MAC Layer Resource Scheduling through Virtualization of Wireless Sensor Networks

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Abstract

In this paper, we propose a joint throughput and time-resource allocation scheme for the virtualization of IEEE 802.15.4-based Wireless Sensor Networks (WSNs). Virtualization is realized through utilization of the Guaranteed Time Slot (GTS) mechanism of cluster-tree topology to schedule resources on a Media Access Control (MAC) layer. We develop a scheduler that is located in the Personal Area Network (PAN) coordinator and that virtualizes the network into an aggregate of independent profiles, assigning the available resources to each profile with end to- end (ETE) delay guarantees. The scheduler solves the problem of managing resources available in the network in an optimization framework, taking into consideration the individual profile and sensor requirements. Moreover, it uses the proposed heuristic Fair Resource Allocation (FRA) algorithm to derive the solution in polynomial time. We validate the scheduling performance via Discrete Event Simulation (DES) and compare the proposed FRA algorithm with Round Robin (RR) and Proportionally Fair (PF) scheduling algorithms in several scenarios. The proposed scheme demonstrates efficient resource management while maintaining profile isolation in all cases, whereas other algorithms lead to increased latency and lower throughput in the network.

Keywords— *IEEE 802.15.4, Resource Allocation, Scheduling, Virtualization, Wireless Sensor Networks, ZigBee.*

