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Medium Access Control Methods in Sensor and Actuator Based Wireless Networks - A Review

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Abstract

The objective of this review paper is to discuss the various channel access methodologies applied in various sensor and actuation based wireless networks. In most of Wireless Sensor Networks (WSNs) researchers have focused on priority centered approaches for channel accessibility. This paper also explains the procedure for Medium Access Control (MAC) in Cyber Physical Systems (CPSs) which is a combination of Wireless Sensor Actuator Networks (WSANs) and WSNs. Finally, we discuss the successive collision avoidance technique using the IEEE 802.11 MAC protocol, and also brief on how the Internet of Thing (IoT) approach connects and transfers information among smart devices linked in a wireless network.

Keywords: Medium Access Control, sensor, actuator, CPS, CSMA, backoff mechanism

Introduction

In Cyber Physical Systems (CPSs) [1], Cyber denotes computational and control systems, while physical denotes natural and man-made systems. CPS indicates the integration of both these elements into a single governing body. Started in late 2006, the US based National Science Foundation (NSF) [1], along with other agencies, organized several workshops on CPS. CPS, as mentioned, acts as a governing system over networked computers to send out instructions for various processes. CPS also receives results regarding how these processes work.

CPS is a new generation of systems that can compute, communicate, and control a network of systems, while also interacting with humans. To put it in an easy way, CPS monitors the behaviors of physical processes. Also, it finds much use in various fields, such as the electrical, biomedical and engineering fields. CPS is much more common than we think, and are almost found everywhere. The general workflow of CPS is given as: Monitoring, Networking, Computation, and Actuation [1], which is depicted in **Figure 1**.

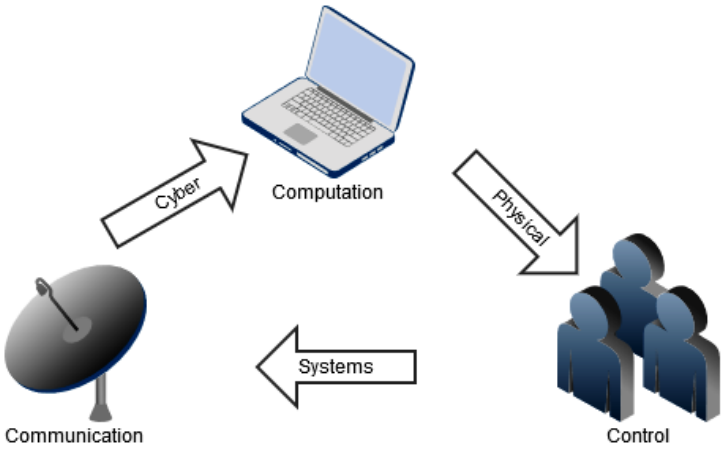

Figure 1 CPS communication process.

- Monitoring: The very first step is done to achieve the primary aim. It also gives the result and ensures the system works correctly.
- Networking: This helps in the generating and gathering of various data, and later leads to them being processed or analyzed, depending on the process required.
- Computing: In this, the gathered data is processed or analyzed. It sends valid instructions for further event occurrence.
- Actuation: Once the instructions (events) are performed successfully, it will send feedback as control instructions to the Monitoring step. In this way the whole process is carried out in a closed loop structure.

Medium access control is an approach to avoid collisions that can be used in any wireless network. Network congestion occurs when a channel is shared among different nodes of various wireless networks. There are several priority based techniques that have been applied in wireless networks to avoid collisions while accessing a channel. Therefore, our discussion is on priority based approaches, used to avoid collisions in WSNs and Wireless Sensor Actuator Networks (WSANs) [1]. Moreover our study also focused on the emerging research area of Cyber Physical Systems (CPSs). In CPSs [1], accessing a channel holds a vital position, because a change in the medium access control method affects the performance of the whole networked system. Since this networked system is a combination of various wireless elements, the following related work focuses on those IEEE Medium Access Control [2] protocols which have been used to reduce, as well as avoid, collisions in Wireless Ad hoc Networks [3] and Wireless Sensor Networks (WSNs) [4]. This work also discusses the MAC protocol which is suitable for Cyber Physical Systems.

Due to network congestion in the wireless structure, most of a node's packets are dropped, either on the way to or from the server to which it is connected. As the scale of collision in any wireless network increases, the performance of the network gets decreased. To overcome the issue of collision occurrence in any wireless network, several channel access [2] control mechanisms are implemented. These channel access [2] control mechanisms use the IEEE 802.11 protocol [5] group standards, such as 802.11/a/g/n [5,6], and IEEE 802.15 [6] standards, such as 802.15.4 or 802.15.6 [6].

