Probabilistic Bandwidth Assignment in Wireless Sensor Networks

Dawood Khan, Bilel Nefzi, Luca Santinelli, Ye-Qiong Song

To cite this version:

Dawood Khan, Bilel Nefzi, Luca Santinelli, Ye-Qiong Song. Probabilistic Bandwidth Assignment in Wireless Sensor Networks. The 7th International Conference on Wireless Algorithms, Systems, and Applications (WASA 2012), BJTU, Aug 2012, Yellow Mountains, China. pp.631-647. hal-00745184

HAL Id: hal-00745184
https://hal.inria.fr/hal-00745184

Submitted on 24 Oct 2012

Probabilistic Bandwidth Assignment in Wireless Sensor Networks

Dawood KHAN[1], Bilel NEFZI[2], Luca SANTINELLI[3], and YeQiong SONG[2]

[1] LAAS-CNRS, 7 avenue du Colonel Roche - 31077 Toulouse France
`khan@laas.fr`
[2] Université de Lorraine - LORIA, 615 Jardin Botanique - 54600 Villers-les-nancy France
`bilel.nefzi@loria.fr`, `song@loria.fr`
[3] INRIA, 615 Jardin Botanique - 54600 Villers-les-nancy France
`luca.santinelli@inria.fr`

Abstract. With this paper we offer an insight in designing and analyzing wireless sensor networks in a versatile manner. Our framework applies probabilistic and component-based design principles for the wireless sensor network modeling and consequently analysis; while maintaining flexibility and accuracy. In particular, we address the problem of allocating and reconfiguring the available bandwidth. The framework has been successfully implemented in IEEE 802.15.4 using an Admission Control Manager (ACM); which is a module of the MAC layer that guarantees that the nodes respect their probabilistic bandwidth assignment as well as the bandwidth assignment policy applied. The proposed framework also aims to accurately analyze the behaviors of communication protocols for energy-consumption and reliability purposes. We evaluate the probabilistic bandwidth assignment methods using CSMA/CA access protocol of IEEE 802.15.4. Furthermore, we analyze the behavior of the ACM and compare the performance of the network with and without using the ACM against the original standard. The simulation results show that the use of ACM increases the overall performance of the network.[4]

1 Introduction

Wireless Sensor Network (WSN) is considered as one of the key technologies for building the future Cyber-Physical Systems (CPS) as it allows today's information systems to monitor and control the physical environment. Often, monitoring and acting through the WSN forms feedback loops within which the control decision should be made in real-time. So the QoS (Quality of Service) of the existing WSNs must be enhanced since most of them mainly focus on the energy efficiency without performance guarantees in terms of bandwidth allocation and end-to-end delay. Designing and analyzing the QoS of WSNs is challenging because of the highly dynamic behavior of WSNs. Moreover, the WSNs need to operate with energy saving policies (e.g., duty-cycled nodes), which further complicates the design and analysis. In general, WSN analysis aims to evaluate the performance limits of a WSN deployment and to guarantee certain QoS. Therefore, it is essential to determine the *performance bounds* for end-to-end latency, energy, node buffer size, and reliability with respect to the network density, communication protocols, and network topology.

For preserving scalability, most of existing low-power WSNs adopt contention-based MAC. Providing guaranteed resource is even more challenging due to the random nature of channel access method and radio channel behavior; which can be described by a random probability distribution function. In addition, the node reliability/failure is probabilistic due to sudden sensor loss or decay of battery [1]. Therefore, it is often impossible to provide the deterministic QoS in WSNs.

Furthermore, in WSNs the event/packet (packet generating process) inter-arrivals follow also probabilistic distribution, for example due to the random back-offs in contention based protocols. Jung et al. [2] have shown that the protocols like Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), modeled using Markov chain, can only provide probabilistic resource guarantees.

Complexity and uncertainty makes WSNs intrinsically probabilistic. Thus, we require analysis methodologies for WSNs which provide the performance guarantees (QoS) with the probabilistic bounds.

In contrast to some recent probabilistic end-to-end delay analysis works [3], [4] which focus on the performance evaluation methods, the probabilistic approach developed in this paper offers a degree of flexibility,

---

[4] This work has been partially supported by the ANR Quasimodo project under grant ANR 2010 INTB 0206 01.

while allowing to cope with the dynamics of the environment (channel) and the applications in WSNs. The approach developed can be divided into two parts: i) the analysis, which is a theoretical framework for the analysis of WSNs based on probabilistic network calculus; ii) the Admission Control Manager (ACM), it is a MAC level implementation which ensures that the performance guarantees provided by the analysis part are met. This is achieved in the ACM by actively droping the packets based on the availability of bandwidth (considered probabilistic in this paper) and accepted performance guarantee (QoS) by a node (at the time of composition of the network); in a probabilistic manner.

1.1 Related Work

The IEEE 802.15.4 protocol is the popular standard for WSNs and specifies the Medium Access Control (MAC) sub-layer and the physical layer of Low-Rate Wireless Personal Area Networks (LR-WPANs) [5]. Some works in WSNs [6, 7], analyze the system with deterministic Network Calculus (NC) [8] to provide worst-case performance bounds for end-to-end latency and per-hop node buffer size. These frameworks rely on deterministic MAC protocols such as Time Division Multiple Access (TDMA) and deterministic routing protocols with worst-case analysis. Most often this contention free communication requires cluster tree topology [9] since the mesh topology uses contention based MAC for its reliability and robustness, thus limiting the mesh topologies to provide deterministic worst-case bounds.

WSNs are also required to be adaptive. Most of the approaches over the IEEE 802.15.4, tackle the problem of point-to-point communication within the star with a deterministic model. Relevant time guaranteed communication examples are iGAME [10] where the authors propose, using network calculus, a methodology to study the bandwidth allocation problem, and GSA [11] that tries to minimize the total number of unallocated time-slots by applying a scheduling-based strategy. WSNs have to cope with reactive paradigms, i.e. change the bandwidth allocation according to the events appearing in the environment. Examples of adaptive systems are [12] and [13], where the authors propose an adaptive solution designed to satisfy real-time constraints and maximize event detection efficiency under variable network load conditions. Focusing on adaptive WSNs, [14] advances on the analysis providing a component-based abstraction of WSNs wherein they apply QoS analysis with no strict timing constraints concerns. All these approaches tend to assume or guarantee a worst-case behavior of the WSN application. Instead, recent trends depicts the probabilistic approach, using stochastic network calculus [15, 16], as flexible enough to cope with the requirements of complex and adaptive WSNs application.