I. INTRODUCTION

Wireless Sensor Network (WSN) virtualization is an emerging technology that targets domain specific and task-oriented networks and enables them to support multiple applications for various domains, thus providing more flexibility, diversity, efficiency and increased manageability. This technology is based on the idea of coexistence of heterogeneous nodes in shared physical sensor substrate (i.e. infrastructure), and is a core for the concepts of Internet of Things (IoT), Smart City, Smart Home and Intelligent Transportation Systems (ITS). The traditional WSNs are usually deployed to accommodate only one particular application and are not suitable for reuse by newer applications or sharing by different groups of users/operators [1], [2]. This is inefficient and leads to redundancy when new applications are deployed or functional heterogeneity needs to be implemented. Therefore, the subject of WSNs virtualization is very relevant and important. Virtualization is defined as the abstraction of physical computing or network resources into logical units dedicated to multiple independent applications and/or users [2], [3]. In our work, we virtualize a WSN's physical resources into logical units, thus creating a pool of resources that can be used by any group or subset of a WSN's nodes dedicated to one application at a time. Each subset is unaware of the underlying virtualization processes or of the existence of other subsets. The set of characteristics that we adopted to describe the WSN virtualization is [4]: Networking technology, or the attributes of networks that we perform virtualization on. In our case, WSN technology (or more specifically, IEEE 802.15.4). Layer of virtualization, which specifies the layer of network stack where the virtualization was introduced. In this paper, we consider MAC layer virtualization. Granularity of virtualization, which defines granularity of the extent to which each logical subset can manage itself. This can be a single virtual node, links between nodes or a whole network. Our case deals with isolated groups of nodes (or profiles, as described below). Current research on WSNs virtualization can be classified into two main categories: node-level virtualization and network level virtualization. Node-level virtualization enables node heterogeneity, which means that a sensor node can essentially become a multipurpose device. This can be achieved using Sensor Operation System-based solutions [5] or using Virtual Machine-/Middleware-based solutions [2]. Although these solutions ensure that the nodes are capable of the concurrent execution of multiple tasks, they do not enable sensors to form isolated profiles, or groups of logically connected applications dedicated to different domains of WSN deployment, e.g. smart home, health care, industry or agriculture. On the other hand, network-level virtualization focuses on domain segregated sensor groups, introducing the notion of network sharing and sharing management (scheduling), which is of Especial interest. For instance, a network of sensors installed in a private home could be simultaneously used for hazard monitoring inside the house (such as smoke or carbon monoxide detection) as well as for health-related purposes by the householders (e.g., a doctor or nurse monitoring the health of elderly patients in the house). Profiles can also be formed in accordance with their priority or importance of the application they support. Consider an example of a ZigBee network installed in an apartment building for its condition, safety and security monitoring. According to Underwriters Laboratories Inc. Standards (UL 864) [6] and National Fire Alarm and Signaling Code (NFPA 72) [7], fire hazards are on a higher priority to be reported than plumbing and security hazards or energy efficiency of the building; therefore, the sensors network in this building can be virtualized into prioritized profiles, each supporting a different application. Packets of profiles with higher priority will be routed to the PAN coordinator quicker than the packets of profiles with lower priority. Network-level virtualization can be classified into two types: virtual network/overlay-based solutions and cluster-based solutions [2], [8]. In virtual network/overlay-based solutions, logical networks are created on top of an existing physical network to form virtual application-specific groups. References [8] - [12] discuss the concurrent utilization of nodes and the establishment of virtual links (between sensors in different administrative domains); others have investigated the routing of packets through these links to connect other IP-smart objects to the network without use of conventional gateways [13]- [15]. Works [16] and [17] propose architectures to utilize both node-level and network-level virtualization towards realization of IoT concept. Although WSN deployment and connection to the Internet and cloud for virtualization purposes has been extensively discussed, not much detail has been provided about the physical implementation of these schemes or of the deployment of any lower-level standard. Therefore, in this work we target the realization of virtualization concept on lower layers of communication stack. The design features of virtualization that we focused on in our paper are [4]: _ Abstraction. A WSN is abstracted into virtual profiles. The network resources are then divided as logical units between the abstract profiles. Thus, the virtualization can be viewed as the abstraction of physical resources of a network. Flexibility and heterogeneity. Virtualization on lower layers introduces better flexibility and heterogeneity [4]. For example, resources abstraction allows dismissal of concern about kinds of applications running by profiles. The only attribute which matters is general type and amount of traffic produced by applications. This results in higher flexibility. Moreover, MAC layer virtualization enables facilitation of different upper-layer technologies on the same physical WSN, which increases heterogeneity. Manageability (allocation). The random nature of the CSMA/CA (the default medium access technique used by the IEEE 802.15.4) [18] may diminish the QoS level in the network. Thereby, a service provider cannot make any guarantees on packet delay, or achieved rates by separate nodes or groups of nodes. Moreover, monopolization by a group of nodes with heavy traffic is probable, which means that there is a possibility of ”choking” other less active groups of sensors, which nonetheless might have important information to deliver. Therefore, manageability of a network in terms of dedicated resources is a critical factor in virtualization of a WSN to satisfy the service level agreement (SLA). In this paper, we use the GTS mechanism as the main mechanism for the channel access. This allows us to introduce and attain minimum QoS guarantees for each profile, such as delay and throughput. Isolation. The manageability of the network introduces the concept of isolation between profiles with respect to resources allocation. This enables coexistence of logically separated and independent subsets of nodes supporting various applications on the same WSN (provided that the network operates within the Admission Control constraints). This facilitates development of network management business models, in which different profiles are managed by separate service providers with minimum service guarantees. The resource virtualization of a network will ensure that the current state of a provider will not affect the states of others. Contribution. In this paper we propose a TDMA-based scheduler for WSNs MAC layer. This scheduler provides a resource management solution for isolated profiles on a shared physical network of sensors, thus enabling the virtualization on a WSN. The purpose of this scheduler is to allocate the available network resources in accordance with the requirements of individual profiles while maximizing total throughput in the network and providing ETE guarantees for critical data. We investigate the IEEE 802.15.4 standard, which is the most popular standard for layers 1-2 in low-rate, low-power WSNs. Virtualization is achieved using the synchronization mechanism and GTSs supported by the standard. We formulate and solve the problem in a utility-optimization framework, while choosing the class of linear utility functions, which enables coexistence of throughput- and time-resource provisioning to satisfy the requirements of profiles with different types of data: bursty and periodic respectively. Since virtualization enables the separation of different Service Providers (SPs) both from one another and from the Sensor Infrastructure Providers (SInPs) [3], our work presents the potential for new deployments and management of WSNs, which would introduce new business cases, services and models in the context of sensor networks.