Since today's world is revolving around Internet technologies, an effective channel access [2] mechanism has to be introduced to avoid collisions. Moreover, new technologies are built with sensor devices, as well as sensor cum actuator based devices. These smart devices assist people in performing any task in an easy and a rapid way in association with the Internet. When any transmission has to be carried out from one part of the globe to the other part, a sensor with actuator built devices plays a major

role in the process. In this type of wireless communication, Cyber Physical System [1] takes a lead by executing relevant tasks at an appropriate time.

To provide channel access to several smart devices at a time, CPS [1] uses the IEEE 802.15.4 MAC protocol [6,7]. Though this channel access control [2] protocol is mainly used for WSNs [4,6], it is effectively applied in WSANs [7,8]. From a research study, it is said that WSANs [7] are an extension of WSNs [4,6]. This sensor, with an actuator based wireless network, is suitable for executing CPS [1] based applications. In these, wireless networks sensors collect the data and send it for further processes to be completed. However, in WSNs [4,6] sensor devices collect the information, but will not disseminate the data for further action.

The IEEE 802.15.4 standard [6,7] is considered to be a less costly protocol, with a short data bit range which consumes less power during transmission. So, this protocol standard is widely used as a transmission protocol for wireless networks, which comprise sensor cum actuator built devices. In [7] it is discussed that, during data transmission, the above protocol acts as a link between the wireless structure devices and the Internet server. Because of this significant factor, in most WSAN [1] based applications, the IEEE 802.15.4 protocol [6,7] is strongly recommended for channel access and handover of data.

Collision avoidance methods using IEEE 802.11 MAC protocols

It has been shown in many research papers that the IEEE 802.11 MAC protocol [3] performs an important task in wireless networking while accessing a channel. The MAC protocol with slot-reservation method helps the nodes to avoid collisions when it tries to transmit any packet through a medium. This approach is a conventional Carrier Sense Medium Access-Collision Avoidance (CSMA/CA) [3] method of the 802.11 MAC protocol. Later various methods, like Point Coordination Function (PCF) [3] and the Distributed Coordination Function (DCF) [3], were used to avoid collisions in a wireless communication while accessing the medium.

As explained in [3], the PCF has centralized medium access, whereas DCF has medium access in a distributed manner. The latter approach uses a slotted and non-slotted process of binary exponential [3] backoff methods. In these procedures, the contention window is measured vigorously to lessen the collisions that occur during transmission of packets by the nodes involved in it. This scenario is set only for wireless LAN networks.

The traditional procedure for decreasing the number of collisions which depend on backoff periods are enhanced by the Virtual Backoff Algorithm (VBA), mentioned in [9]. The authors of this paper have used the concept of the sequencing number technique [3] in the VBA to reduce collisions by increasing the delay in the transmission. In [9], VBA is applied with the 2 choices being the Virtual Backoff Algorithm with Counter Sharing (VBA-CS) [9] and the Virtual Backoff Algorithm with Non Counter Sharing (VBA-NCS) [9]. Comparatively, VBA-CS tries to lessen the collisions that happen in each node's backoff periods. Though the test results have shown that this procedure is better than previous approaches, it can only be applied to wireless networks of a homogeneous type.

In the work of [10], the authors have revised the perception of VBA-CS to CPS kinds of applications through the Learning Automata (LA) model [10] as LAVBA. We know that in CPS environments, the characteristics of each wireless network is different, and so the number of trials to access the channel is set according to the nature of a network involved in that application. The procedure had come up with improved results in terms of average delay and amount of loss percentage during packet transmission. In this methodology, they have assumed that the nodes exhaust less energy by neglecting the bandwidth range of a node. This is especially done when a node from a wireless sensor network needs to access a medium. The following **Table 1** shows the comparison of the VBA-CS, VBA-NCS and LAVBA approaches in the IEEE 802.11 MAC protocols.

Table 1 Comparison of IEEE 802.11 MAC based methods.

Parameters	**VBA-NCS**	**VBA-CS**	**LAVBA**
Mode of process	Beacon-enabled	Beacon-enabled	Non-Beacon
Type of network	Ad hoc network	Ad hoc network	Heterogeneous wireless network
Energy consumption	High	Medium	Moderate
Throughput (%)	Around 60	60 - 70	75
Collision rate	Medium	Medium	Low

Collision avoidance methods using IEEE 802.15.4 MAC protocols

Most papers have focused on collision avoidance in wireless sensor networks. WSAN as Cyber Physical System [4,11,12] is a developing research area which revolves around the physical and cyber world. Since smart devices are based on WSAN [7,8], in this section, we discuss the CSMA/CA algorithms related to the 802.15.4 protocol.

