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Review Article

A Survey of Adaptive and Real-Time Protocols Based on IEEE 802.15.4

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The IEEE 802.15.4 standard is a protocol that has been widely used in many applications exploiting wireless sensor networks (WSNs). However, it does not provide any means of differentiated services to improve the quality of service (QoS) for time-critical and delay-sensitive events. Furthermore, adaptive throughput performance for individual nodes cannot be supported with the current specifications. In this survey paper, we first discuss the negative aspects of IEEE 802.15.4 MAC in contention access period, contention-free period, and the overall cross-period, respectively, in terms of adaptive and real-time guarantees. We then give an overview on some interesting mechanisms used in existing adaptive and real-time protocols in compliance with IEEE 802.15.4. Careful examination of such research works reveals that by optimizing the original specifications and dynamically adjusting the protocol parameters, the total network efficiency can be significantly improved. Nevertheless, there are still certain challenges to overcome in pursuing the most appropriate protocol without introducing any unacceptable side effects.

1. Introduction

Wireless sensor networks (WSNs) are being deployed in a variety of real-life applications, such as factory automation [1], distributed and process control [2, 3], real-time monitoring of machinery health [4, 5], detection of liquid/gas leakage, and radiation check [6]. This has been made possible by the adoption of two industrial standards: (1) IEEE 802.15.4 standard [7], which defines the physical and medium access control (MAC) layers of the protocol stack; and (2) the ZigBee specification [8], which covers the networking and application layers.

IEEE 802.15.4, in particular, is the emerging next-generation standard uniquely designed for low-rate wireless personal area networks (LR-WPANs) [7]. And it has become one of the most popular communication protocols for wireless interconnection of fixed/or portable devices [9]. Nevertheless, the current specifications of IEEE 802.15.4 lack quality of service (QoS) mechanisms that are required for adaptive and real-time WSN applications. Actually, it has been known that WSNs based on IEEE 802.15.4 suffer from severe adaptivity and timeliness issues, especially when power management is enabled for conserving energy.

In many WSN applications, different data packets may have different importance depending on the information they contain. For example, an alarm message should have priority over a packet with noncritical sensor readings. Unfortunately, IEEE 802.15.4 treats all packets in the same way, which may result in unfairness and degradation of the network performance, particularly in high-load conditions. In addition, the MAC design is inadequate to deal with when certain nodes are sending data more frequently compared to others. Also, the traffic and network conditions in a WSN are usually very dynamic because of the noisy wireless channel and the failure probability of sensor nodes. Hence, data transmissions should be flexible enough to support a wide variety of scenarios to adapt to the actual operating conditions. All of the above requirements make the original MAC design of IEEE 802.15.4 inadequate to achieve network efficiency. Providing QoS support in WSNs for improving their timeliness and adaptivity performance under severe energy constraints has attracted tremendous research works [10–12] recently. Lots of adaptive and real-time protocols based on IEEE 802.15.4 have been proposed. In an adaptive and real-time protocol, each node is expected to perform real-time computations and to send high-quality data with guaranteed QoS [13]. Communications must be both adaptive and conducted on time. In fact, the standard IEEE 802.15.4 MAC protocol shows great potential for flexibly fitting different requirements of WSN applications by adequately setting its parameters (low-duty cycles, guaranteed time slots (GTS)) [14].

In this survey paper, we will talk about limitations of original IEEE 802.15.4 MAC protocol in terms of contention access period (CAP), contention-free period (CFP), and the whole in detail. Further, a number of adaptive and real-time protocols based on IEEE 802.15.4 are discussed. According to these existing research works, we finally present an in-depth analysis of current challenges and technological trends, and possible solutions are predicted.

The remainder of this paper is organized as follows. Section 2 gives an overview of IEEE 802.15.4 standard specifications. In Section 3, we will discuss major features of IEEE 802.15.4 MAC in CAP that limit network efficiency, and look at current approaches to overcome these constraints. Further analysis and discussions of such approaches are also presented in this section. Sections 4 and 5 talk about similar issues in CFP and overall cross-period, respectively. Finally, Section 6 concludes this paper.

2. Overview of IEEE 802.15.4 Medium Access Control

According to the standard IEEE 802.15.4 [7], it defines two different channel access methods: beacon-enabled mode and nonbeacon-enabled mode.

In beacon-enabled mode, a PAN is formed by a PAN coordinator, which is in charge of managing the whole network, and optionally, by one or more coordinators which are responsible for a subset of nodes in the network. beacon frames are periodically sent by the PAN coordinator to identify its PAN and synchronize nodes that are associated with it. The PAN coordinator defines a superframe structure characterized by a *beacon interval* (BI) and a *superframe duration* (SD). BI specifies the time between two consecutive beacons, and consists of an active period and, optionally, an inactive period. The active period, also called superframe, is corresponding to SD and can be divided into 16 equally sized time slots, during which frame transmissions are allowed. While during the inactive period, all nodes may enter a low-power state to save energy. The superframe structure of beacon-enabled mode is depicted in Figure 1.

BI and SD are determined by two parameters, the *beacon order* (BO) and the *superframe order* (SO), respectively, which are broadcasted by the coordinator via a beacon to all nodes. They are defined as follows:

$$\begin{gathered} \mathrm{BI} = \mathrm{aBaseSuperframeDuration} * 2^{\mathrm{BO}} \\ \mathrm{SD} = \mathrm{aBaseSuperframeDuration} * 2^{\mathrm{SO}} \\ \text{for } 0 \leq \mathrm{BO} \leq \mathrm{SO} \leq 14. \end{gathered} \tag{1}$$

SD can be further divided into a CAP and a CFP. During the CAP, a slotted CSMA/CA (carrier sense multiple access with collision avoidance) algorithm is used for channel access. While in the CFP, communication occurs in a TDMA (time division multiple access) style by using a number of GTSs, preassigned to individual nodes. It is also worth pointing out that the nonbeacon-enabled mode is entirely contention based. There is no superframe and nodes are always active. In this paper, we only select the more commonly used beacon-enabled mode as a basic operating mode in consideration.

2.1. CSMA/CA. The slotted CSMA/CA backoff algorithm mainly depends on three variables: (1) the *backoff exponent* (BE) enables the computation of the backoff delay, which is the slot periods a device must wait before attempting to access the channel; (2) the *contention window* (CW) represents the number of backoff periods during which the channel must be sensed idle before the transmission can start; (3) the *number of backoffs* (NB) represents the number of times the CSMA/CA algorithm is required to backoff while attempting to access the channel.

Upon receiving a data frame to be transmitted, the slotted CSMA/CA algorithm performs the following steps.

