

WirArb: A New MAC Protocol for Time Critical Industrial Wireless Sensor Network Applications

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ABSTRACT: Wireless sensor networks are typically designed for condition monitoring applications and to conserve energy but not for time-critical applications with strict real-time constraints that can be found in the industrial automation and avionics domain. In this paper, we propose a novel medium access control (MAC) protocol defined as wireless arbitration (WirArb) which grants each user channel access based on their different priority levels. The proposed MAC protocol supports multiple users and each user is pre-assigned a specific arbitration frequency which decides the order of channel access. With this mechanism, we can ensure that the user with the highest priority will immediately gain channel access and we can guarantee a deterministic behavior. To evaluate the proposed MAC, we use a discrete-time Markov chain model to mathematically formulate the WirArb protocol. Our results show that the proposed protocol provides high performance to ensure deterministic real-time communication and bandwidth efficiency.

KEYWORDS: Wireless arbitration, wireless sensor networks, deterministic, real-time, cross-layer.

I INTRODUCTION

Wireless technologies have become increasingly popular for emerging applications targeting the consumer market and the industrial automation domain [1]. Merging wireless communication and real-time systems is a non-trivial task, especially for industrial applications where the sensors and actuators are part of control loops, and predictable network performance in terms of message transfer delay and reliability is required [2]. This paper will address the problem of accessing the wireless channel and providing timeliness guarantees. In wired networks, data packets can be efficiently scheduled using the Controller Area Network (CAN) bus, which has already been proven to be useful in industry. The medium access control (MAC) protocol in CAN is collision-free and uses a priority mechanism making it possible to schedule the bus if message characteristics (transmission times, jitter, etc.) are known, while also making it possible to compute the upper bound on message delay. The CAN protocol belongs to the family of dominance or binary countdown protocols [3].

For wireless networks, the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) has mainly been used as a collision-free solution to compete for channel access. CSMA/CA is used as default media access mechanism in wireless local area networks (WLAN) based on the IEEE802.11 standard and in wireless sensor networks (WSNs) based on the IEEE802.15.4 standard. However, for time critical applications which require deterministic communication and have strict deadlines, it has been shown that the CSMA/CA protocol is not suitable due to unpredictable time delay being generated by random distribution of the backoff time [4]. CSMA/CA typically ensures minimum delay for low traffic loads, but as traffic load increases, the delay becomes unacceptable and throughput deteriorates. Since CSMA/CA is a random access scheme, it does not prioritize transmissions based on the physical processes monitored by the sensors and actuators [5], [6]. In addition to the above slotted contention-based CSMA/CA, a recent survey reviews and classifies asynchronous real-time MAC protocols in [7]. Compared with synchronous contention-based CSMA/CA, reduced real-time performance could be induced as it is necessary for the

asynchronous random access mechanism to adopt certain strategies to overcome the decoupled situation between the transmitter and the receiver, which will increase transmission delay due to over-hearing, over-emitting and even packet collisions. To improve the reliability of industrial wireless networks, current available standards such as WirelessHART [8], [9], ISA 100.11a [8], WIA-PA [10] and IEEE802.15.4e [11], uses a Time Division Multiple Access (TDMA) protocol combined with CSMA/CA to schedule the user channel access. One drawback with using TDMA in mission critical applications is that in the event of an emergency event with the highest priority, the transmission of the critical data packet needs to wait for its transmission time slot, which is unacceptable for applications with strict deadlines. Another drawback with TDMA-based WSNs for critical applications is that if a slot for emergency messages had to be reserved in every frame, the channel utilization will be reduced, especially if the refresh rate is high. This is one of the main reasons why TDMA-based WSNs are not a good choice for time-critical wireless sensor network applications. This is highlighted in the literature [4], although a series of real-time MAC protocols are designed to facilitate the expected transmission latency for WSNs, they only manage to meet the real-time requirement by attempting to reduce the data processing time between transmitter and receiver rather than immediately reacting to different emergency events. Regardless of whether CSMA/CA or TDMA induces higher latency by avoiding additional channel conflict and contention, neither is suitable for the real-time control system where different triggered events are limited within different hard time-bounds.

