service curve:

\[
\beta(t) = R_n(t-T_n), \quad \text{where } R_n \text{ is the guaranteed bandwidth of a GTS defined as: } R_n = n.(T_{\text{data}}. C/BI). \text{ And } T_n \text{ is the latency of the service expressed as: } T_n = BI - n.TS. \text{ } T_{\text{data}} \text{ defines the maximum duration used for data frame transmission inside a GTS, without taking the control overheads into account. As a result it is shown that the delay bound guaranteed by the service curve } \beta(t) \text{ for an Data flow bounded by a } (b,r) \text{ curve is: } D_{n,\text{max}} = b/n.((T_{\text{data}}. C)/BI) + (BI - n.TS).
\]

The bandwidth allocation algorithm makes use of the above mentioned formulae to share a unit GTS among different incoming flows. If an incoming flows bandwidth or timing requirements could not be satisfied by a single GTS then another GTS is assigned for this new request.

The i-Game approach is very useful for those WSN applications where the bandwidth requirement of the application is much less than the unit GTS capacity. This algorithm performs much better than the explicit standard specification in term of bandwidth utilization and also timing guarantees.

Another GTS based BAS scheme, called as Adaptive GTS Allocation (AGA) Scheme is designed in [10] to handle different traffic requirements like hard, soft, periodic, aperiodic and bursty. It solves problem related to starvation and provides fairness, low latency. The coordinator is in charge of BAS and calculates the GTS schedule for the new beacon interval depending on the bandwidth requests and traffic priority sent by end devices in the CAP period of previous Beacon Interval.

In order to dynamically allocate GTS slots AGA performs a classification on the requested bandwidth. In the classification phase, devices are assigned priorities in a dynamic fashion based on recent GTS usage feedbacks. Devices that need more attention from the coordinator are given higher priorities. In the GTS scheduling phase, GTSs are given to devices in a non-decreasing order of their priorities.
The coordinator maintains a state transition machine which is responsible for classifying the end device nodes into traffic types (Very High, High, Medium, and Low) and assigning priorities. At the end of each super frame, the network coordinator examines the GTS usage of all devices and then decides the next states to which every device transits. This state transition is based on Markov model where the state represents the nodes traffic pattern. A transition from one state to another depends on the bandwidth requested and used by the node during the GTS. If one device has issued a successful GTS request in the CAP or transmitted data within its allocated GTS to the network coordinator during the period of the current superframe, the device is defined to have a GTS hit. Otherwise, the device is considered to have a miss.

Figure 1. A Markov Chain Model

The figure 1 shows the Markov chain model for the traffic and priority transition for different nodes. The devices with more frequent GTS usage have larger probabilities to stay in heavy traffic states (e.g. Very High and High). In addition, temporarily unstable transmission behaviors of devices are more tolerated. The use of traffic classes along with the device priority can be used to filter sudden changes in the traffic as shown in the diagram. The high-traffic-level devices with temporary interruption of GTS usage are slightly demoted to lower priorities. On the other hand, if a low-traffic-level device successfully issues a GTS request, its priority is greatly promoted to receive GTS service as soon as possible.

The GTS scheduling is performed by the coordinator depending on the assigned priorities and available bandwidth. The GTS scheduling mechanism also uses a threshold to check the device priorities. If the device priority is lower than the threshold, it means that the traffic is low and the bandwidth is not fully utilized. Hence instead of reserving a GTS, such a transmission uses CAP.

The AGA scheme is shown to perform better compared to the algorithm specified by the IEEE 802.15.4 standard. This scheme is useful for the application with variable bandwidth requirements, since the algorithm dynamically adjusts itself with the traffic request assigning GTS slots depending on the traffic load. Since BAS is based on stochastic method it cannot meet strict timing guarantees.

An optimal GTS scheduling algorithm (GSA) is proposed in [12] based on EDF scheduling of messages within the GTS slots in order to guarantee the timing behavior. GSA is optimal as well as work conserving. Since GSA is based on EDF which is an optimal scheduling algorithm if there exists a GTS schedule within a super frame for the bounded requests made by the EDF devices then GSA will reserve and allocate GTS slots.

This algorithm is useful when most of the traffic in the WSN is time sensitive. GSA is able to handle bursty, periodic and aperiodic traffic and is shown to perform better than the FCFS based GTS allocation strategy of IEEE 802.15.4 in terms of meeting the deadline and GTS utilization. GSA tries to smooth out the traffic of a transaction by distributing the GTSs of a transaction over as many beacon intervals as possible while satisfying the time constraint of the transaction.