Step 1. A set of state variables is initialized: NB $= 0$, CW $= 2$, and BE $=$ *macMinBE*. If the battery life extension variable is set, the maximum value of BE can be only 2.

Step 2. The MAC layer delays for a random number of complete slot periods in the range 0 to $2^{\mathrm{BE}} - 1$, which is generated to initialize a backoff timer.

Step 3. After the completion of the backoff periods, a clear channel assessment (CCA) is performed to check the state of the wireless medium.

Step 4. If the channel is busy, the state variable are updated as follows: $\mathrm{NB} = \mathrm{NB} + 1$, $\mathrm{BE} = \mathrm{Min}(\mathrm{BE} + 1, \mathit{macMaxBE})$, and $\mathrm{CW} = 2$. If the maximum number of backoffs ($\mathrm{NB} = \mathit{macMaxCSMABackoffs} = 5$) is reached, the algorithm shall terminate with a channel access failure status. Otherwise, it falls back to *Step 2*.

Step 5. If the channel is assessed to be idle, the MAC sublayer must ensure that the contention window is expired before starting transmission. For this, the MAC sublayer first decrement CW by one. If CW $= 0$, then the frame is transmitted. Otherwise, the algorithm must go back to *Step 3* to perform a second CCA. Figure 2 represents the above steps graphically.

2.2. GTS Mechanism. Upon receiving the request, the coordinator first checks the availability of GTS slots in the current superframe, based on the remaining length of the CAP and the desired length of the requested GTS. Provided there is sufficient capacity in the current superframe, the coordinator determines, based on a first come first serviced (FCFS) fashion, a device list for GTS allocation in the next superframe, and informs the device about the allocation of slot in the GTS descriptor in the following beacon frame.

GTS deallocation can be performed by the coordinator or by the device itself. For device initialized deallocation, it sends GTS request with characteristic-type subfield set to zero using CSMA/CA during CAP. However, in most cases, the PAN coordinator has to detect the activities of the devices

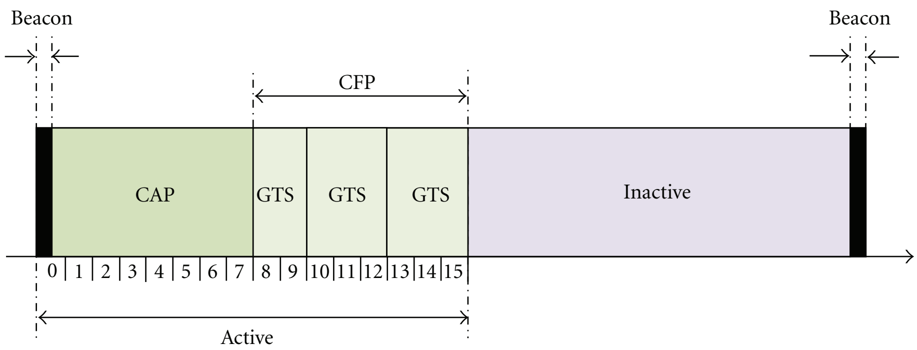


Figure 1: IEEE 802.15.4 superframe structure.

occupying GTSs and determine when the devices stop using their GTSs. If the coordinator does not receive data from the device in the GTS for at least 2*n superframes, the coordinator will deallocate the GTS with starting slot subfield set to zero in the GTS descriptor field of the beacon frame for that device. The value of n is defined as follows:

$$n = 2^{8-\mathrm{BO}}, \quad 0 \leq \mathrm{BO} \leq 8,$$
$$n = 1, \quad 9 \leq \mathrm{BO} \leq 14. \tag{2}$$

3. Approaches for Contention Access Period

In beacon-enabled mode, IEEE 802.15.4 medium access control is ruled by the slotted CSMA/CA mechanism in the contention access period. However, the standard slotted CSMA/CA mechanism does not provide any means of differentiated services to improve the quality of service for time-critical events (such as alarms, PAN management messages, and time slot reservation). Also, the IEEE 802.15.4 MAC layer cannot support different throughput performance for individual nodes with the current specifications. If certain nodes are sending data more frequently compared to others, with the standard slotted CSMA/CA mechanism, it is hard to achieve network efficiency. Numerous results have shown that the CSMA/CA-based 802.15.4 MAC has a very poor performance in terms of adaptivity and real-time guarantees, especially when a large number of sensor nodes start transmitting simultaneously [15–17]. Thus, it is very important to understand the fundamental reasons of this limitation in order to mitigate its negative impact.

The behavior of slotted CSMA/CA is affected by four initialization parameters, which are (1) the minimum backoff exponent (*macMinBE*); (2) the maximum backoff exponent (*macMaxBE*); (3) the initial value of CW ($\mathrm{CW}_{\mathrm{init}}$); (4) the maximum number of backoffs (*macMaxCSMABackoffs*).

For *macMinBE* and *macMaxBE*: the IEEE 802.15.4 standard provides a fixed backoff range which limits the default value of *macMinBE* as 3, and *macMaxBE* as 5, giving only the range of $[2^3, 2^5]$ for randomly selecting the actual backoff value. Changing the value of *macMinBE* or *macMaxBE* will have an impact on the network performance. For example, if the BE value is decremented to a value less than the default value 3, the lower boundary of the possible backoff value will decrease also. It will shorten the waiting time when CCA detects the channel busy or when a packet collides with a different packet in the channel. This gives a higher chance of selecting a shorter backoff time, and makes the node try the CCA more frequently, leading it to a higher possibility of making a successful transmission. As a result, the throughput will increase significantly compared to other nodes with a longer waiting time.

A performance evaluation study in [9] also shows that the network throughput is independent from the initial value of the backoff exponent *macMinBE* for a large-scale WSN, which is because the lower limit of the backoff delay interval $[0, 2^{\mathrm{BE}} - 1]$ is not affected by the choice of *macMinBE*. However, the impact of *macMinBE* on the network throughput is quite important in small-scale networks. In fact, increasing *macMinBE* will lead to relatively lower network throughput (since the capacity of the network is not entirely used for high *macMinBE*), but to significant higher success probability thanks to more efficient collision avoidance.

For $\mathrm{CW}_{\mathrm{init}}$, the initial value of CW is another medium access parameter that is useful to differentiate packet transmissions in slotted CSMA/CA of IEEE 802.15.4. It represents the number of CCAs, which is performed prior to each packet transmission to determine whether the medium is busy or idle.