II. RELATED WORKS

Much of available work on WSNs virtualization on lower layers deals with cluster-based solutions, where physical partition of all nodes is usually applied and each group forms a task-oriented cluster. For example, [19] and its extension [20] discuss dynamically self-organizing tree-based VSNs and their maintenance, as well as inter-VSN and intra-VSN communication. An extensive research has been done on the topic of virtual clusters (VC) formation and scheduling on MAC layer in WSNs towards reducing the network's energy consumption. Thus, several energy-efficient contention-based MAC protocols and their amendments were proposed, such as Sensor MAC (S-MAC) [21], its enhanced version, Timeout MAC (T-MAC) [22], and the modifications for networks with moving nodes: Mobile S-MAC (MS-MAC) [23] and Mobile T-MAC (MT-MAC) [24]. The basic idea is that the nodes form VCs with common local sleeping schedule and use contention-based channel access when they are awake. Some algorithms were proposed to improve these protocols, for instance [25] - [28]. The authors of [28] proposed to use separate channels for inter- and intra-cluster communications and to combine contention-based carrier sense multiple access (CSMA) with contention-free-based time division multiple access (TDMA) periods for urgent data. During the contention-free period each VC assigns time slots to sensors within it with the highest priority, based on priority index calculations. Whereas these works deal with organizing sensors into groups, they target the energy consumption and life-span of a WSN, and not profiles/flows separation and quality of service (QoS) control over them, which are essential for WSN virtualization. The problem of data flows prioritization on MAC layer has already been addressed by some works, but not in a context
of WSN virtualization. Thus, research works in MAC layer of IEEE 802.15.4 WSNs [29] and [30] present models, which facilitate priority-based service differentiation by means of assigning various Backoff Exponent (BE) in CSMA with collision avoidance (CSMA/CA) algorithm to different service classes. In [31] authors use the concept of virtual collision domain and present two algorithms to calculate the collision-free virtual domain and to dynamically adjust the back off period to serve rate-sensitive data with minimal rate requirements. While these works improve the network's throughput and address the issue of rate requirements, due to use of contention-based channel access the ETE delay cannot be guaranteed, and hence cannot be used for networks with critical data profiles. Some other works dealt with TDMA-like scheduling and showed its advantages over the contention-based scheduling. Authors of [32] introduced a platform for development of cross-layer protocols in multi-hop mobile ad hoc networks (MANET), which virtualizes the network on MAC layer in TDMA fashion to allow fair comparison between various network protocol stacks (virtual protocols) in almost identical propagation environment. Each virtual protocol has an access to a virtual link layer and virtual time. In this case, the TDMA scheme had an advantage of preventing interference
between different stacks globally. In [33] a multimode hybrid MAC protocol (MH-MAC) was introduced. This protocol can switch between asynchronous and synchronous modes, with or without contention, to support WSNs with heterogeneous nodes producing infrequent bursts of data. It was shown that the data bursts are handled better by the contention-free synchronous mode than by the asynchronous contention-based one.

III. THEORETICAL BACKGROUND AND ASSUMPTIONS

A. Topology and Resources

The IEEE 802.15.4 enables three basic types of network topology: star, mesh and cluster-tree [18], [53]. In star network topology, all devices are directly connected to the PAN coordinator and can communicate with other devices on the network strictly through the coordinator. In mesh network topology, each node can directly communicate with any other node that is within radio range [54]. The data is routed in ad-hoc fashion through several ”hops” to the destination. Cluster-tree network topology is a special case involving a mesh network with only one possible routing path between two nodes [54]. The cluster tree routing protocol is much lighter than the mesh routing one. Moreover, IEEE 802.15.4's beacon-enabled mode introduces

a synchronization mechanism. This mode allows ETE delay guarantees to be made on a per-cluster basis using GTS in the super frame contention-free period (CFP). Topology plays a very important role in virtualization. Although mesh networks are more robust, they are not able to support resource management due to pure CSMA/CA protocol employed; they also waste bandwidth and energy because of overheads and redundant routing. On the other hand, clustertree topologies support synchronization, which can be effectively used for isolating groups and sharing resources between them.

B. IEEE 802.15.4 Beacon-Enabled Mode and the Super frame
Structure

The IEEE 802.15.4 MAC sub-layer supports two modes: beacon-enabled and non-beacon-enabled. In the non-beacon enabled mode, nodes use an unsynchronized random channel access protocol, which is unable to give any time or resource guarantees. In contrast, the beacon-enabled mode uses periodical beacon frames (superframes) to synchronize the nodes with the PAN coordinator. According to the standard [18], the super frame structure of the beacon-enabled mode is defined by the coordinator and is bounded by two beacons; it may also include an inactive period, (see Fig. 1). The active portion of the super frame is divided into 16 equal slots, within which transmission is allowed, and contains a contention access period (CAP) and a CFP. During the CAP, nodes must compete for the channel (through a slotted CSMA/CA random access mechanism), whereas in the CFP they are allocated GTSs during which they can transmit without any contention. The beacon is transmitted during the first slot of a frame. The GTSs form the CFP, which always appears at the end of the active portion of the superframe and starts immediately following the CAP, as shown in Fig. 1. The coordinator can allocate up to seven GTSs, and a GTS may occupy more than one slot period [18]. However, a minimum CAP portion of 440 symbols (1760 bits) should remain for contention-based access of other network devices or for new devices wishing to join the network. If no GTSs are allocated, the CAP lasts for the whole active period of a frame.