Contributions of the paper:

We propose a probabilistic methodology to dimension a WSN which is modeled with network components. Each network component is identified by a probabilistic arrival stream of data and a probabilistic communication resource guaranteed to it. By hierarchically composing components and probabilistic resource guarantees, it is possible to ease the overall analysis of the system and appropriately configure the network. In particular, we address the problem of allocating and reconfiguring the bandwidth assigned to each node using a MAC level ACM, and we do analysis of MAC-level protocols. The ACM avoid unnecessary transmissions when the bandwidth is not sufficient, which helps to reduce the number of collisions, thus saving energy. Our flexible methodology enables WSN designer to analyze different communication protocols either contention-based like CSMA/CA or contention-free, such as TDMA.

2 Component based WSN Modeling

Component based design envisions the system as a composition of components. Each component abstracts a process or a physical entity into a black box with interfaces to observe and drive its behavior. We model the WSN nodes as basic computational units which implement functions with temporal or QoS requirements [14]. Therefore, WSN nodes can be abstracted as components and the communication (and associated requirements) between nodes representing the link among components. This abstraction makes it easy to analyze and design a WSN; since we can abstract the cluster as one component resulting from the composition of other components. Moreover, component-based approach to the network modeling decomposes

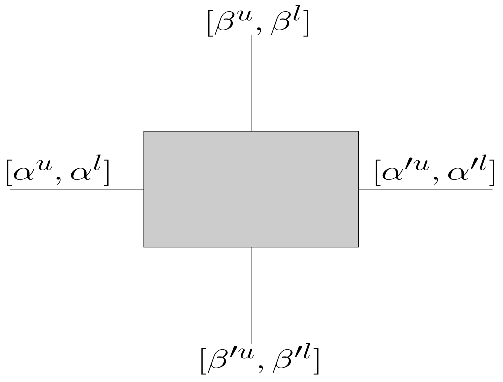


Fig. 1. A model of a component with its interface abstracting a part of a system.

the complexity of WSN systems into parts; which can be individually analyzed, thus reducing the overall complexity.

The component has an interface associated with it that describes the functional and non-functional behaviors of the component. The interface plays a central role in the component-based design of complex systems such as WSNs; because it defines the notion of composability: *two or more components are compatible if they work together properly.* Figure 1 depicts a generic WSN component and its component interface abstraction.

2.1 System model

We consider a WSN-based CPS for monitoring application where the system consists of a set of sensor nodes collecting data; which is then sent towards collection points (sinks) with bounded transmission delays. We also consider the hierarchical cluster-tree topology for its flexibility and scalability[5]. At the lowest level there are star topologies where a Coordinator (C) manages End-Devices (EDs) to form a leaf cluster. We can obtain a large scale network by extending and interconnecting the star topology clusters in a hierarchical manner creating the so called cluster-tree topology as shown is Figure 2. In the cluster-tree topologies coordinators manage either EDs (nd_i) or other coordinators C_k.

Without the loss of generality we assume that coordinators C_i do not sense (i.e., their assigned bandwidth is entirely redistributed to the children) and their main function is to maintain the topology and to hierarchically allocate the bandwidth.

2.2 Node Component model

Following the reasoning of Network Calculus and Real-Time Calculus [8, 17] we define abstraction for WSN components.

Workload and Bandwidth abstraction The cumulative functions R and S represent the amount of workload and bandwidth respectively; $R(t)$ and $S(t)$ give respectively the amount of workload required and bandwidth available/requested in the time interval $[0, t)$. While $R(t)$ describes a concrete trace of an event/packet stream; the arrival curve α, [8] provides an abstract model which provides an upper-bound on any admissible trace of event/packets in any time interval of length Δ. The same reasoning is applicable to the service $S(t)$ and its service curve β in the interval domain.

Generic aperiodic events are more appropriately modeled with a distribution function (hence a random variable) and its Cumulative Distribution Function (CDF) X, corresponding to the arrival distribution

---

[5] The assumptions are merely considered for the ease of explanation. However, the approach is valid for other application scenarios and network architectures.

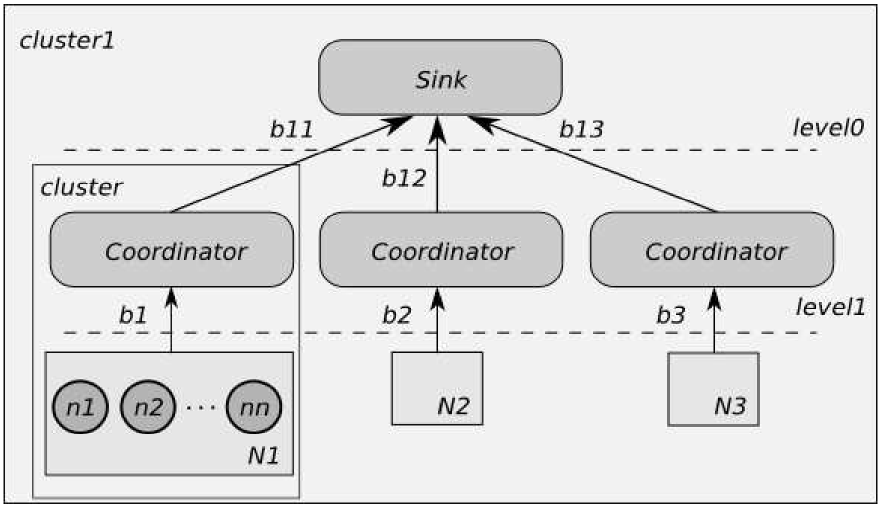


Fig. 2. WSN hierarchical architecture with end devices, control coordinators and clusters elements. Our simulation applies this architecture with $N_1 = 5$, $N_2 = 15$ and $N_3 = 10$.

of workload/events (of packet arrival). With probability distributions it is possible to better capture the aperiodicity of aperiodic events. We do not consider any particular CDF in our framework for the packet generating process (simulations most of the time consider a Poisson process) as it is not in the scope of this paper.