In this paper, we address the problem of wireless channel access by proposing *WirArb* which has similar functions as the CAN bus. The proposal combines the physical layer and MAC layer to guarantee real-time performance. Before the period of data transmission, channel access arbitration will be performed first. Each user in the network is pre-assigned a dedicated arbitration frequency with the purpose to identify channel access priorities which is utilized to deterministically determine the channel access order. This procedure will ensure that in each arbitration cycle the most critical event can be the only one to obtain the highest priority, and immediately gain access to the wireless medium. Through the proposed scheme we can guarantee real-time performance, where all messages will meet their individual deadlines, for time critical industrial wireless applications. We provide a stochastic theoretical model that focuses on the performance evaluation of the *WirArb* scheme by employing a discrete time Markov chain (DTMC) analysis. As formulated analytical expressions for the theoretical analysis, it can be used to calculate the performance in terms of system throughput and communication delay. Furthermore, we compare the channel utilization between *WirArb* and TDMA-based WSNs such as WirelessHART and GinMAC for time-critical applications (for example safety) that require high refresh rate. The obtained results show that the proposed solution outperforms TDMA-based WSNs in terms of latency, throughput and channel utilization.

II. RELATED WORK

In order to serve the stringent real-time requirements for time-critical event-based wireless applications, and overcome mentioned drawbacks on nondeterministic time delay as well as channel utilization, several MAC protocols supporting real-time have previously been presented [12]. Arbitrary contention is the main reason for the transmission delay caused by random backoff and retransmissions. Thus, CSMA/CA-based technologies are used to reduce the harmful impacts from unexpected data collision. In [13], Ye *et al.* presented the SMAC protocol for wireless sensor networks where the sensor nodes utilize the benefits of collision avoidance of the RTS/CTS handshake mechanism. However, because of the scheduling of the fixed duty cycle, this will cause an unacceptable delay which makes this MAC protocol unsuitable for time-critical applications, especially for applications in industrial automation. There are similar protocols based on SMAC in the literature, such as SMAC-AL [14] and DSMAC [15], which replace an adaptive duty cycle to reduce the forwarding delay. However, this class of protocols involves end-to-end delay due to the sleep period to avoid collision with others. In order to reduce the delay from unnecessary sleep, a wake-up scheduling method such as LEEMAC [16], DMAC [17], DW-MAC [18] or SPEED-MAC [19] is developed to decrease sleeping delay. Although the aforementioned protocols can reduce the delivery delay by scheduling the sleep slot, they are not designed for deterministic delay guarantee due to random backoff. All these MAC protocols (including but not limited to [13]–[19]) involves the CSMA/CA mechanism being

more valuable to protect ordinary wireless sensor networks from packet collisions rather than time-critical Wireless Sensor and Actuator Networks (WSAN) with hard requirements for deterministic delay guarantees. HyMAC [20] is a class of MAC protocols merging TDMA and FDMA together. Although HyMAC guarantees a certain end-to-end delay, the main drawback is the lack of ability to adapt to the harsh wireless channel conditions of industrial automation or avionics. In [21], Suriyachai *et al.* presented the GinMAC protocol which they claim can give support for real-time guarantees for time-critical applications in industrial wireless sensor networks. However, their approach to TDMA scheduling will result in exclusive time slot usage which may prevent an emergency task from sending data immediately because it needs to wait for transmission slots.