The standard specifies that the transmitter node performs the CCA twice in order for the purpose of protecting acknowledgement (ACK) frame and giving enough time for a receiving device to process the frame. When an ACK frame is acquired by the transmitter, the receiver should send it after t_{ACK} time which varies from 12 to 31 symbols (one backoff period is 20 symbols). Hence, one time of CCA can potentially cause a collision between a newly transmitted packet and an ACK packet. Nevertheless, one time of CCA gives a strong priority to obtain the channel. For a backoff counter, the range of the counter drawn for a high-priority packet's backoff procedure should be bounded by a smaller constant value than a normal packet's in order to enable a faster transmission. Provided that ACK collision is not so severe, the flexible CW value will definitely guarantee a better rate of successful transmission for a device with high priority compared with the conventional IEEE 802.15.4 MAC protocol, where every device initiates the CCA procedure with the same CW.

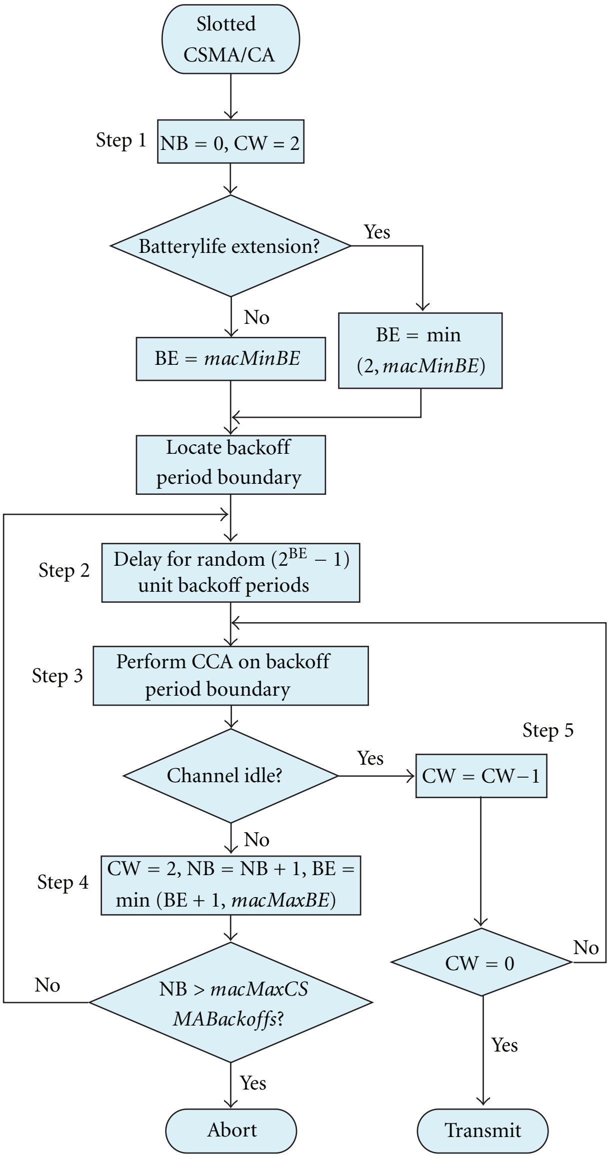


Figure 2: Slotted CSMA/CA algorithm.

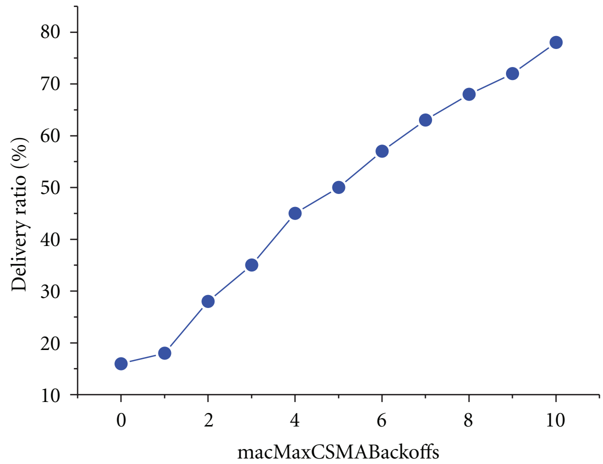


Figure 3: Impact of the *macMaxCSMABackoffs* on the delivery ratio.

The parameter *macMaxCSMABackoffs*, which represents the maximum number of times the CSMA/CA algorithm is required to backoff while attempting to access the channel, also serves to affect network performance for IEEE 802.15.4. In an ideal communication environment, nearly all undelivered packets are dropped by the protocol because they exceed the maximum number of backoff stages (i.e., *macMaxCSMABackoffs*). In this way, a larger *macMaxCSMABackoffs* which means a larger number of CSMA backoffs, can result in more packets that can be transmitted successfully and lead to a lower packet loss rate. As Figure 3 shows [18], increasing the *macMaxCSMABackoffs* parameter, while leaving all other parameters to their default values, results in an almost linear increase in the delivery ratio. However, the end-to-end delay will increase with the value of *macMaxCSMABackoffs*. This is because a larger *macMaxCSMABackoffs* value implies a larger number of packets is successfully transmitted, which takes a longer backoff time, and in turn may cause longer end-to-end delay.

These impact of MAC parameters on the performance of 802.15.4 PAN suggests that the MAC low-efficiency problem, which is originated by the CSMA/CA algorithm, is made worse by the default parameter settings, which appears to be inappropriate for most WSN applications. Hence, the key question to answer is whether a more appropriate parameter setting can solve the problem without introducing unacceptable side effects. Recently, a wide variety of parameter tuning approaches in CAP have been proposed to improve network efficiency.

3.1. Adaptive Backoff Exponent Mechanism. Koubaa et al. provide a service differentiation mechanism in [13], particularly based on the *macMinBE* and *macMaxBE* parameters. Due to different importance of data traffic and command traffic, the particular mechanism considers command frames as the high-priority service class and data frames as the low-priority service class. The differentiated service strategies are presented in Figure 4. Instead of having the same CSMA/CA parameters for both traffic types, the algorithm assigns each class its own attributes, and denote [$macMinBE_{HP}$, $macMaxBE_{HP}$] and CW_{HP} the backoff interval and the contention window initial values for high-priority traffic related to command frames, and [$macMinBE_{LP}$, $macMaxBE_{LP}$] and CW_{LP} the initial values for low-priority traffic related to data frames.

By setting CW_{HP} higher than CW_{LP}, it results that low-priority traffic has to assess the channel to be idle for a longer time before transmission. And providing lower backoff delay values for high-priority traffic by setting $macMinBE_{HP}$ lower than $macMinBE_{LP}$ would improve its responsiveness without degrading its throughput.