Definition 1 (Bounded Workload $R^+(t)$). *The "largest "cumulative work function such that the probability of CDF X having event count larger than or equal to $R^+(t)$ is lower than a threshold value of Ω.*

$$R^+(t) = \sup\{R(t)|P[X(t) \geq R(t)] \leq \Omega\}, \tag{1}$$

The extension of the NC to the aperiodic events results in the probabilistic bound where

$$\alpha(\Delta) \ : \ R^+(t) - R^+(s) \leq \alpha(t-s) \ \ \forall s < t, \tag{2}$$

with $\alpha(0) = 0$ and $\Delta = t - s$. The probabilistic arrival curve is the couple *curve*, *probability threshold* $\langle \alpha, \Omega \rangle$, where the probability threshold Ω represents the accuracy of α being the upper bound: *the probability that the events are upper bounded is* $1 - \alpha$.

Definition 2 (Bounded Bandwidth $S^-(t)$). *The "smallest "cumulative bandwidth function such that the probability of CDF Y having bandwidth smaller than or equal to $S^-(t)$ is lower than a threshold value Λ, where Y is the distribution for bandwidth availability.*

$$S^-(t) = \inf\{S(t)|P[Y(t) < S(t)] \leq \Lambda\}. \tag{3}$$

The service curve β lower bounds the available resources in any time interval of length Δ. Therefore, interval based probabilistic resource provisioning curve is represented as:

$$\beta(\Delta) \ : \ S^-(t) - S^-(s) \geq \beta(t-s) \ \ \forall s < t. \tag{4}$$

The probabilistic bandwidth provisioning curve is the couple $\langle \beta, \Lambda \rangle$ where the probability thresholds Λ gives the probability to find bandwidth provisioning below the lower bound β. The model is capable of modeling any possible bandwidth supply in the interval domain, including the bandwidth provisioning by the control coordinators in WSNs. Figure 3 shows the upper and lower bounds applied for building interfaces; in this work we are only interested in lower bounds on bandwidth and upper bounds on workload, which are sufficient to guarantee schedulability among components. In practice, finding the arrival function may be easy as usually the work-arrivals follow the Poisson distribution function for which there is a closed form expression. However, we can also model some other CDFs with the numerical-approximation for count models of the CDF or based on simulations, see [18]; again this is not the goal of the current work.

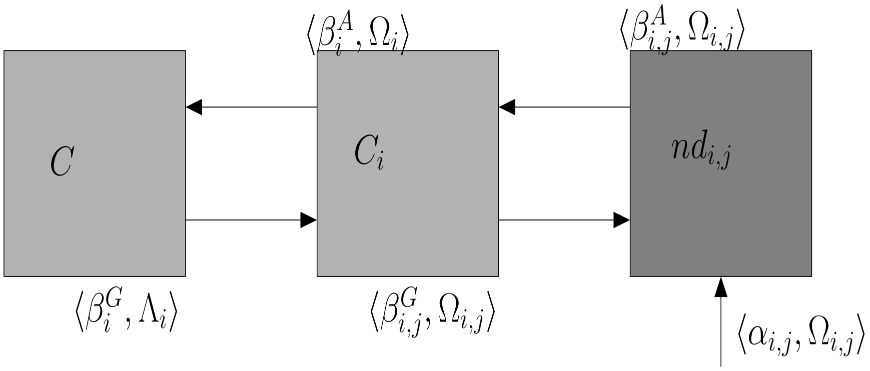


Fig. 3. WSN Component composition.

Component Interfaces To model interfaces of WSN components we make use of an approach similar to the real-time calculus [17] and to the assume/guarantee interfaces [19] tailored towards guarantees on the bandwidth-availability, and requests. *An interface of a generic network component has input and output variables related to event streams (the arrivals) and resource availability (the services).* We refer our interface model to *Probabilistic WSNs Interface* (PWI) with the intention of describing component behaviors in terms of curves and their threshold bounds, outlining its probabilistic nature and behavior.

In our framework, the input interface $\langle\alpha_{i,j}, \Omega_{i,j}\rangle$ (the node's bounded sensing rate) describes the j-th ED component $nd_{i,j}$ of the i-th cluster. The input event/packet stream translates[6] into a resource demand $\langle\beta_{i,j}^A, \Omega_{i,j}\rangle$; which defines the probabilistic bandwidth requested from the coordinator, *assumed* to transmit properly the messages resulting from the event sensing. This is the upper bounded bandwidth requested by a node from its coordinator, based on the nodes constraints such as QoS, deadline, end-to-end delay etc. The ED receives the bandwidth from its parent as $\langle\beta_{i,j}^G, \Lambda_{i,j}\rangle$, which is the lower bound bandwidth *guaranteed* by the coordinator. The tuple $(\langle\alpha_{i,j}, \Omega_{i,j}\rangle, \langle\beta_{i,j}^A, \Omega_{i,j}\rangle, \langle\beta_{i,j}^G, \Lambda_{i,j}\rangle)$ forms the PWI of an ED $nd_{i,j}$.

Similarly, the component link between the coordinator C_i and its parent coordinator is given by $\langle\beta_i^A, \Omega_i\rangle$ and $\langle\beta_i^G, \Lambda_i\rangle$ (in terms of bandwidth). These are the assumed (i.e. requested from parent coordinator) and the guaranteed bandwidth (i.e. by the parent coordinator) respectively. Similarly, the coordinator C_i's PWI formed with child nodes is given by $\langle\beta_i^G, \Lambda_i\rangle$ and $\langle\beta_{i,j}^G, \Lambda_{i,j}\rangle$. The Figure 3 depicts the network components, their interfaces and their composition. Moreover, ED components may also have outputs representing residual resource $(\langle\beta'_{i,j}, \Lambda'_{i,j}\rangle)$ and output-arrivals $(\langle\alpha'_{i,j}, \Omega'_{i,j}\rangle)$, see [20]. We do not discuss the residual resource and output-arrivals in this paper as the analysis here is resource-oriented.