The GSA algorithm contains three different procedures. 1) A schedulability check is used to check whether all the requested number of slots can be scheduled within its deadline using EDF schedulability check. This is done by adjusting the deadline of every transaction and the actual transmission time available in GTS ignoring the inactive and CAP, since the slots cannot be scheduled in these periods. 2) The GSA algorithm calculates the end-to-end delay of each transaction. This calculation depends on the number of GTS slots allocated in every beacon interval before its deadline. This end-to-end line must be less than the deadline of the transaction. 3) Finally, GSA tries to reduce the bursty behavior due to EDF scheduling by spreading the GTS slots of every transaction by allocating a minimum of GTS slots to the transaction in every beacon interval. Due to this spreading of GTS slots the transaction with lower priority get a chance to schedule earlier in the unutilized slots, thus maintaining work conservation as well as reducing the response time of the lower priority transactions.

The performance study reported in [12] shows that the GSA algorithm performs better in providing timing guarantees and bandwidth utilization for periodic, aperiodic and bursty traffic.
3. Bandwidth Allocation and Scheduling in Multihop WSNs

As we move on from single hop to multihop communication networks we will see that the problem becomes highly complicated because of the interference and slot shortage. Most of the practical solutions depend on CSMA based approach. However using CSMA leads to a significant wastage of bandwidth in a multihop communication. Multihop CSMA performance studies show that the maximum end-to-end throughput is 1/8 and 1/24 of the link throughput for a line of nodes and a 2-D grid respectively [14]. It does not provide end-to-end timing guarantees.

TDMA based bandwidth reservation and slot scheduling in a multihop performs better than CSMA based networks and also enables QoS guarantees. However the problem of slot scheduling gets highly complex due to wireless interference and slot shortage. In this section we will try to expose some of the inherent problems in wireless communication. These problems impose necessary constraints in many of the solutions described in the following sections. This is followed by some of the solutions to purely TDMA based networks.

A transmission interferes with nodes that are within a number of hops, \( H_i \), from the transmitter and receiver depending on the signal to noise required for a correct reception [1].

\[ (B \text{ sends to } A \text{ and } C \text{ sends to } D) \text{ do not interfere with each other and can occur simultaneously. However, according to carrier sense multiple access, one, either } B \text{ or } C, \text{ is inhibited from transmitting to its destination due to its exposure to another. The exposed terminal problem is viewed as a source of an inefficiency of the network.} \]

- **Slot Shortage problems [2]**: In addition to hidden and exposed terminal problems, slot shortage problems are also great challenges in designing a QoS routing on TDMA. Slot shortage problems mean the problems that there should exist at least one route from source to the destination, which satisfies the QoS requirement. However, for the sake of inappropriate slots selection, the route that originally exists cannot be discovered no. The slot shortage problem caused by inappropriate slots selection will affect not only the discovery of self-route but also the discoveries of the neighboring routes. Taking slot shortage problems into consideration can increase not only the successful rate of route discovery but also the network throughput. Thus, slot shortage problems are important issues in designing a QoS routing protocol on TDMA or IEEE 802.15.4 which uses GTS and cluster tree or mesh for communication (this can be further extended if we find solution for a pure TDMA).

Link interferences in multihop wireless networks make the problem of selecting a path satisfying bandwidth requirements an NP-complete problem [1], even under simplified rules for bandwidth reservation. This is in sharp contrast to path selection in wire line networks where efficient polynomial algorithm exists. Assume that a node \( A \) has remaining capacity \( C_i \). We must have \( C_i >= b_i \) for all \( A \in V \), where \( b_i \) is the requested bandwidth. The Path with Remaining Capacity (RC) is defined as:

**Instance**: A graph \( G = (V, E) \) two vertices \( s \) and \( t \) from \( V \) and a capacity \( C_i \in N \) for each vertex \( i \) from \( V \).

**Question**: Is there a simple path from \( s \) to \( t \) in \( G \) that satisfies the constraint,

\[ C_i >= b_i \text{ for all } A \in V \]  

Hence, to find the best path such as to conserve remaining capacity at the nodes is an NP- Hard problem [1].