In addition to the specification of different CSMA/CA parameters, priority queuing is applied to reduce queuing delays of high-priority traffic (Figure 4). In this case, slotted CSMA/CA uses priority scheduling to select frames from

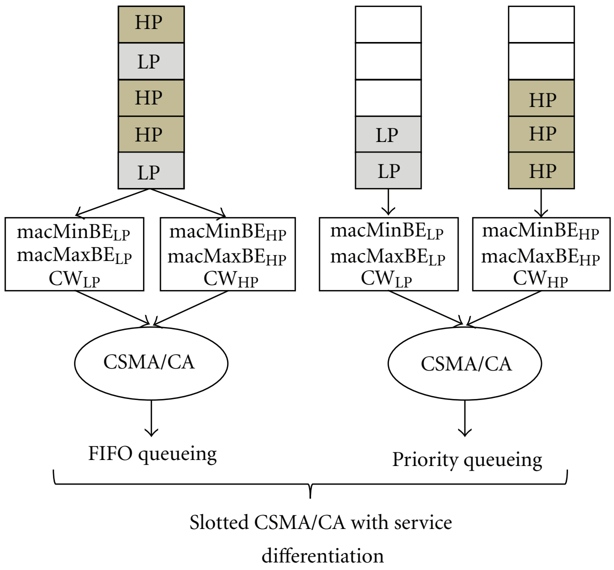


Figure 4: Differentiated service strategies.

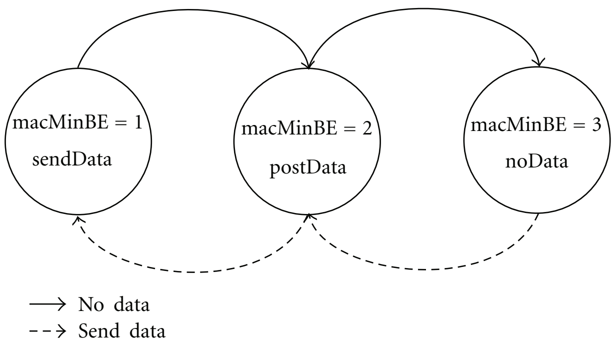


Figure 5: State transition scheme.

queues, and then applies the adequate parameters corresponding to each service class.

This differentiated service scheme for slotted CSMA/CA in IEEE 802.15.4 serves to improve the performance of time-sensitive messages. And it has been shown that tuning adequately the BE parameter of slotted CSMA/CA may result in an improved quality of service for time-critical messages.

A new state transition scheme is additionally proposed in [14]. By adjusting the *macMinBE* value of some nodes to a smaller value and by dynamically changing the value depending on the transmission conditions, the scheme shortened the backoff delay of nodes with frequent transmission.

In the MAC modifications, the value of the *macMinBE* is a number between 1 and 3, which changes flexibly as the condition of the node changes. As seen in Figure 5, each node has three states, *noData*, *postData*, and *sendData*, with each state having the default *macMinBE* value of 3, 2, and 1, respectively.

In the state transition scheme, The three states are switched dynamically and the nodes are requested to count the number of idle beacon frames (with no transmission) and the number of successful transmissions within a beacon frame, before the CCA process. By counting the numbers we can allow the nodes with more data to transmit to a higher priority in the network. The state transition scheme will not make additional fairness problems because if a node has nothing to send any more it increases the *macMinBE* so that it can be excluded from the high-priority nodes.

The change lets the modified node take advantage in transmitting data compared to the nonmodified nodes, causing higher throughput performance for the modified node. By implementing the state transition scheme, the throughput performance of the overall network is significantly improved.

Also, Rao and Marandin present a brief study of the CSMA/CA mechanism in [19], with emphasis on the improper BE distribution which results in frequent packet collisions and a loss in systems performance. And they additionally provided an algorithm called the adaptive backoff exponent (ABE) which reduces the probability of devices choosing identical number of backoff periods at collision rates, thus improving the system's performance considerably at these rates.

The ABE algorithm is primarily based on three important principles. Firstly is the idea of providing a higher range of backoff exponents to the devices, to reduce the probability of devices choosing the same number of backoff periods to sense the channel. Secondly is to do away with a constant minimum backoff exponent (*macMinBE*) value as used in the standard CSMA/CA. In this algorithm, the minimum backoff exponent shall be variable, hence devices are not likely to start off with the same backoff exponent when they wish to start a data transmission. And thirdly is the way the minimum backoff exponent is maintained. Since the algorithm implements a variable *macMinBE*, the variation factor is each node's contribution to the network traffic. Only devices that are involved in a transmission are taken into consideration. And devices that are not transmitting do not come under the purview of the algorithm.

According to this algorithm, all devices that are contributing more to the network traffic are slapped with higher *macMinBEs*, and devices which contribute less to the network congestion will use lower minimum backoff exponents. Therefore devices with higher *macMinBE* values are likely to wait longer than devices with lower *macMinBEs*, leading to an overall improvement in effective data bandwidth.

3.2. Adaptive Contention Window Mechanism. A frame tailoring (FRT) strategy is proposed in [20] to avoid ACK and data packet collision while allowing one-time CCA so that it can be exploited to provide strong prioritization in addition to the standard CSMA/CA.

In this scheme, the length of t_{ACK} is determined as depicted in Figure 6, depending on packet length, and the term frame tail is defined as the length of the remainder after the total packet length is divided by the backoff slot length (i.e., 20 symbols). If a frame tail is from 0 to 8 symbols, a receiver transmits an ACK packet at the very next backoff slot boundary as depicted in Figures 6(a) and 6(b). On the other hand, if a frame tail ranges from 9 to 19 symbols, an ACK transmission by the receiver is postponed to one backoff slot after the next backoff slot boundary to allow

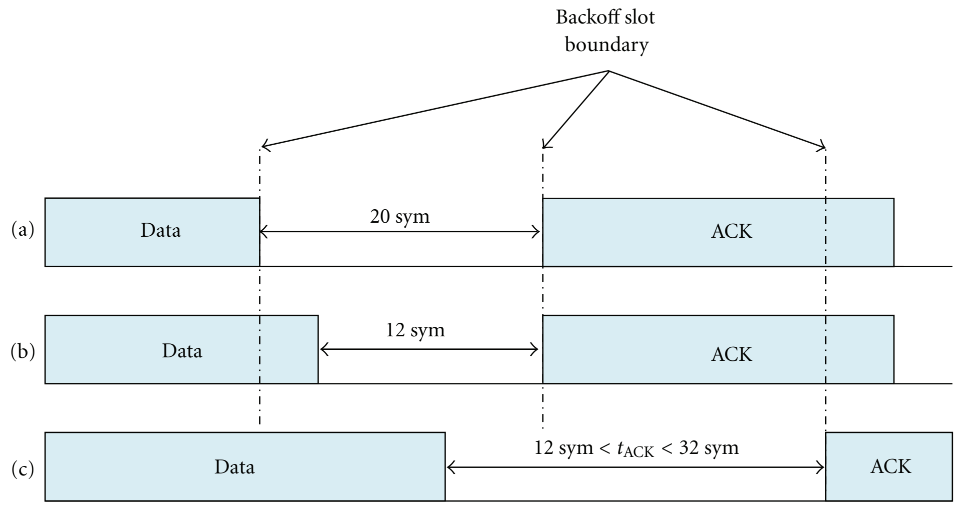


Figure 6: Variable t_{ACK} depending on the data packet length.