Various applications and performances of CPSs are discussed in [4,11,12]. The authors of [7] explained how CPS can be used in beacon-enabled and non-beacon enabled modes for avoiding collisions that occur while accessing a channel. This paper briefs about the superframe structure applied in beacon-enabled mode, and also discusses the traditional CSMA/CA [7] algorithm, which applies Clear Channel Assessment (CCA) [7] with required backoffs. In this approach, a contention window is used to delay the process of contending nodes when the server is busy. How the collision avoidance process can be carried out without a contention window is also described in [7]. However, the conventional algorithm mentioned in [7] is not suitable for smart nodes.

In [13] the collision avoidance algorithm is based on Guaranteed Time Slots (GTSs) [13], which function on 2 levels. At the first level, all the devices are assigned with the priorities based on the GTS request from it. Devices requiring more GTSs are given top priority. According to the adaptive methodology of GTS, which is called Adaptive GTS Allocation (AGA) [13], a node's packets are transmitted by the coordinator. This AGA algorithm executes a beacon-enabled mode of the IEEE 802.15.4 MAC protocol [13]. At the next level, nodes with a lower priority are considered if the server is idle. By giving more attention to top prioritized devices, a solution to the problem of node starvation was attempted. During critical situations, the coordinator would be busy with the data transmission of high priority nodes by letting the contending node (holding important data) in a Contention Free Period (CFP) [13]. So, AGA fails to adapt to emergency situations occurring in the Contention Access Period (CAP) [13] of a network.

Usually, in a conventional 802.15.4 CSMA/CA algorithm 2, CCAs [14] are used to check the status of a coordinator (busy or idle). However, in [14], the authors showed that with more numbers of CCAs, the level of collisions can be controlled up to certain extent during network communication. Based on the number of CCAs generated by a node, the coordinator allows accessing a channel. If a node encounters several backoff periods, then that node will be given a chance to access the medium. A node put in the waiting period can start contention from its last CCAs, so that it can try to access a channel in the forthcoming trials. In [14], it was proved that nodes contending for a channel more recently will be given less priority than those which have been contending for a longer time. This shows that the channel allocation by the coordinator is not fair for all the contending nodes in that network, by neglecting the precarious state that occurs.

In [15] the authors proposed a mechanism to utilize the channel efficiently, based on priority, in WSNs [15]. In this priority based CSMA/CA algorithm, the sensor nodes are categorized into 3 types, such as priority with level 0, 1, and 2, according to the type of data and node capacity. After 2 consecutive Clear Channel Assessments [15], a node with priority 0 gets medium access from the coordinator. The nodes with priority 1 and 2 are set in a Contention Free Period [15], and their Contention

Window is decreased by 1. This is to handle data types of multimedia sent from the nodes. So, this approach gives preference to top prioritized data to enhance the functioning of the network by consuming less energy. However, most critical data handling is given less priority, which decreases the performance of the wireless network.

The authors of [16] focused on sensitive applications based on data rate which operate in a non-beacon enabled mode of the 802.15.4 MAC protocol. In this paper, they introduced separate virtual MACs that comprised 2 types of collision avoidance algorithms, such as Adaptive Backoff Window Control (ABWC) [16] and Virtual Collision Avoidance (VCA) [16]. The ABWC vigorously regulates the backoff window according to the data rate in the local collision region of the network. The VCA mechanism avoids the withdrawal of data rate transmission in a virtual collision region of network. These 2 approaches emphasize more on data rate constraint broadcasting and generating collision free packet transmissions virtually. However, at certain level, packets are blocked to avoid more collision, which is a drawback of this approach.

In [17] the authors have shown how collisions can be reduced by implementing Adaptive Priority-Based (APB) [17] Service-differentiation CSMA/CA ([17]. This mechanism comprises 2 approaches, such as the adaptive backoff approach and the priority-based service-differentiation algorithm. In the former method, a node is assigned an appropriate backoff period based on the status of the channel. In the latter approach, each node is assigned with a backoff exponent value (PBE) [17] and a contention window length (LCW) [17]. A node with less PBE and LCW is treated as a top priority node, as it holds the most important data. Thus, this procedure allows for accessing a channel to these nodes (high priority) immediately. As a result, when a channel is busy, a large value is set as a backoff period to reduce collisions in a network. When a low prioritized node is contending for a channel and the high priority node is ready for transmission, the former node packet is blocked, even though it holds critical data. This degrades the performance of the network.

The following **Table 2** shows the comparison of the AGA, ABWC&VCA and APB approaches in the IEEE 802.15.4 MAC protocols.

Table 2 Comparison of IEEE 802.15.4 MAC based methods.