3 WSN Modeling

With a probabilistic model for WSN components, the bandwidth assignment problem become a probabilistic problem. The bandwidth is allocated in accordance to the requests from the nodes. Each node communicates the tuple $\langle\beta^A, \Omega\rangle$ to its parent node; that is the probability of demand/request is bound by Ω. In other words it is going to ask for a service greater than β^A in $1-\Omega$ percent of the cases.

3.1 Bandwidth Assignment

With the probabilistic model, we can guarantee that a coordinator will provide β^G in Λ percent of the cases. For the remaining cases the resource provisioning is less than β^G with probability of $1-\Lambda$. The coordinator then, computes the resource share for the nodes it manages (lower layer nodes) by normalizing the available resource (allocated to the coordinator by its parent coordinator) with respect to the resource demand from its nodes.

---

[6] That is α_i and β_i^A have same distribution function.

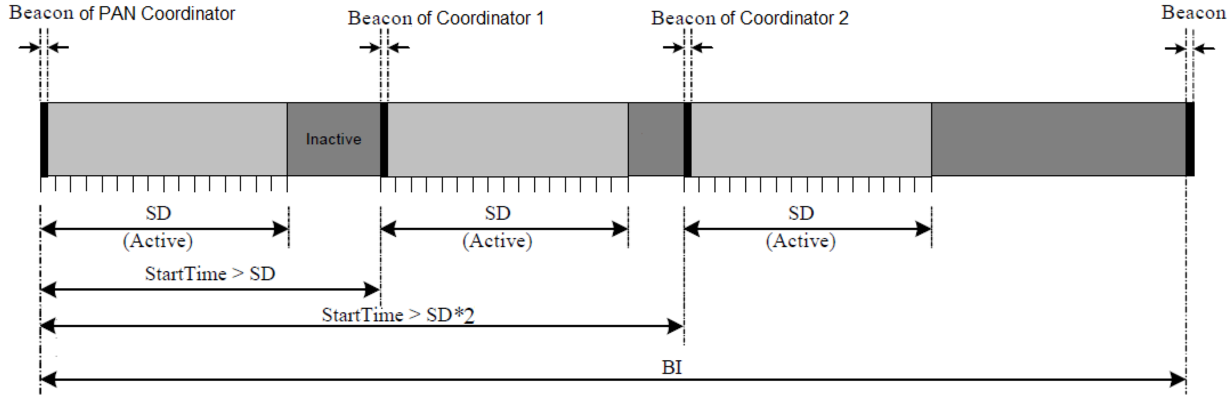


Fig. 4. The `superframe` structure of the PAN coordinator and an example of beacon scheduling of three coordinators.

The i-th coordinator of a cluster asks for the resource from its parent node; which guarantees a resource $\langle \beta_i^G, \Lambda_i \rangle$. The resource demand of C_i $\langle \beta_i^A, \Omega_i \rangle$ (requested by cluster coordinator C_i from its parent), comes form the combination of the resource requests of the nodes underneath, $\beta_i^A = \sum_{j=1}^{N_i} \beta_{i,j}^A$ with probability $\Omega_i = min_i\{\Omega_{i,j}\}$. Finally, the resource that C_i provides to its ED nodes $nd_{i,j}$ $\langle \beta_{i,j}^G, \Lambda_{i,j} \rangle$ is

$$\beta_{i,j}^G = \frac{\beta_i^G}{\beta_i^A} \beta_{i,j}^A$$
$$\Lambda_{i,j} = \Lambda_i - \Omega_{i,j} - \Lambda_i \cdot \Omega_{i,j} \tag{5}$$

where $\Lambda_{i,j}$ is the probabilistic of the interface.

For the bandwidth allocation among the coordinators; the parent coordinators normalize the available resource using the accumulated resource requests $\sum \beta_i^A$ of its children cluster C_is. The normalized resource is then distributed among children cluster nodes with a probabilistic guarantee computed using the probability guarantee of the resource-request, and the probabilistic guarantee of the coordinators resource availability. The resource guarantee for cluster coordinators follows the same principle as in Equation (5) where instead of nodes $nd_{i,j}$ is applied to the coordinators C_i.

3.2 Bandwidth based Component Composability

The probabilistic model allows us to a define flexible relationship among the curves; consequently, this results in the notion of probabilistic composability.

Definition 3 ("Greater than or Equal to "($\succeq$). *We define the greater than or equal to operator*[7] *($\succeq$) over two probabilistic curves $\langle \omega, \Omega \rangle$ and $\langle \lambda, \Lambda \rangle$ with ω and λ the curves and Ω and Λ their respective bounding probabilities, as $\langle \omega, \Omega \rangle \succeq \langle \lambda, \Lambda \rangle \iff \omega \geq \lambda \wedge \Omega \geq \Lambda$*

The following lemma provides the probabilistic guarantees for the composition of two WSN components; wherein one component is assuming a service and the second component is guaranteeing some service. The Lemma 1 is the probabilistic bound on the service that a component will offer to its workload after the composition, i.e. after a cluster coordinator guarantees some service.

Lemma 1 (Resource Reliability). *Given two probabilistic curves $\langle \beta^A, \Omega \rangle$ and $\langle \beta^G, \Lambda \rangle$ respectively an upper and lower bounding probabilistic curves, then* $\min\{1, \Omega + \Lambda - \Omega \cdot \Lambda\}$ *is the service-reliability probability.*

Proof. The output response of the component depends on two inputs, which are β^A and β^G. We know that probability of β^A being larger is Ω and the probability of β^G being smaller is Λ. Therefore, probability of the

---

[7] Based on the concept of stochastic dominance and stochastic ordering used in decision theory and decision analysis

components service reliability depends on, $P[\beta^A \wedge \beta^G]$. This probability for the independently distributed random variables can be found as $P[\beta^A] + P[\beta^G] - P[\beta^A] \cdot P[\beta^G] = \Omega + \Lambda - \Omega \cdot \Lambda$, and since probability can never be larger than one, we have $\min\{1, \Omega + \Lambda - \Omega \cdot \Lambda\}$.