adequate time to prepare the ACK transmission. As a result, t_{ACK} becomes more than 20 symbols as shown in Figure 6(c). Then, the CCA operations of other contending nodes during this time interval report that the medium is idle. To protect ACK transmissions in such cases, two-time CCAs are mandated in IEEE 802.15.4 slotted CSMA/CA. FRT strategy is to adjust each data packet length so that t_{ACK} becomes exactly 12 symbols as shown in Figure 6(b). By doing so, one-time CCA will never declare an idle medium during the time period between a data and an ACK, and hence by adopting one-time CCA for a particular transmission, high prioritization can be achieved.

The proposed frame tailoring strategy effectively separates the medium access of each group of packet transmissions according to packet's priority. By adopting the proposed scheme, the probability of transmission deferment to the next active period due to competitive contention is relaxed and bounded delay is provided to high-priority packets.

Furthermore, Kim and Kang proposed a mechanism of contention window differentiation (CWD) in [21] to provide multilevel differentiated services for IEEE 802.15.4 sensor networks. CWD is a mechanism assigning various values of CW according to the priority classes. Let $class0, \ldots, classQ$ be the set of priority classes ordered by

$$classQ \prec class(Q-1) \prec \cdots \prec class0, \tag{3}$$

where $\prec$ denotes the order of priority. Equation (3) implies that $class0$ and $classQ$ are the highest and lowest priority classes, respectively. They differentiate the corresponding CW value of priority $classQ$ by $\text{CW}[Q]$ as follows:

$$\text{CW}[0] \leq \text{CW}[1] \leq \cdots \leq \text{CW}[Q]. \tag{4}$$

The relationship in (4) is intuitive, since a device with a smaller CW has a better chance of transmission than a device with a larger CW in general. In other words, a device with high priority can start transmission when a device with low priority is performing the CCA procedure. It guarantees a better rate of successful transmission for a device with high priority compared with the conventional 802.15.4 MAC protocol, where every device initiates the CCA procedure with the same CW.

Numerical results show that the IEEE 802.15.4 standard in WSNs can support adaptive and timely packet transmissions by tuning the MAC parameters to more appropriate values. However, the increase in reliability is usually achieved at the cost of a higher latency, and high adaptivity and low delay may demand a significant energy consumption and network complexity, thus making a great many approaches not feasible at best. And due to the random nature of CSMA/CA algorithm, an appropriate parameters setting which guarantees both adaptivity and bounded latency for real-time applications is hardly achieved. There are also other challenges, it is not clear how to adapt the parameters to the changes of network and traffic regimes by algorithms that can run on resource-constrained nodes. A simple and accurate model of the influence of these parameters on the success probability, real-time performance, and adaptivity to various conditions as a whole is not available. What is worse, the cost to be paid, in most cases, will turn out to be even higher in a real environment.

The above discussed approaches and analysis pave the way for further research. Since most appropriate MAC parameters should depend on real operating conditions and specific QoS requirements, the ideal adaptive and real-time approach for CAP should dynamically select appropriate parameters to offer the required QoS support according to various operating conditions.

4. Approaches for Contention-Free Period

Based on the standardized IEEE 802.15.4 protocol, timeliness guarantee and adaptive throughput are the most important features that we have to pay attention to. Besides, timeliness guarantee is also appealing to WSN applications. As the

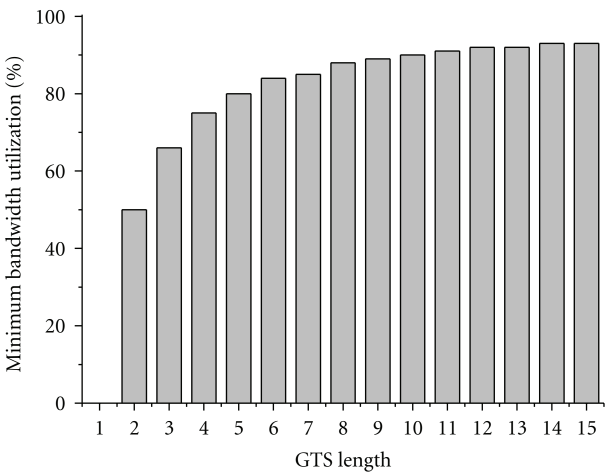


Figure 7: Minimum utilization limits of an explicit allocation.

requirements of WSNs, low data rate, low power consumption, and low cost wireless networking becomes more and more outstanding recently. Therefore the IEEE 802.15.4 protocol also provides real-time guarantees by using the GTS mechanism. This feature is quite attractive for time-sensitive WSNs. In fact, when operating in beacon-enabled mode, that is, beacon frames are transmitted periodically by a central node called PAN coordinator for synchronizing the network, the IEEE 802.15.4 protocol allows the allocation/deallocation of GTSs in a superframe for nodes that require real-time guarantees. Hence, the GTS mechanism provides a minimum service guarantee for the corresponding nodes and enables the prediction of the worst-case performance for each node's application.

However, the GTS mechanism also presents several negative impacts.

(1) It presents some limitations in terms of efficiency and deployment with a large number of nodes.

(2) because only up to seven GTSs (1 up to 15 time slots per GTS) can be allocated during each superframe, the GTSs can be quickly consumed by a few number of nodes, preventing the others from having a guaranteed service.

(3) A node with a low arrival rate that has been allocated a GTS may use it only partially (when the amount of guaranteed bandwidth is higher than its arrival rate). This leads to underutilization of the GTS bandwidth resources.