C. Assumptions for the Framework

We assume a single WSN with one PAN coordinator with the remaining devices being either routers or end devices. We also assume a cluster-tree topology of unity depth, where all end devices and routers are direct children of the coordinator. This topology inherits the simplicity of a star topology, while at the same time being enhanced by the synchronization mechanism (the superframe structure). The beacon frame is considered to have only an active period (an extension to the case with both active and inactive periods is straightforward). The upper layers can be defined by any appropriate standard which operates on those layers, e.g. ZigBee. In order to fulfil the flexibility and heterogeneity feature of virtualization, we rather assume a generic representation of data produced by a network than a set of particular running applications. Thus, we consider only two main and most widely adopted types of data generated by the network (and, respectively, profiles generating these data): periodical data [17], [31] - [33], [55] - [59], and busty data [28], [33], [60] - [66]. These two data types and their combination

generally describe any kind of application that can run on a network. Periodical data is generated by sensors at predefined time instances and has a known volume. This can include profiles monitoring the environment or the status of a home. In contrast, profiles, that generate busty data, require elevated throughputs at random (often rare) time instances, keeping quiet during other times. One good example involves municipal authorities monitoring an accident or disaster (for example, tracking a bush fire or investigating an automobile collision). Our goal is to develop a MAC-layer scheduler that will utilize the same network infrastructure to accommodate both types of profiles. Approach of resource allocation based on requirements of various data classes (traffic) was investigated in wired and mobile networks and was shown to be effective for scheduling in networks hosting applications with different needs. Therefore, it is a promising solution for heterogeneous WSNs as well, where the profiles may have different demands for resource allocation based on the type of data they produce [44], [67], [68]. Thus, we can separate resource provisioning into two logical types: time-slot provisioning and throughput provisioning. Time-slot provisioning is aimed at periodical profiles which require guaranteed time slots each frame (or every several frames) during which they can send periodical data to the sink. These time slots are allocated during the CFP of the frame. Throughput provisioning is aimed towards busty profiles which require throughput guarantees during random events, which can be achieved by allocating the remaining time slots. In this way, busty data devices benefit from increased throughput during the events, whereas the periodical data devices benefit from guaranteed and uninterrupted transmission during the CFP of each scheduling period.

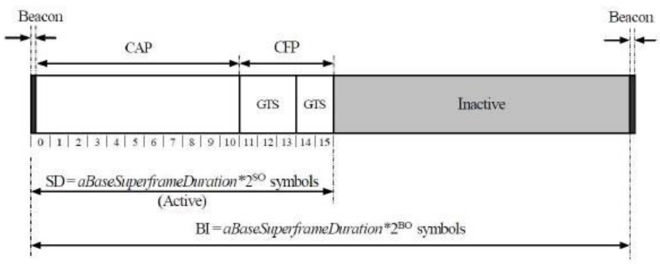

Fig. 1. The Super frame structure of IEEE 802.15.4 [18]

IV. SOLUTION BY GREEDY ALGORITHM

The optimization problem formulated in Section IV is an MILP and can be solved using the brunch-and-bound technique. This method finds the global optimum of any linear programming (LP) problem by enumerating the points in a sub problem's feasible region [72]. Because this algorithm searches for the global optima, it is computationally complex and cannot be used in real-time scheduling. We propose a reduced-complexity heuristic FRA algorithm, which belongs to the family of Greedy Algorithms, in order to solve the optimization problem in (20). This algorithm is suboptimal, but distributes resources according to each profile's weight (see Section IV-B) while ensuring that the minimum reserved requirements are met. First, the algorithm performs the reserved resource allocation. Then, the remaining resources are allocated proportionally according to each profile's weight. As seen in the previous section, weights are functions of the buffer state; thus, profiles with longer queues will benefit by being allocated more extra resources. This efficiently prevents buffer overflow while preserving the concept of network virtualization. In addition, profiles with small queues, or no queue, are still allocated a fraction of extra resources, thus ensuring that they can transmit any newly arriving packets and reducing the overall delay.