The solution to bandwidth allocation and scheduling for a TDMA based multihop WSN is based on approximation algorithms and heuristics which try to find a near optimal solution. However, many of these problem do not take the spatial advantage of the topology and are either too optimistic or pessimistic while considering the interferences. We will highlight some of these solutions in TDMA based mobile ad hoc networks and WSNs with a mesh topology.
3.1 Distributed BAS based on optimizing the network cost

The authors of paper [1] prove that the problem of path selection in a multihop TDMA–based wireless network that satisfies the requested bandwidth is a NP-complete problem, and suggest a heuristic algorithm based on Dijkstra’s shortest path algorithm. The algorithm is based on the fact that if \(b\) units of bandwidth needs to be reserved between two nodes than in order to avoid interference reserve \(b\) units of bandwidth on all the neighbors within interference of these two nodes. The route finding and bandwidth reservation is modeled as a path with remaining capacity problem i.e. to find a route such that all the nodes along the path have remaining capacity greater than the requested bandwidth. This route searching is based on Dijkstra’s shortest path algorithm where the cost of the node is its remaining capacity. The goal of this algorithm is to accommodate as many routes in the given wireless network. This is achieved by considering the remaining capacity on the node as the cost for the Dijkstra’s shortest path algorithm. This algorithm than finds a shortest route which maximizes the remaining capacity of the network. The simulation study shows that this cost factor is able to accept more number of flows with better bandwidth distribution. The authors describe a distributed bandwidth and slot reservation algorithm which is based on the remaining capacity in terms of available slots at each node. The nodes exchange this information with its neighbors so that it has local information of the remaining capacity in its neighborhood. This distributed algorithm first tries to find a source to destination path that meets the bandwidth constraints of all the nodes and its neighbors that avoids interference. If such a path is found then the algorithm reserves the requested bandwidth along all the nodes and its neighbors along this route.

This distributed algorithm reserves the bandwidth on each of the \(H_i +1\) neighboring nodes along the path, where \(H_i\) is the interfering hop count. Since this algorithm does not consider the spatial topology this rule guarantees the requested bandwidth but could lead to a pessimistic solution.

In paper [3], the authors have modeled the interference based timeslot allocation in multihop routing as an integer linear programming problem. Since this is a NP-hard problem the authors have mentioned alternate approximate algorithm for the same problem. The algorithm first tries to find interference optimal cost bounded paths. An optimal bandwidth allocation algorithm is then used to allocate timeslots along the found paths for connection requests with unit bandwidth requirements.

The two algorithms for calculating a cost (unit cost is associated with every link, i.e. finding shortest path) efficient routing path are based on the following definitions:

- **Link interference**: The sum of bandwidth of the existing connection that interferes with the current link.
- **Maximum path interference**: The maximum among all the link interferences and the total path interference is the sum of all the link interferences on the given route. The route finding algorithm is based on these maximum and total path interferences, such that the algorithm constructs an interference-optimal cost bounded paths. The time slot allocation algorithm than allocates the requested bandwidth along the selected route. This time slot allocation algorithm is similar to the three hop backward decision policy algorithm. This algorithm creates a list of free slots for three hop backward links. The final allocation is based on find a connected list of slots from destination to source from the list of free slots created in the previous step.

3.2 Distributed BAS based on 3-hop heuristic

The paper [2] proposes a dynamic, on-demand and distributed bandwidth allocation strategy for QoS routing in TDMA-based networks, which will be described below.

A source node makes a bandwidth request i.e. number of TDMA slots for finding a bandwidth capable route from source to destination. The route discovery satisfying the bandwidth requirements is based on a variant AODV routing protocol.

The distributed slots reservation protocol is based on certain slot inhibition policies (SIPs) and slot decision policies (SDPs). The SIPs are set of rules governing the selection of time slots along the path from source to destination. These selection rules are based on interference problems among 1-hop and 2-hop neighboring nodes. SIP policies select TDMA slots for a link between two adjacent nodes such that these slots do not overlap with any of the ongoing interfering communication. Once the protocol selects a set of collision free slots using SIPs, the SDPs selects the best slots among all the available collision free slots that satisfies the requested bandwidth.

As mentioned earlier it is important to select right slots so that it does not interfere with the slots along the same route. If the interference is limited to 1-hop distance then the maximum interfering slots along a route are within 3 hop distance, this is due to hidden terminal problem. The first SDP considers this three hop distance to select non interfering TDMA slots. According to this heuristic the decision of the slot reservation along a link is made by the node 3-hop distance towards the destination. On the other hand, the second heurist is least conflict first which selects slots
that cause the least interference with the next two links. The third heuristic tries to select only the requested number of slots from a set of collision free time slots based on the bandwidth utilization. The slots with higher bandwidth utilization are preferred over the lower ones in order to further increase the slot utilization.

The distributed protocol selects a set of collision free slots along a particular route during the route request phase of Ad-hoc on demand distance vector (AODV). However, the final reservation of the slots is done only during the route reply phase from destination to source node. The paper [2] also presents a slot adjustment algorithm in case the slots selected during the route request phase are already reserved by some other route. The slot adjustment algorithm tries to adjust the time slots among the neighboring nodes in order to avoid interference.