Now, for a CFP of a length k time slots, the minimum utilization limit is defined as follows in [22]:

$$\left(U_{\min}^{k}\right) = \frac{k-1}{k}, \quad 1 \le k \le 15. \tag{5}$$

Figure 7 presents the minimum utilization limits for different GTS length values, for one node. From Figure 7, it can be understood that the lowest utilizations can be experimented for GTSs with one time slot allocation. This is because the arrival rates of the flows can be low fractions of the indivisible R_{TS} (defined as the guaranteed bandwidth per one time slot), which triggers the motivation for sharing the time slot with other nodes, if the delay requirements of the flows can still be satisfied. This case is most likely to happen in sensor networks since their arrival rates may be particularly low.

In order to overcome the previously described limitations of the explicit GTS allocation in the IEEE 802.15.4 protocol, a great number of effective approaches have been developed. In this paper, we mainly focus on four popular adaptive and real-time approaches for CFP.

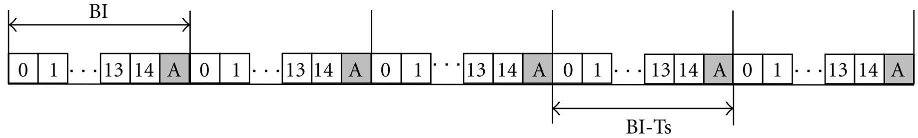
4.1. Adaptive GTS Allocation Scheme (AGA). Huang et al. proposed an energy-efficient protocol [23] that would be superior to the explicit GTS allocation mechanism. The AGA mechanism relies on assigning priorities in a dynamic fashion based on recent GTS usage feedbacks with the consideration of low latency and fairness. An ideal GTS allocation scheme has a good estimate of the future GTS usage behaviors of devices. With the estimate, the PAN coordinator allocates GTS resources to needy devices and reclaims the previously allocated but unused GTSs.

To achieve the above goal, the AGA mechanism arranges two phases in the scheme. 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 nondecreasing order of their priorities. A starvation avoidance mechanism is presented to regain service attention for lower-priority devices that need more GTSs for data transmissions.

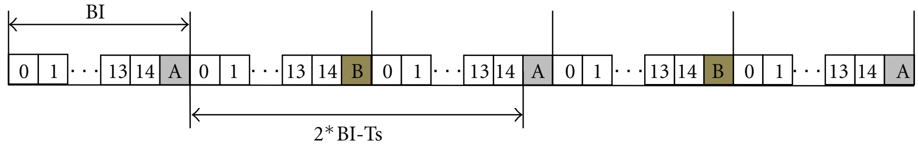
The AGA scheme is developed based on the standard of the IEEE 802.15.4 MAC protocol and completely follows the specification defined in [7] without introducing any extra protocol overhead. Therefore the priority number of a device reflects its long-term transmission characteristics, that is, the scheme provides a multilevel AIMD [24] algorithm for updating the priority numbers. And the scheduling criteria are based on the priority numbers, the superframe length, and the GTS capacity of the superframe. And the numerical results indicate that the AGA scheme greatly outperforms the existing implementations.

4.2. Implicit Allocation Mechanism (i-Game). Based on the basic idea of sharing the same GTS by multiple flows, Koubaa et al. proposed the implicit allocation mechanism [22]. The allocation is based on implicit GTS allocation requests, taking into account the traffic specifications and the delay requirements of the flows.

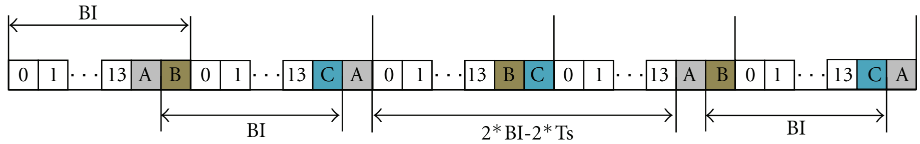
While the GTS allocation mechanism is based on the traffic specification of the requesting nodes, their delay requirements, and the available GTS resources [25]. Instead of asking for affixed number of time slots, a node that wants to have a guaranteed service sends its traffic specification and delay requirement to the PAN coordinator. Then, the latter runs an admission control algorithm based on this information and the amount of available GTS resources.



(a) One time slot allocation used by one node



(b) One time slot allocation used by two nodes under round-robin scheduling



(c) Two time slot allocation used by three nodes under round-robin scheduling

Figure 8: Different implicit GTS allocations.

The new allocation request will be accepted if there is a schedule that satisfies its requirements and those of all other previously accepted allocation requests; otherwise, the new allocation request is rejected. The *i*-Game has the advantage of accepting multiple flows sharing the same GTS, while still meeting their delay requirements. It also improves the utilization of the CFP by reducing the amount of wasted bandwidth of GTSs and maximizes the duration of the CAP, since the CFP length is reduced to a minimum. With the help of network calculus, this GTS mechanism shows how to fairly share the allocation of k time slots in the CFP between N requesting nodes, with respect to their flow specifications. Observe in Figure 8 that changing the scheduling policy results in a change of the service curve, even if the guaranteed bandwidth is the same.

4.3. Knapsack Algorithm. A knap problem is formulated to obtain optimal GTS allocation such that a minimum bandwidth requirement is satisfied for the sensor devices. Hanson et al. in [26] have already shown that the knapsack scheme can achieve better GTS utilization and higher packet delivery ratio than the standard IEEE 802.15.4 scheme does.

The main object of the proposed knapsack algorithm is to improve the GTS allocation scheme in the IEEE 802.15.4-based MAC when used for a large number of medical and physical sensor devices deployed in a wireless body area sensor network (WiBaSe-Net) [27]. Shrestha et al. also proposed an optimization model, which takes the priority that is based on the packet generation rate of each device into account. In this allocation model, it assumes that if a device does not send GTS request or misses the beacon frame, it can use slotted CSMA/CA to transmit its data. If the request is unsuccessful, the device waits for the next beacon to send another GTS request. If the packet waiting time exceeds this delay limit, the sensor device simply discards the packet. The coordinator collects all the GTS requests during CAP and solves the knapsack algorithm for GTS allocation before transmitting the beacon frame. It saves the remaining bandwidth that is not allocated for GTS to use in the next super frame. That is the advantage that with the minimum bandwidth requirement the sensor devices can still meet their needs.

4.4. GTS Scheduling Algorithm (GSA). Na et al. proposed the GSA algorithm [28], which differs from the existing algorithms in that it is an on-line scheduling algorithm and allows transmissions of bursty and periodic messages with time constraints even when the network is overloaded. The evaluation of GSA mechanism is up to 100% higher than the FCFS-based scheduling algorithm.

GSA mechanism is for beacon mode to meet the delay constraints of time-sensitive transactions in star topology. GSA is proved to be optimal and work conserving. Different from the earliest deadline first (EDF) scheduling, which results in bursty transmissions of payloads for transactions with delay constraints, GSA smooths 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. By doing so, GSA reduces the average services to more transactions. This can significantly benefit many time-sensitive applications, where the starting time of the first message and the stability of traffic have great impact on the performance of these applications.