With this premise, it is possible to define the probabilistic composability for WNSs.

Theorem 1 (Probabilistic Composability). *Given two components i and j and two probabilistic curves $\langle \beta_i^G, \Omega_i \rangle$ and $\langle \beta_j^A, \Lambda_j \rangle$ being respectively the probabilistic lower bound to the resource provisioning (the guarantee) of the i-th component and the probabilistic upper bound to the resource demand (the assumption) of the j-th component; then i and j are composable with a probability p iff*

$$\langle \beta_i^G, \Omega_i \rangle \succeq \langle \beta_j^A, \Lambda_j \rangle \ \wedge \ p \leq min\{1, \Omega_i + \Lambda_j - \Omega_i \cdot \Lambda_j\} \tag{6}$$

Proof. The theorem follows as a consequence of Lemma 1

4 Application to IEEE 802.15.4

4.1 CSMA/CA using IEEE 802.15.4 `superframe` structure

In the beacon-enabled mode of IEEE 802.15.4, a coordinator in a Personal Area Network (PAN) periodically sends beacon frames to synchronize the associated nodes. The standard defines a `superframe` structure between two successive beacon transmissions. The `superframe` structure is divided into an active portion and a low power inactive portion. Figure 4 shows an example of the `superframe` structure. The `superframe` structure is specified by two values; the `superframe` duration (SD) which defines the active portion and the beacon interval (BI) which defines the interval between two consecutive beacons. The SD and BI periods are defined using two parameters; the `superframe` order (SO) and the beacon order (BO), respectively. Equation (7) gives the definition of SD and BI as a function of SO and BO, respectively. In this equation, `aBaseSuperframeDuration` is a constant value defined by the standard which is equal to $15.36ms$

$$\left.\begin{aligned} BI &= aBaseSuperframeDuration \cdot 2^{BO} \\ SD &= aBaseSuperframeDuration \cdot 2^{SO} \end{aligned}\right\} \qquad 1 \leq SO \leq BO \leq 14 \tag{7}$$

The standard supports the cluster tree topology wherein the coordinators form a multi-hop tree. The root coordinator is called PAN coordinator. Every coordinator provides a synchronization services (through beacon transmissions) to other devices or other coordinators. Therefore, to avoid beacon collision a beacon scheduling scheme has to be used among coordinators. The IEEE 802.15.4 standard imposes that BO and SO have to be equal for all `superframes` on a PAN and suggests the scheduling of beacons so that active periods of neighbor coordinators and two-hop neighbor coordinators do not overlap. Figure 4 gives an example of beacon scheduling of three coordinators.

Each child forwards data only during its parents active period. In particular, to transmit data to the PAN coordinator, the child coordinators and the EDs must transmit their data during the active period of the PAN coordinator. Therefore, the maximum bandwidth to be assigned by the PAN coordinator, can be the maximum number of messages (noted `MaxNbMsgs` hereafter) that are to be transmitted to the PAN coordinator during the SD of every BI. We have done some preliminary simulations to determine suitable values of `MaxNbMsgs`. Of course, it depends on the duration of the SD period. Table 1 shows the values of `MaxNbMsgs` as a function of SO.

4.2 Admission control manager

The ACM, Figure 5, is a component of the MAC layer in every node of WSN. The ACM ensures that the *bandwidth assignment* policy is respected. The network has two working stages; a setup stage and a normal

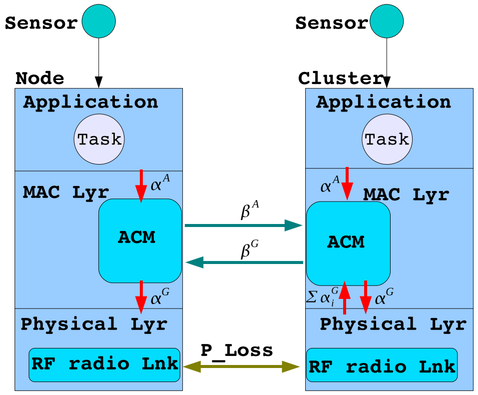


Fig. 5. System view and ACM.

working stage. The setup stage works as follows. First, the PAN coordinator gathers service requests from all the nodes of the network. Then, it runs the bandwidth assignment algorithm[8]. Finally, the bandwidth determined by the algorithm for each node is assigned as the guaranteed service to cluster coordinators and EDs. During the normal working stage the ACM becomes active. We note that the PAN coordinator can decide to re-execute the setup stage sometime later. The decision can be based on the reception of new service requests or changes in the network; like node mobility or death.

The ACM constantly monitors all the packets received by the MAC layer (from upper and lower layers) and decides which ones are accepted or dropped, exercising admission control tests. The decision to drop packets is based on the assigned guaranteed service to the node, $\langle \beta^G, \Lambda \rangle$. However, the ACM of the ED and the ACM of the cluster coordinators work in a different manner. For EDs, it monitors only the packets received from the application layer and ensures that the number of forwarded packets to the parent node does not exceed β^G. The Λ^G is not taken into consideration in the packet dropping process of the EDs ACM. For cluster coordinators, the ACM monitors the packets received from children EDs and the application layer. The dropping of the packets received from children EDs is based on Λ^G of the transmitting ED; while as it is based on the β^G of the cluster coordinator for the packets it receives from its application layer. We note that the ACM of the PAN coordinator monitor all received packets but does not drop any of them in case it is the destination. We now can define a metric based on the packets dropped by the ACM, called as packet-loss ration as:

Definition 4 (Packet-Loss-Ratio(PLR)). *The packet-lost-ratio (PLR) for i^{th} node is defined as $l_i(t) = \frac{L_i(t)}{R_i(t)}$, where $L_i(t)$ gives the packets lost in an interval $(0, t]$.*

This is be achieved by keeping two counter in an ACM; that is to count L and R. This gives us an estimate of PLR at each event (i.e. packet dropped or packet arrived). Therefore, intuitively for a given bandwidth assignment higher PLR means lower energy usage by a node; since the unnecessary transmission due to limited bandwidth were avoided. This is because energy-saving due to dropping dominates the total energy consumption; simply put ACM tries to ensure than energy is only consumed for potentially successful transmissions. Although, higher PLR may seem to indicate a noticeable performance issue (QoS); however, it is important to note that the packets are dropped in an ACM based on the agreed level loss indicated by the probabilistic bounds. Moreover, higher PLR does not always indicate a problem; for example when high PLR at the PAN node is acceptable (as it may be within required QoS level).