The distributed slot reservation protocol demonstrates a practical heuristic based solution to the NP-complete problem of route selection and time slot allocation. The heuristics and slot adjustment protocol of DSRP helps to discover a number of routes with good bandwidth utilization.

Another work reported in [8] based on 3-hop neighbor interference based heuristic shows that since the problem of calculating the maximum available bandwidth in terms of conflict free TDMA slots is NP-complete, a possible solution to calculate the maximum available path is to calculate a set of non conflicting slots on three adjacent links which locally maximizes the bandwidth from the source and to propagate this calculation along the path to the destination.

The locally maximizing distributed algorithm is termed forward algorithm (FA), because for a given path, it iterates over the hops from the source to the destination calculating the maximum bandwidth for a given three hop nodes along the forward partial path.

The algorithm begins with constructing a list of free slots along a given path. These slots are conflict free over one hop neighborhood such that it does not transmit or receive at the same time along with its conflicting neighbor.

The forward algorithm operates on this set of non conflicting slots such that the partial route use mutually exclusive set of slots, so that they do not conflict on a three hop path.

The end to end bandwidth of the path is the number of slots selected by the forward algorithm at the destination where the algorithm terminates.

This algorithm is implemented using a modified version of AODV protocol.

The evaluation of this algorithm with optimal solution shows that this distributed algorithm is very close to the upper bound of the maximum available bandwidth with much less complexity.

3.3 BAS based on k-hop coloring

RT-LINK: A Time-Synchronized Link Protocol for Energy-Constrained Multi-hop Wireless Networks [13] is a TDMA-based link layer protocol designed for networks that require predictability in throughput, latency and energy consumption. This protocol supports hardware-based out-of-band global time synchronization which offers a robust and scalable alternative to in-band software-based schemes. The protocol frame consists of a synchronization pulse followed by scheduled slots and contention slot. This frame structure is quite similar to IEEE 802.15.4; however the RT-LINK makes use of hardware sync pulses instead of using the beacon frame. IEEE 802.15.4 requires having a cluster tree network topology in order to operate in a slotted beacon mode communication. RT-LINK can also operate within a mesh topology. The devices within the network make a bandwidth request within contention slots. These requests are flooded towards the gateway node which is in charge of creating the TDMA based collision free schedule for the devices.

In order to avoid interference and reserve slots within TDMA frame RT-LINK makes use of the topology information within the network. This topology information is used to construct connectivity and interference graphs and schedule nodes based on k-hop coloring. Links which interfere for a TDMA slot can be removed from the network graph, thus, reducing the degree of nodes while checking to maintain network connectivity.

RT-LINK performs a node coloring and ordering over this logical topology in order to have a low latency time slot schedule. The paper described one heuristic which is used for having a minimum-delay capability schedule. This heuristic consists of forming a spanning tree from the logical topology. As each node is traversed by the breadth first search starting from the root node, it is assigned the lowest value in the color set that is unique from any 1 or 2-hop neighbors. If there are no free colors, a new color must be added into the current set. The next step in the heuristic tries to eliminate redundant slots that lie deeper in the tree by replacing them with larger valued slots. This manipulation allows data from the leaves of the tree to move as far as possible towards the gateway in a single TDMA cycle. The real world deployment of RT-LINK protocol for a WSN shows the practical use of this communication protocol.

Besides the above mentioned protocols there are various others which provide solution using optimization, network calculus, etc. However here we
have presented only the solution which takes interference in to account while scheduling TDMA slots.

4. Conclusion

This survey has presented a comprehensive overview of the state-of-the-art researches and solutions to bandwidth allocation and scheduling in both single hop start topology and multihop WSNs. The problem of time slot scheduling in a multihop communication networks is NP-complete and as such many of the existing solutions rely on heuristic algorithms which may provide near optimal solutions. The knowledge about the network topology and spatial interference is a key to reducing the inherent constraints in wireless communication and increasing the bandwidth utilization and throughput in QoS based TDMA networks. The use of a stochastic approach taking the knowledge about the application could reduce complexity for bandwidth allocation and slot allocation. However this would not give the optimal result.

Most of the solutions are based on mesh topology. Considering cluster tree based networks could present new constraints or ease the problem of bandwidth allocation and scheduling. Further research is needed in cluster tree topology based IEEE 802.15.4 on Guaranteed Time Slots. Since providing strict QoS requirements is of utmost importance in BAS, most of the existing literature deals with protocols and algorithms limited to TDMA or GTS schemes, due to the fact that the inherent backoff randomness in CSMA schemes makes it difficult to assure QoS requirement under heavy traffic load. A CSMA scheme with constrained backoff can be considered for BAS, under light traffic conditions with soft QoS requirements.

5. References