To satisfy two requirements, one is how many GTSs are needed by the payload and the other is how to arrange these GTSs to satisfy the time constraint, GSA is described in the following three steps. First, it checks if all the transactions are schedulable by adding the new transaction to its current transactions. Second, if the transactions are schedulable, then in Step 2 it not only estimates the delay of serving, but also analyzes the relationship between the delay of serving and the number of GTSs allocated to the delay of serving in each interval. Third, based on this relationship, in Step 3

GSA allocates the minimum number of GTSs to the delay of serving in each beacon interval so that the payload can be maximally spread out. To ensure that all GTSs are maximally utilized and the scheduling of GTSs is optimal, GSA adjusts the allocations of GTSs whenever the payload that needs to be transmitted in a CFP changes. These GTSs are evenly spread out over multiple beacon intervals to ensure a smooth traffic flow between the PAN coordinator and sensor nodes.

Each of these discussed approaches has contributed to improve the performance of GTS allocation mechanism in origianl IEEE 802.15.4. The AGA scheme uses the idea of assigning priorities in a dynamic fashion based on recent GTS usage feedbacks with the consideration of low latency and fairness. And the *i*-Game has the advantage of accepting multiple flows sharing the same GTS, while still meeting their delay requirements. Besides, the knapsack algorithm, which is based on the solution of the knapsack problem, ensures that the radio bandwidth in the GTS is utilized in an optimal manner. Furthermore, the GSA mechanism smoothes 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. By doing so, GSA reduces the average services to more transactions.

Nevertheless, they also have certain drawbacks to some extent. In *i*-Game and GSA, for example, the information of delay requirements needs to be exchanged with the controller, which incurs signaling overhead. The GSA scheme also has high computational complexity due to the execution of a number of algorithms. In the *i*-Game approach, since the algorithm starts the GTS allocation from the last time slot in a round-robin manner, it may fail to serve a flow with hard real-time deadline, which needs to be assigned the first GTS in the CFP. Additionally, it requires a control packet for flow specification in the higher layer. The knapsack algorithm does not provide a detailed priority differentiation mechanism and AGA scheme also has implementation overhead since extra information for devices shall be recorded to allocate GTS resources. Furthermore, energy consumption issue should also be a major concern. All of these above limitations require our future research. In spite of the difficulty of developing an appropriate approach meeting all requirements, we shall do the best to cater specifical needs in different conditions.

5. Cross-Period Approaches

In a cross-period approach, the length of CAP or CFP is dynamically adjusted to various operating conditions. And usually, such changes may have significant impact on both CAP and CFP performance of IEEE 802.15.4 protocol. Hence, setting BO and SO has become one of the most important tasks of the PAN coordinator to determine the superframe structure. Koubaa et al. in [29], analyzed the impact of BO and SO on the performance of slotted CSMA/CA and showed that higher superframe orders provide better network throughput than lower superframe orders due to their increased immunity against the CCA deference symptom.

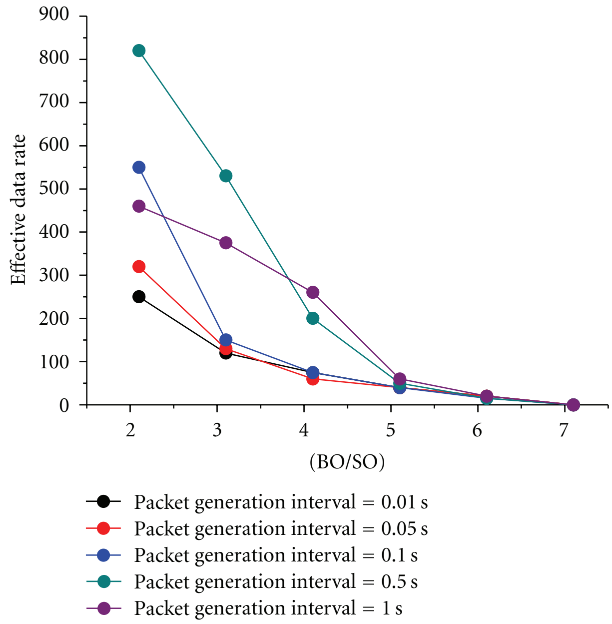


Figure 9: Effective data rate.

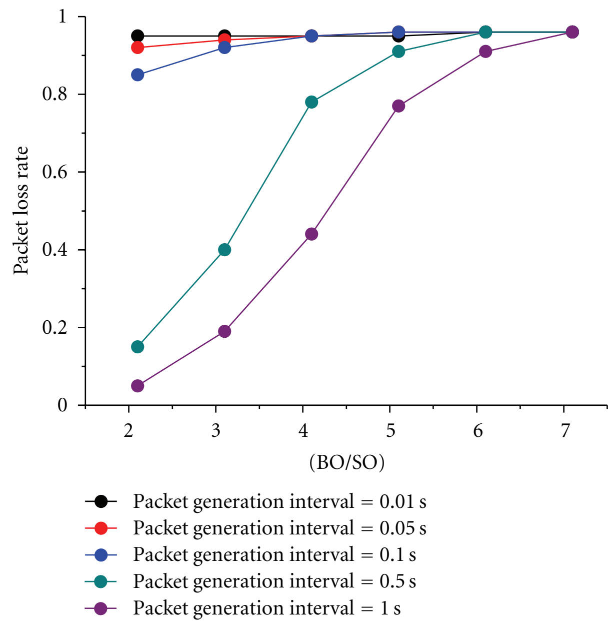


Figure 10: Packet loss rate.