Let us take the example of an ED which has obtained $\langle \beta^G = 2\ \texttt{packets/superframe}, \Lambda^G = 50\% \rangle$ from its parent, named C_F. The ACM of ED is responsible for ensuring that no more than two packets are transmitted to its parent C_F every `superframe`. For example, if the application generates four packets during the actual `superframe`, two of them will be dropped. The ACM of the C_F transmits the two received packets to its own parent only 50% of the time; for other 50% of the time the ACM can transmit zero or one packet to its own parent (i.e. 50% of the time, it may drop one or both packets).

---

[8] Based on the implementation of Equation 5.

Table 1. Maximum number of messages that can be transmitted to the PAN coordinator

SO	2	3	4
`MaxNbMsgs`	80	120	220

4.3 Simulation Setup

As a test case we consider the network shown in Figure 2. It is composed of one PAN coordinator (Network Coordinator), three cluster coordinators and 30 EDs, five EDs attached to the first coordinator, 15 EDs attached to the second coordinator and 10 EDs attached to the third coordinator.

All coordinators, including the PAN coordinator, have a non overlapping active periods. The network uses the ZigBee [21] tree routing protocol. The simulation is performed using OPNET simulator [22], and Table 2 summarizes all the simulation parameters.

Table 2. General simulation parameters

Application parameters		
Packet length		100 bits
Service Request $\langle \alpha_i^A(p/s), \Omega_i^A \rangle$ first set of sim		variable
Service Request $\langle \alpha_i^A(p/s), \Omega_i^A \rangle$ second set of sim		$\langle 2\,p/s, 1 \rangle$
Inter-arrival distribution		constant
Destination		PAN coordinator
P_G		0.9
Network parameters		
Cm, Rm and Lm		20, 3 and 2
MAC parameters		
`superframe`	BO	8
	SO	2, 3 and 4
Beacon Start Time	C_1, C_2 and C_3	0.49s, 1s and 1.7s
CSMA/CA	Minimum Back-off Exponent	3
	Maximum Back-off Number	4
Acknowledgment		disabled
PHY parameters		
Data rate		250 kb/s
P_{loss}		0.1
Other parameters		
Simulated duration		900s
Energy model		Micaz

We performed two sets of simulations. The first one illustrates the behavior of the ACM. The second one compares the results of our bandwidth allocation scheme using the ACM against the original IEEE 802.15.4 standard. The simulations and the results are described next.

4.4 The behavior of the ACM

We fix the value of SO to three and varied the EDs service request. The duration of the active period is constant and $\beta^G = 120\,\texttt{packets/superframe}$, see Table 1. We also note that coordinators do not transmit messages. We report the bandwidth assigned by the PAN coordinator to each ED; the total number of packets sent; the total number of packets received by the PAN coordinator (which is the destination); the total number of packets dropped by the ACM; and the total number of packets dropped due to CSMA/CA failure or collision.

Table 3 illustrates the obtained results. We observe that if the total service request is less than the guaranteed bandwidth, cases of $\langle \alpha_i^A = 0.5(pkts/s), \Omega_i^A = 0.8 \rangle$ and $\langle \alpha_i^A = 1(pkts/s), \Omega_i^A = 0.8 \rangle$, the ACM drops a few packets. In fact, the ACMs of EDs do not drop any packets, since the guaranteed service is higher than the requested service and the packet inter-arrival distribution is constant. However, since the

Table 3. Results of the first set of simulations. pkts, sf, and Nb designate packets, `superframe`, and number respectively.

$\langle \alpha_i^A(pkts/s), \Omega_i^A \rangle$	$\langle 0.5, 0.8 \rangle$	$\langle 1, 0.8 \rangle$	$\langle 2, 0.8 \rangle$
$\langle \beta_i^A(pkts/sf), \Omega_i^A \rangle$	$\langle 1.96, 0.8 \rangle$	$\langle 3.96, 0.8 \rangle$	$\langle 7.86, 0.8 \rangle$
Total service requests	58.98	117.96	235.92
$\langle \beta^G(pkts/sf), \Lambda^G \rangle$	$\langle 4, 0.98 \rangle$	$\langle 4, 0.98 \rangle$	$\langle 4, 0.98 \rangle$
Nb of created pkts	13500	26970	53940
Nb of received pkts	5462	8252	8337
Nb of dropped pkts by the ACM	114	243	26694
Nb of dropped pkts due to CSMA/CA failure or collision	7924	18475	18909

guaranteed probability is not equal to one, some of the packets will be dropped by the ACMs of cluster heads. When the total service request exceeds the guaranteed bandwidth the ACMs of EDs drop the packets to respect the allocated bandwidth; that is $\langle \alpha_i^A = 2(pkts/s), \Omega_i^A = 0.8 \rangle$. We also notice that the admission of packets by ACM for transmission does not guarantee the packets successful transmission. This is illustrated by the number of dropped packets due to CSMA/CA failure or collisions. In fact, multiple nodes may try to transmit accepted packets at the same time which results in a collision. We recall also that transmissions are not acknowledged and the duty cycle is equal to 3.125%. Nevertheless, the use of ACM minimizes the number of dropped packets due to collision or CSMA/CA failure as we will see in the next subsection.