B. FRA versus Optimal Solution Analysis

To evaluate the gap and the tradeoff between optimal and suboptimal solutions, we used the Optimization Toolbox of MATLAB on Lenovo ThinkPad machine with Intelr Core™ i7 processor, 2.20 GHz CPU and 8 GB RAM. The optimal solution was found using the branch and bound algorithm. The random values of weights wp and vp were assigned and the problem was solved by both algorithms for the same setting. Then the average was taken over 1000 solutions. The average value of the objective function and the average time to run both algorithms are plotted in Fig. 4 and Fig. 5 as functions of increasing number of profiles. In Fig. 4 we can observe a constant gap of about 10 Kb=s between the solution found by FRA and the optimal solution. On the other hand, Fig. 5 shows that the FRA algorithm runs about 200 times faster than the optimal solution. This is the desired feature for the WSN nodes with limited energy and memory resources.

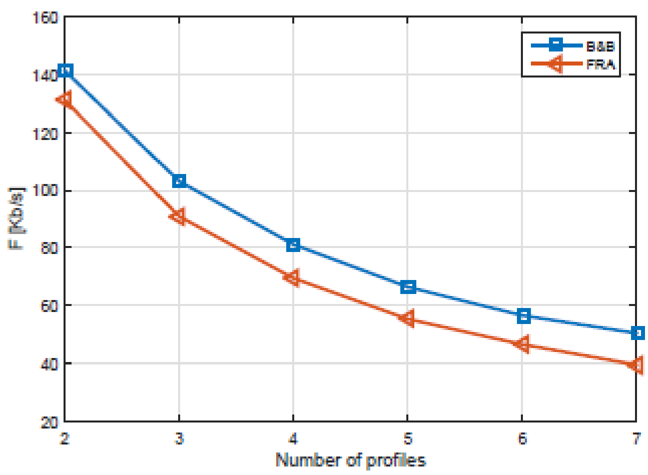

Fig. 4. Gap between optimal and suboptimal solutions.

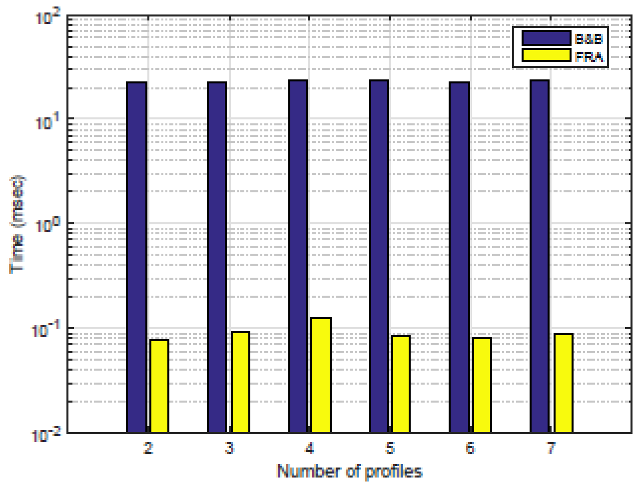

Fig. 5. Time to run the optimal and suboptimal solutions.

V. CONCLUSION

In this paper, we considered the approach to bridge the gap of WSNs virtualization on lower layers of communication stack. Our main goal was to realize the virtualization concept through abstraction of physical resources into logical units and managing their allocation to different profiles, supporting various applications. In order to satisfy heterogeneity and flexibility requirements, we assumed that all profiles can be categorized into two general groups: profiles producing periodical data and profiles producing busty data. Each group has different resource requirements. We solved the resource-sharing problem in a linear optimization framework, making sure that each individual profile's requirements were satisfied. Furthermore, we developed a two level scheduling mechanism that comprises the top-level main scheduler, which assigns resources to each profile, and a sequence of lower-level internal schedulers, that control flows inside each profile by assigning resources to sensors within the profile. We also proposed a reduced-complexity heuristic algorithm, which is used by the general scheduler to obtain a decision for each scheduling period. Moreover, an event detection mechanism was developed to increase the efficiency of resource-sharing and the flexibility of the scheduling. The simulation included two scenarios to validate the proposed virtualization scheme and its ability to isolate profiles as well as its effectiveness. The results show that the scheduler, based on the proposed algorithm, manages resource allocation effectively and keeps the profiles independent of each other, thus proving the feasibility of our solution for virtualization on the MAC layer. Moreover, the event detection mechanism showed good performance in a case, in which one of the profiles was oversaturated. The mechanism allowed this profile to ”borrow” resources not being used by another profile, which prevented the divergence of end-to-end delay, increasing the effectiveness of resource utilization in the underlying virtualization process and making it less sensible by individual profiles.

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