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Eligible earliest deadline first: Server-based scheduling for master-slave industrial wireless networks☆

Michael Short

School of Science, Engineering and Design, Teesside University, Middlesbrough TS1 3BA, UK

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Industrial automation and control systems are increasingly deployed using wireless networks in master-slave, star-type configurations that employ a slotted timeline schedule. In this paper, the scheduling of (re)transmissions to meet real-time constraints in the presence of non-uniform interference in such networks is considered. As packet losses often occur in correlated bursts, it is often useful to insert gaps before attempting retransmissions. In this paper, a quantum Earliest Deadline First (EDF) scheduling framework entitled 'Eligible EDF' is suggested for assigning (re)transmissions to available timeline slots by the master node. A simple but effective server strategy is introduced to reclaim unused channel utilization and replenish failed slave transmissions, a strategy which prevents cascading failures and naturally introduces retransmission gaps. Analysis and examples illustrate the effectiveness of the proposed method. Specifically, the proposed framework gives a timely throughput of 99.81% of the timely throughput that is optimally achievable using a clairvoyant scheduler.

1. Introduction

The use of wireless communication systems in monitoring and control applications such as factory automation, smart grid and process control has been increasing at a steady rate in recent years [1–10]. This is partly due to a number of recent improvements in the technology, reliability and cost of wireless communication equipment; see for example the survey papers by Akyildiz et al. [9], Rashid and Rehmani [10], Christin et al. [11] and Ajith Kumar et al. [12]. Research on routing protocols to minimize energy consumption [13], low-overhead operating systems for sensor/actuator nodes [14] and novel energy-scavenging techniques [15] have all made contributions that help increase the battery life of devices and hence maximize network up-time.

Wireless systems have the distinct advantage of reducing equipment installation complexity through the lack of a need for wiring and harnessing, enabling easier trouble-shooting and system re-configuration; this reduces the long-term maintenance requirements associated with wired systems [1–4]. However, the use of wireless technologies in these applications is not without problems, which include out-of-order packet transmissions, high levels of packet jitter and high probabilities of packet losses. These problems are especially problematic in control applications that can have strict timing constraints [1–4]. Some of these problems can be ameliorated to a certain extent by careful planning of node locations [5], using redundant ratio transceivers [8] or by using higher level (application layer) compensation techniques [16]. The use of master-slave (request-response) type architectures and their close Time Division Multiple Access (TDMA)-based variants connected in star

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E-mail address: m.short@tees.ac.uk

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or mesh topologies is also a popular method to help reduce such problems [4–6,17,18]. The focus of this paper is mainly upon industrial master-slave networks connected in star topologies, in which messages are scheduled using a master-controlled slotted timeline approach or a master-controlled TDMA 'superframe' approach. Typically, devices in such networks will operate with equipment using frequencies in the unlicensed Industrial, Scientific and Medical (ISM) radio band and although error detection and correction techniques are routinely employed, they can suffer from large amounts of interference in an industrial environment [4,5,7].

Since interference can affect the successful delivery of packets, care must be taken to ensure that the control or monitoring devices do not operate with an inconsistent view of the physical process. Aside from using redundancy in the frequency spectrum (e.g. [7]), a key method to increase the reliability of packet delivery (and hence transaction reliability) is to allow some spare or 'slack' time in the communications schedule and employ retransmissions in case of detected errors (temporal redundancy). In this paper, a scenario in which master-slave scheduling of request-response transactions takes place in the presence of non-uniform and bursty interference is considered, and in situations in which more complex patterns of real-time communication than those afforded by a simple cyclic schedule are required to take place. Specifically, the case in which transactions are under the control of a master node using the Earliest Deadline First (EDF) real-time scheduling algorithm is considered, for transactions having relative deadlines equal to their periods. In such circumstances if the scheduler has accurate knowledge of the upcoming channel error state *prior* to scheduling a transaction, then scheduling the *feasible* transaction with earliest deadline has optimal properties [19]. However, this implies the scheduler must be clairvoyant and unfortunately, such a 'Feasible EDF' scheme cannot be implemented in practice [19]. The use of on-line (statistical) estimates of the channel state or probe packets is required prior to making scheduling decisions; neither technique can be 100% accurate due to the nature of the problem, and both consume unwanted additional node and/or bandwidth overheads [19].

A simple but practical alternative to Feasible EDF is explored in this paper. The proposed technique – entitled 'Eligible EDF' - does not attempt to estimate or predict the channel state in either the master or the slave nodes, and it does not use probe packets. Transactions are scheduled using EDF without explicit knowledge of the channel state and hence errors will occur; re-scheduling of failed transactions in the case of packet losses is handled by a simple but effective replenishment strategy controlled by a server. This server reclaims unused channel utilization to replenish failed slave transactions, a strategy which prevents 'domino' deadline failures affecting other pending transactions. Under some mild assumptions related to the boundedness of the packet size and the worst-case slave turnaround times, this situation is well represented as a Quantum scheduling instance for which a very simple optimal server is known. By replenishing failed transactions within this server according to their absolute deadlines, retransmissions are handled effectively and a close approximation of Feasible EDF is obtained. This occurs since retransmission attempts are temporarily separated by a minimum gap as a natural by-product of the server operation, and infeasible channels are effectively polled (within the main schedule) until they become feasible. This helps to de-correlate packet losses and increases the reliability of packet delivery without starvation of feasible channels occurring. Together, this seems to give a flexible and robust means to schedule transmissions in a master-slave wireless network. Computational experimental results indicate that the achieved timely throughput is very close ($\approx$ 99.81%) to the optimal timely throughput which can be obtained using a clairvoyant Feasible EDF scheduler having perfect channel state estimation.

The remainder of this paper is organized as follows. Section 2 of the paper describes related work on industrial wireless communications with specific focus upon scheduling in master-slave configurations. Section 3 describes the assumed models of the communication system and channel errors. Section 4 describes the proposed scheduling technique. Section 5 presents a series of computational experiments using simulations to evaluate the technique, and presents analysis of the results obtained. Conclusions and areas for further work are considered in Section 6.

2. Related work

As mentioned in the introduction, this paper assumes a master-slave configuration for the wireless network, which has a (possibly hierarchical) star-type or mesh-type topology. In the master-slave star connected approach a single (typically central) master node has control over the overall communication by sending out requests to slaves to elicit responses in a static (pre-determined) or dynamic cyclic order [4,17,18,20]. A number of technologies for wireless factory automation applications have been surveyed and compared with respect to attributes such as flexibility, security and Quality of Service (QoS) [11,12]. The technologies surveyed include the Wireless Interface for Sensor and Actuators (WISA), WirelessHART, ISA100.11a, Zig-Bee, ZigBee PRO, and 802.15.4e Factory Automation MAC Layer. Although each technology can typically configured in one of several different ways, a popular configuration for Supervisory Control And Data Acquisition (SCADA), Distributed Control Systems (DCSs), process monitoring and factory automation applications is a (possibly hierarchical) star configuration, such as is depicted in Fig. 1.

The figure shows several workcells, each containing a master node and multiple slave nodes. Typically, the master node in each workcell (which would consist of Programmable Logic Controllers (PLCs), Programmable Automation Controllers (PACs) or other embedded automation or control devices) would communicate with slave communication nodes (which would consist of remote I/O and sub-control units) via short/medium-range packet radio systems. Normally the designation of master node in each workcell is relatively easy to assign, due to the differentiation between the automation/control device and the sub-control or I/O units. In some cases, the master node may even be an access point, with the main automation