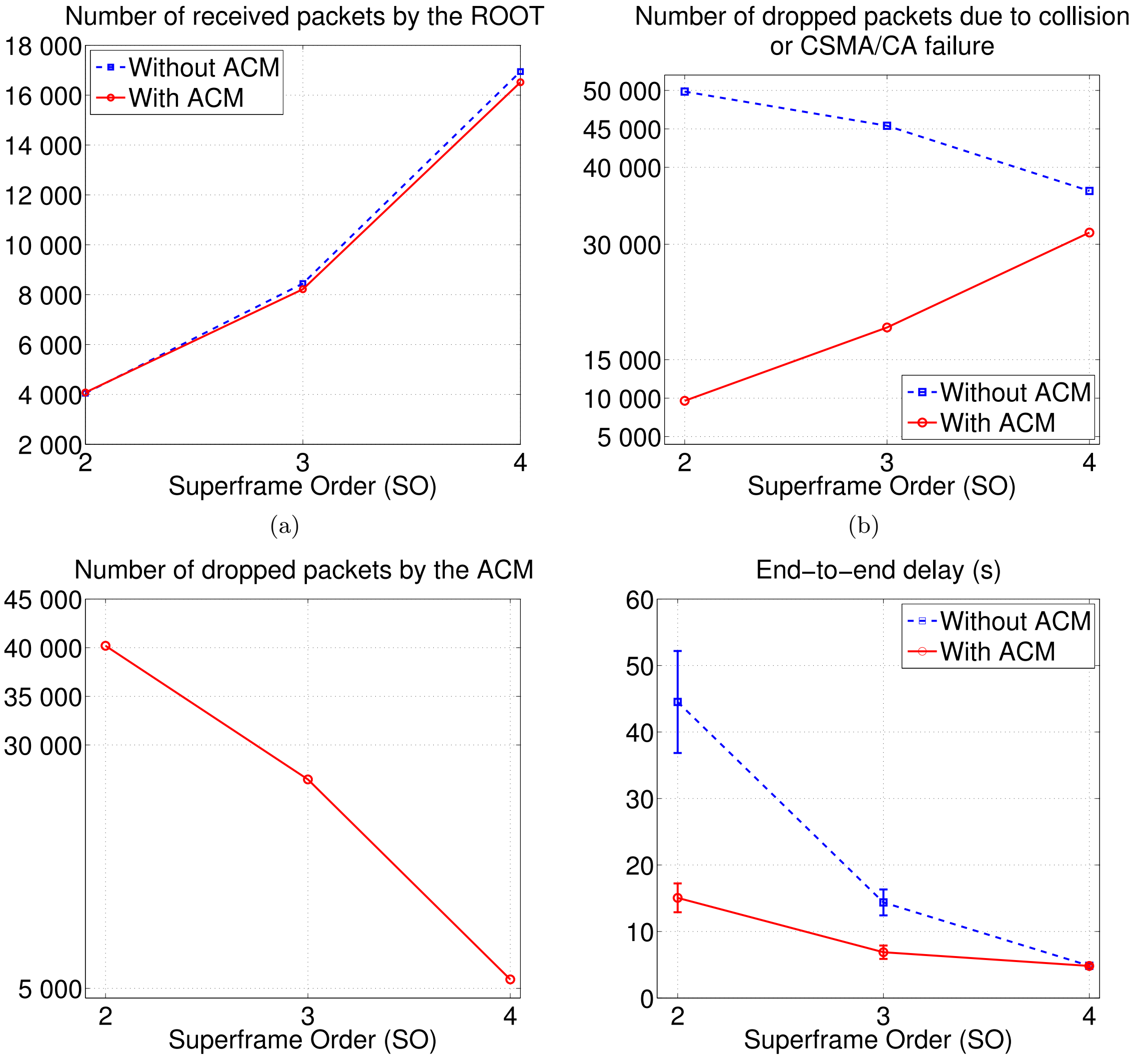
4.5 Comparison with the original standard

In this simulation set, we fixed the service request of EDs and varied the SO. We measure the number of packets received by the PAN coordinator, the number of packets dropped either due to CSMA/CA failure or due to collisions, and the average end-to-end delay of the received packets. We compare the results of our bandwidth allocation scheme using the ACM against the original IEEE 802.15.4 standard (without the use of any bandwidth allocation scheme and control). For comparison we have set the service request probability (Ω_i^A) of each ED to 1.

Figure 6 shows the simulation results. Figure 6(a) corresponds to the number of the received packets by the PAN coordinator. We can notice that when using ACM and bandwidth-allocation: the number of received packets increases as SO increases. In fact, increasing SO means increasing the guaranteed bandwidth as pointed out in Table 1; therefore, each ED receives higher allocated bandwidth. We also observe that we obtain similar results for the number of received packets with and without the use of the ACM. However, both versions (with and without the ACM) do not follow the same path to obtain these similar results. Indeed, without using the ACM, dropped packets are caused by collisions or CSMA/CA failure. However, when the ACM is used, packets are dropped mainly by the ACM (though some packets are dropped by collisions or CSMA/CA failures). Figure 6(b) and figure 6(c) illustrates this result. The use of the ACM, therefore, avoids useless transmissions; as the chance of failure/collision increases due to the limited bandwidth. The ACM ensures that the allocated bandwidth is respected by dropping the packets before they attempt their transmission; which can reduce the number of collisions. Consequently, this decreases the end-to-end delay. Figure 6(d) shows the end-to-end delays of the received packets with and without the use of the ACM. Indeed, the results show that the use of the ACM decreases the end-to-end delay of the received packets. Another direct consequence of actively dropping overloaded packets by ACM instead of leaving them dropped because of too collisions is that there will be less retransmissions, so less energy waste.

5 Conclusions

In this paper we proposed an approach which applies a component based and hierarchical cluster-tree topologies for WSNs by modeling and analyzing such distributed systems in a probabilistic approach. We also proposed a MAC level Admission Control Manager (ACM) which does bandwidth assignment and control for the required performance guarantees (QoS) in a probabilistic manner using the probabilistic bounds.