Parameters	**AGA**	**ABWC&VCA**	**APB**
Mode of process	Beacon-enabled	Beacon-enabled	Beacon-enabled
Type of network	WSN	WSN	WSN
Priority based on	GTS	Data rate	PBE & LCW
Packet loss	Medium	Low	Medium
Collision rate with criticality	Adequate	Fair	Fair
Energy consumption	Medium	Low	Medium

Successive collision avoidance methods

The authors of [8] proposed a 2-level network for data transmission in Hospital Wireless Networks [8]. In the first stage, the data is collected from Body Area Networks (BANs) [8] connected with the patients. The data collected from the patients are placed in a queue maintained at Patient Data Controller (PDC) [8]. The PDC processes the data according to priority, and transmits the information to the headquarters based on criticality. By using Reinforcement-Learning (RL) [8] Queue Management technique, the instructions are delivered to the concerned doctors or staff heads in the hospital. In this approach, they use multiple queues to monitor the patient's conditions (high priority to low). In addition, the authors tried to arrange and schedule critical information from PDC to the headquarters using game

theoretical method. Though the system focuses on prioritized data, it does not consider all system parameters to give importance to critical data.

In [18], it was shown that successive collisions can be avoided using the Semi-Distributed Backoff (SDB) [18] approach in the IEEE 802.11 protocol based wireless network. The process is carried out in 2 modes, such as S-mode (sender) [18] and R-mode (receiver) [18]. Initially a counter value is assigned to each node, which ranges from 0 to number of nodes ready for transmission. A unique id (considered as a signature) [18] is assigned to each node at the sender. All these transmission packets are maintained in a buffer. When any node counter value becomes zero, the node transmits the packet after applying the sender side backoff procedure. At the receiver end, using the signature correlation [18] method, the signature id is checked from the transmission. If the number of signatures has more than one collision occurring, the communicated node packet is dropped and negative acknowledgement (NACK) [18] is sent to corresponding sender node. Otherwise, a node receives acknowledgement (ACK) [18] to denote successful transmission. The SDB methodology used for Wireless Local Area Network [18] assures channel accessibility. However, at the subsequent stage when collision occurs, a packet is dropped rather than delaying the transmission.

In paper [19], a case study was conducted on the Smart Home and Ambient Assisted Living (SHAAL) [19] system. In this system, health and home related sensors are used to gather and process data according to the instruction received. The system is managed in such a way that a buffer is maintained to execute the information according to priority. High priority is assigned to health related data, and low priority is assigned to other sensed data. The buffer acts like a First Come First Served (FCFS) [19] queue.

The system is tested in 2 set ups, such as centralized and de-centralized, with the help of the IEEE 802.15.4 protocol [19]. Though the system functions in 2 different configurations, it will forward high prioritized data first, followed by low priority data (the smart home data). When any unpredictable situation rises, the SHAAL system [19] fails to handle or manage such an occurrence. The following **Table 3** depicts the comparison of PDC with the RL, SDB, and SHAAL approaches in WSANs.

Table 3 Comparison of successive collision avoidance methods.

Parameters	**PDC with RL**	**SDB**	**SHAAL**
Mode of process	Non- Beacon	Beacon-enabled	Non-Beacon
Type of network	BANs	Ad hoc	WSAN
Priority based on	Patient condition	Unique id	Health related data
Queue maintained	Yes (high to low)	No	Yes (FCFS)
Packet loss	Medium	Moderate	Medium
Collision probability	Fair	Medium	Less

In addition to the above discussion, in [20,21], the authors discussed how the Internet has changed the lives of human in the present day. The authors specified that Internet of Things (IoT) [22] had made the way easier for hardware devices to combine with computational devices to perform certain activities, such as gathering the information on, scheduling the events for, and estimating the arrival and departure times of automobile vehicles. Moreover, this new technological approach assists people in remote or inaccessible locations by providing necessary instructions. These instructions help them to get medical care free of cost.

The authors of [23] explained how devices connect with other devices to enable reliable communication while transferring useful information. This is only practically possible if these devices are connected through integrated databases. These databases fetch the information from the sensor coordinators that are located in different regions, but are connected with the Internet. Internet enriched

applications become a part of CPS to manage the overall maintenance of the wide area wireless system, in which human intervention is increasingly reduced.

Conclusions

This paper discusses the various approaches that have been made to avoid, as well as to reduce, collision, using the sequencing technique based virtual backoff algorithm in the IEEE 802.11 MAC protocol. It shows how the IEEE 802.15.4 MAC protocol can be used in both time-slot mode and unslotted mode for sensor and actuator based wireless networks. In the IEEE 802.15.4, collision avoidance is ensured based on top prioritized data rather than most critical data. Further, it discusses how most of the approaches prevent collision in the slotted mode of the 802.15.4 MAC protocol. Additionally, the study states how succession collisions have been effectively reduced in the 802.11 MAC protocol. Above all, it discusses how Internet based applications maintain a large wireless structure application, which is connected with an integrated database.

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