III. EXPERIMENTAL RESULTS

In this section we analyze the channel utilization by comparing *WirArb* with a TDMA-based WSN, such as WirelessHART. We define the channel utilization in the average number of transmissions per time slot in a superframe that have been received successfully by the gateway. In this paper we compare *WirArb* with WirelessHART, which is based on TDMA. In WirelessHART each event is at most allocated one fixed length time slot which is limited to $10ms$. As can be seen from Fig. 10, event $e_1, e_2, e_3, \dots, e_i, \dots, e_N$ can be correspondingly acquired by the $1^{st}, 2^{nd}, 3^{rd}, \dots, i^{th}, N^{th}$ time slot within each frame periodically. As a result, the total number of time slots allocated to any active user $n_i, \forall i \in \{1, 2, \dots, N\}$ is n . In addition, consider the time critical applications where an emergency event could be triggered when a specific condition is satisfied, such as in safety and security services. In the event of emergency, actuators must react within the required deadline. For instance, if the response time for the emergency event is limited to $250ms$, after the frame of TDMA is assigned to this emergency. Although a total of n time slots are scheduled to, only the $(N+1)^{th}$ slot in the current frame when the emergency was triggered is effectively used while other $n-1$ slots will remain null. That is because the emergency event could not happen periodically. Let us consider the delay boundary for regular data transmission which is fixed to $250ms$, and the time slot is limited to $10ms$. Therefore, in the case of TDMA-based network, we can calculate that the maximum number of network users the constraint that no more than one user can use a channel in a given time slot. We assume that regardless of periodic regular data or aperiodic emergency data, the links are scheduled to communicate continuously. It can be seen that full channel utilization can always be achieved by the *WirArb* protocol regardless of the number of network users or the length of superframe. The maximum number of network users is determined by the priority of emergency events, which implies that any new user can access a channel at any time, once it obtains the highest priority (assuming that the receiver has enough capacity to distinguish arbitration frequencies). It is not necessary to reserve any time slots to use the non-periodic scheduling strategy of *WirArb*.

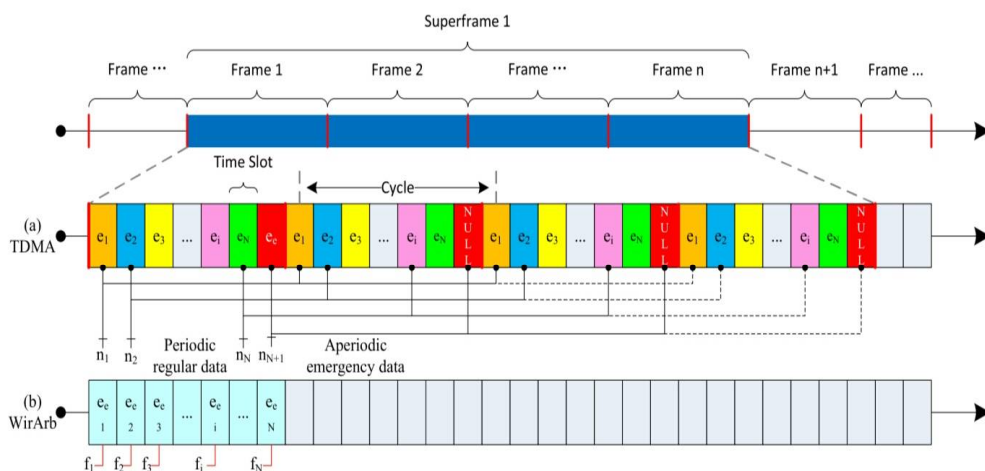
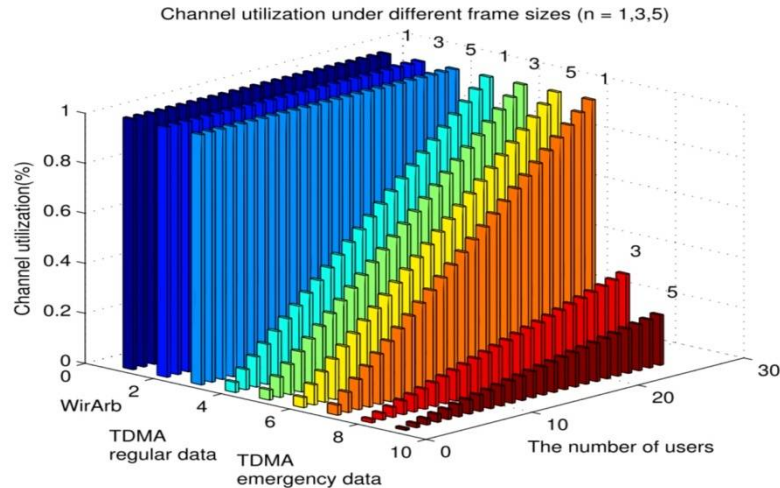
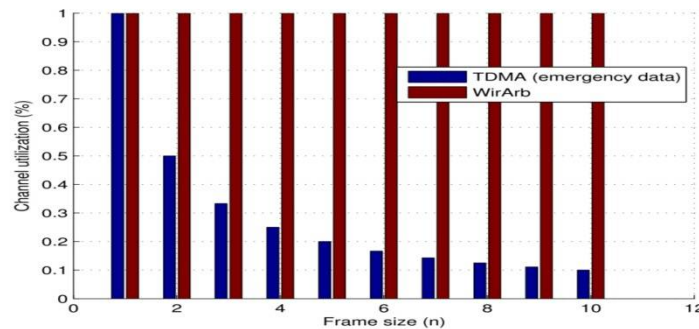