A simulation study of effective data rate and packet loss rate has been provided in [30]. Figure 9 shows the measured effective data rate (SO = 1). We can find that as the value of BO decreases, effective data rate grows gradually. This is mainly because the smaller BO resulting in higher duty cycle can achieve larger bandwidth, which implies larger effective data rates. Figure 10 gives the measured packet loss rate (SO = 1). It has been shown that for the same packet-generation interval, a higher BO leads to a smaller packet loss rate. This is because under the same traffic load, the

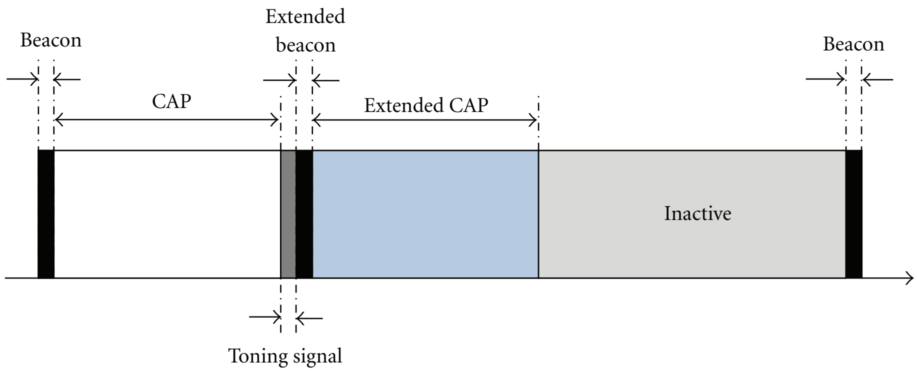


Figure 11: Superframe structure of IEEE 802.15.4 with an extended contention access period.

smaller BO resulting in larger duty cycle enables the network to transmit more packets.

Jeon et al. illustrated PECAP (priority-based delay alleviation algorithm) in [31] about how to set BO and SO at the end of the CAP. In this algorithm, the active period is temporally increased to reduce the sleep delay. Nodes having high-priority packets will request the coordinator to execute an extended CAP by sending a priority toning signal. Thus nodes that have high-priority packets can alleviate delay due to the less contentious environment. Figure 11 shows the superframe structure when the PECAP algorithm is applied. The key advantage of the PECAP algorithm is that it provides exclusive transmission opportunities to the high-priority packets and transmissions of important data can be ensured with timeliness guarantees.

Another example of cross-period approaches is the AGA scheme. Huang et al. proposed a threshold value T_h, which is dynamically adjusted and depends partly on the BO value, due to the consideration of CAP and CFP traffic load. When the CFP traffic load is light, GTS resources are transferred for contention-based access in CAP to filter unnecessary GTS allocation. Besides, the AGA scheme takes advantage of BO changes flexibly. As the BO increases, there is a higher probability that many devices have requested GTS service in the superframe. Hence, in such cases, a more strict threshold value is set to prevent the scarce GTS resources from distributing to those devices with extremely low priorities.

6. Conclusions

In this paper, we mainly focus on limitations of original IEEE 802.15.4 MAC specifications in contention access period, contention-free period, and overall cross-period, respectively. A variety of adaptive and real-time protocols, which are to overcome these constraints, have also been presented and discussed. While it is true that existing research works have significant impact on improving network performance, in terms of adaptive and real-time guarantees, a great number of problems still exist, such as high latency, great energy consumption, system complexity, and implementation overhead. Requirements of all aspects usually cannot be satisfied simultaneously. Hence, our further study on IEEE 802.15.4 MAC is badly needed for developing a more comprehensive and appropriate protocol catering various needs in real operating conditions.

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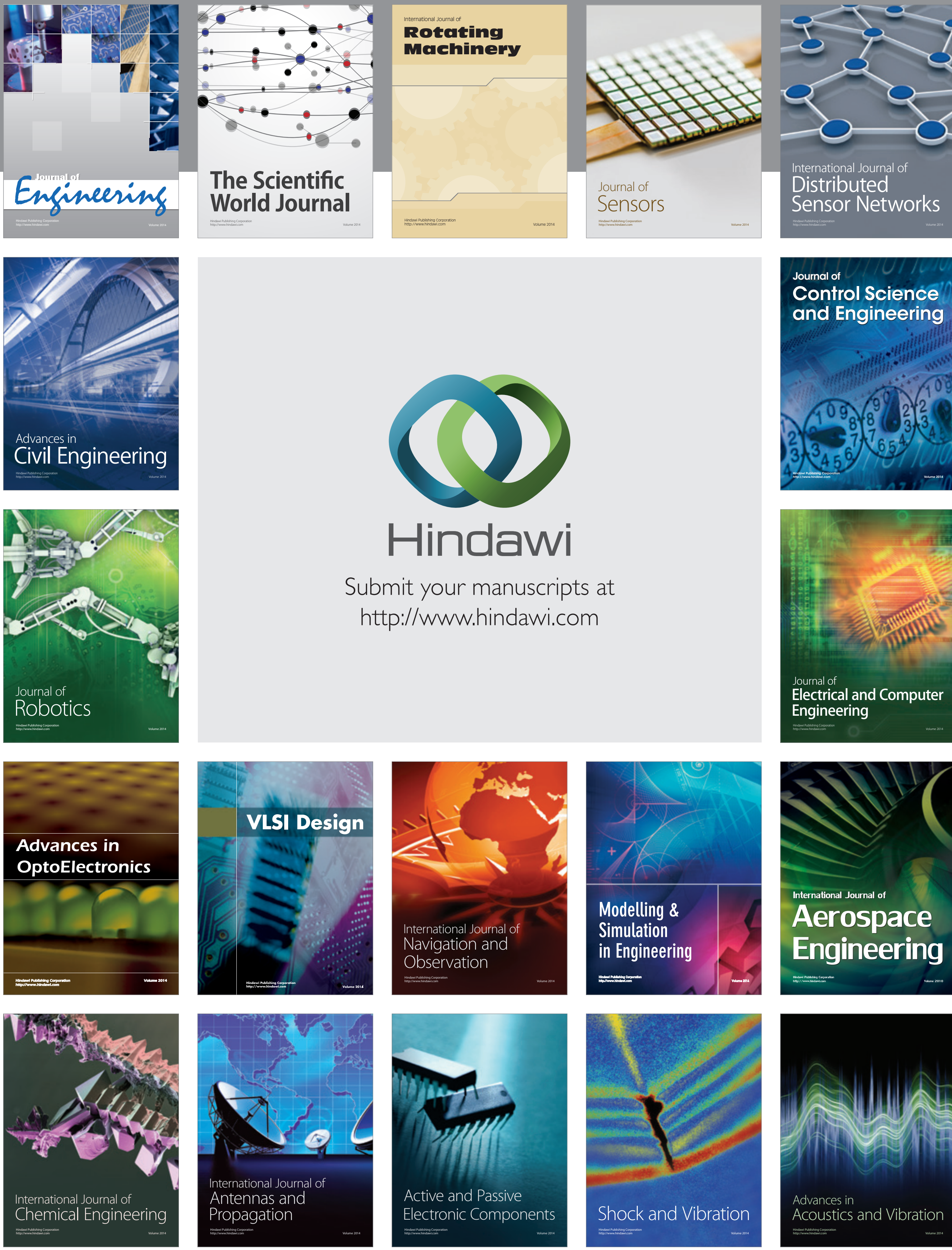
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