(a) (b) (c) (d)

Fig. 6. Results of the second simulation set. "Without ACM" corresponds to the standard IEEE 802.15.4.

Our framework offers flexibility of a probabilistic approach, therefore, we are able to provide probabilistic guarantees for the system functionality, or degradation; in harsh environments and complex systems.

The probabilistic bandwidth assignment approach has been successfully implemented in IEEE 802.15.4 through the admission control manager. The simulation results showed that the ACM drops packets to respect the bandwidth assigned by the PAN coordinator (to every device in the network). Consequently, we were able to decrease the number of useless transmissions while providing the same performance; that is the number of received packets. Which ensures that the energy is conserved by avoiding useless transmissions. Moreover, we were able to ameliorate the end-to-end delay. Nevertheless, because of the inherent behavior of CSMA/CA, the dropping of packets due to the collisions cannot be totally prevented by the use of ACM. Moreover, we can apply our framework to a contention-free access protocol with more success.

In the future we intend to improve our framework by: i) applying it to a contention-free access protocol; ii) applying the analysis to different network topologies; iii) inferring network characteristics such as the lifetime; and iv) checking its applicability to real WSN platforms/testbeds in the dynamic network conditions and testing the adaptivity of the probabilistic approach.

References

1. Sastry, S., Radeva, T., Chen, J., Welch, J.L.: Reliable networks with unreliable sensors. In: Proceedings of the 12th international conference on Distributed computing and networking. ICDCN'11 (2011) 281–292
2. Jung, C., Hwang, H., Sung, D., Hwang, G.: Enhanced markov chain model and throughput analysis of the slotted csma/ca for ieee 802.15.4 under unsaturated traffic conditions. Vehicular Technology, IEEE Transactions on **58**(1) (jan. 2009) 473 –478
3. Wang, Y., Vuran, M., Goddard, S.: Cross-layer analysis of the end-to- end delay distribution in wireless sensor networks. In: 30th IEEE Real-Time Systems Symposium, IEEE Computer Society (December 2009) 138–147
4. He, W., Liu, X., Zheng, L., Yang, H.: Reliability calculus: A theoretical framework to analyze communication reliability. In: 30th International Conference on Distributed Computing Systems, ICDCS '10, IEEE Computer Society (2010) 159–168
5. LAN-MAN Standards Committee of the IEEE Computer Society: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). IEEE Press (2006)
6. Schmitt, J.B., Roedig, U.: Sensor network calculus - a framework for worst case analysis. In: Prooceedings of Distributed Computing in Sensor Systems, First IEEE International Conference, DCOSS 2005. (2005) 141–154
7. She, H., Lu, Z., Jantsch, A., Zheng, L.R., Zhou, D.: Deterministic worst-case performance analysis for wireless sensor networks. In: Wireless Communications and Mobile Computing Conference, 2008. IWCMC'08. International. (aug. 2008) 1081 –1086
8. Le Boudec, J.Y., Thiran, P.: Network calculus: A Theory of Deterministic Queuing Systems for the Internet. Springer-Verlag New York, Inc. (2001)
9. Jurcík, P., Koubaa, A., Severino, R., Alves, M., Tovar, E.: Dimensioning and worst-case analysis of cluster-tree sensor networks. ACM Transactions on Sensor Networks **7** (2010)
10. Koubâa, A., Alves, M., Tovar, E., Cunha, A.: An implicit gts allocation mechanism in ieee 802.15.4 for time-sensitive wireless sensor networks: theory and practice. Real-Time Syst. **39**(1-3) (2008) 169–204
11. Na, C., Yang, Y., Mishra, A.: An optimal gts scheduling algorithm for time-sensitive transactions in ieee 802.15.4 networks. Comput. Netw. **52**(13) (2008) 2543–2557
12. Huang, Y.K., Pang, A.C., Hung, H.N.: An adaptive gts allocation scheme for ieee 802.15.4. IEEE Transactions on Parallel and Distributed Systems **19**(5) (2008) 641–651
13. C. Nastasi, M. Marinoni, L. Santinelli, P. Pagano, G. Lipari, G. Franchino: BACCARAT: a Dynamic Real-Time Bandwidth Allocation Policy for IEEE 802.15.4. In: To appear in the Proceedings of IEEE Percom 2010, International Workshop on Sensor Networks and Systems for Pervasive Computing (PerSeNS 2010), Mannheim, Germany, March 29-April 2, 2010., IEEE (2010)
14. Santinelli, L., Chitnis, M., Nastasi, C., Checconi, F., Lipari, G., Pagano, P.: A component-based architecture for adaptive bandwidth allocation in wireless sensor networks. In: IEEE Symposium on Industrial Embedded Systems (SIES). (2010)
15. Jiang, Y.: A basic stochastic network calculus. SIGCOMM Comput. Commun. Rev. **36**(4) (2006) 123–134
16. Xie, J., Jiang, Y.: Stochastic network calculus models under max-plus algebra. In: Proceedings of the Global Communications Conference, 2009. GLOBECOM 2009, Honolulu, Hawaii, USA, 30 November - 4 December 2009. (2009) 1–6
17. Thiele, L., Chakraborty, S., Naedele, M.: Real-time calculus for scheduling hard real-time systems. In: ISCAS. Volume 4. (2000) 101–104
18. Khan, D., Navet, N., Bavoux, B., Migge, J.: Aperiodic traffic in response time analyses with adjustable safety level. In: 14th IEEE International Conference on Emerging Techonologies and Factory Automation - ETFA. (2009)
19. Wandeler, E., Thiele, L.: Interface-based design of real-time systems with hierarchical scheduling. In: RTAS. (2006) 243–252
20. Santinelli, L., Meumeu Yomsy, P., Maxim, D., Cucu-Grosjean, L.: A component-based framework for modeling and analysing probabilistic real-time systems. In: 16th IEEE International Conference on Emerging Technologies and Factory Automation. (2011)
21. : Zigbee Specification Document 053474r17. `http://www.zigbee.org` (January 2008)
22. : OPNET, OPNET Simulator, v 15.0. `http://www.opnet.com`