Fig. 10. The time slots scheduling for regular data and emergency data with TDMA and *WirArb*.



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IV. CONCLUSION

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Wireless sensor networks have gained acceptance in a number of domains, and in the future WSNs might be considered for time-critical real-time applications that can be found within industrial automation and avionics. Control applications in industrial automation typically have a hard deadline on data packet delivery and require deterministic communication. Unfortunately, today's WSNs based on CSMA/CA random backoff and TDMA periodic scheduling cannot offer that fully. Therefore, in this article we propose a new medium access protocol called *WirArb* which achieves time-critical data delivery in wireless sensor networks with low energy expenditure.

In *WirArb* each user is pre-assigned a dedicated arbitration frequency to determine the order for users to gain channel access. In this way we can offer a collision-free and deterministic communication over the wireless medium. The protocol is intended for short-range communication, and for this purpose, our protocol is reliable, even in harsh industrial environments. Since the proposed protocol is in the early stages of development there are several challenges that need to be investigated before a full-scale implementation can be achieved.

REFERENCES

- [1] V. C. Gungor and G. P. Hancke, "Industrial wireless sensor networks: Challenges, design principles, and technical approaches," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4258-4265, Oct. 2009.
- [2] J. Åkerberg, M. Gidlund, T. Lennvall, J. Neander, and M. Björkman, "Efficient integration of secure and safety critical

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- industrial wireless sensor networks," EURASIP J. Wireless Commun. Netw., Nov. 2011.
- [3] A. K. Mok and S. A. Ward, "Distributed broadcast channel access," Comput. Netw., vol. 3, no. 5, pp. 327-335, 1979.
- [4] M. Khanafer, M. Guennoun, and H. T. Mouftah, "A survey of beacon-enabled IEEE 802.15.4 MAC protocols in wireless sensor networks," IEEE Commun. Surveys Tuts., vol. 16, no. 2, pp. 856-876, Second Quarter 2014.
- [5] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," IEEE J. Sel. Areas Commun., vol. 18, no. 3, pp. 535-547, Mar. 2000.
- [6] S. Pollin et al., "Performance analysis of slotted carrier sense IEEE 802.15.4 medium access layer," IEEE Trans. Wireless Commun., vol. 7, no. 9, pp. 3359-3371, Sep. 2008.
- [7] M. Doudou, D. Djenouri, and N. Badache, "Survey on latency issues of asynchronous MAC protocols in delay-sensitive wireless sensor networks," IEEE Commun. Surveys Tuts., vol. 15, no. 2, pp. 528-550, Second Quarter 2013.