Work-in-Progress: Utilization Based Schedulability Analysis for Wireless Sensor-Actuator Networks

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***Abstract*—WirelessHART networks provide the feasibility of achieving real-time performance over wireless through multi-channel and graph routing for process monitoring and control applications. However, real-time scheduling theory for Wireless Sensor-Actuator Network (WSAN) is still not well-developed. Besides, the performance of a WSAN induces a complicated problem involving many interrelated objectives and variables, requiring a scheduling-control codesign. This work aims at addressing these challenges. Specifically, we will develop a real-time schedulability analysis for WSAN, and leverage this result to address multiple key challenging problems in wireless Cyber-Physical Systems in the future. Schedulability analysis remains the cornerstone in any real-time system. In WSAN, it is used to determine whether a set of real-time control loops/flows can meet deadlines. It is also used in various scheduling-control codesign, routing, and priority assignment. In this work, we will develop an analysis based on utilization bound. Because of its extremely low runtime overhead, utilization based analysis has been extensively studied in CPU scheduling. However, no work has been done yet on utilization based analysis for multi-hop wireless network. The key challenge arises from transmission conflict and dynamics in wireless. We will address this by characterizing transmission conflict as task blocking in nonpreemptive CPU scheduling, and then by adopting a hierarchical network structure where we will apply the analysis in each subnetwork.**

I. Introduction

With the advent of industrial standards such as WirelessHART [1] and ISA100 [2], recent years have seen a widespread deployment of Wireless Sensor-Actuator Network (WSAN) for industrial process monitoring and control. In a feedback control loop between sensors and actuators in a WSAN, the sensors measure process variables, and deliver to a controller which then sends control commands to the actuators through the network. Industrial control applications require real-time communication between sensors and actuators in order to avoid plant shutdowns and accidents. For example, in oil refineries, spilling of oil tanks has to be avoided by controlling the level measurement in real-time. However, industry settings pose a harsh environment for wireless communication causing frequent transmission failures due to noisy channels, limited bandwidth, obstacles, multi-path fading, and interference that make it difficult to meet these requirements [3].

Industrial wireless standards such as WirelessHART mitigate frequent transmission failures through multi-channel communication and *graph routing* where a packet is transmitted through multiple paths and multiple channels. These networks therefore provide the feasibility of achieving reliability and real-time performance over wireless for critical process control applications. However, unlike the wired counterpart, real-time scheduling theory for wireless network is still not well-developed. In addition, the performance of a wireless control system induces a complicated problem involving multiple interrelated objectives (e.g., reliability, real-time performance, control performance) and interdependent decision variables (e.g., transmission schedule, routes, sampling rates). Hence, holistic optimization of control performance requires scheduling-control co-design that needs expertise from diverse disciplines. This paper aims at addressing these challenges.

Schedulability analysis remains the cornerstone of any real-time scheduling theory. In real-time WSANs, it is used to determine, both at design time and for online admission control, whether a set of real-time control loops/flows (i.e. end-to-end communication between sensor and actuator) can meet their deadlines. It thus helps the network manager in planning in advance and in adjusting workloads in response to network dynamics for real-time process control applications. For example, when a channel is blacklisted or some routes are recalculated, the analysis can be used to promptly decide whether some control loop has to be removed or some rate has to be updated to maintain real-time guarantee for the system. In WSAN, a schedulability analysis is also used in various scheduling-control codesign [4], [5], real-time routing, and priority assignment [6].

In this paper, we want to develop a schedulability analysis based on *utilization bound* which is a yet unexplored problem for multi-hop wireless networks. This approach determines the maximum total utilization of all flows in the network and determine those as *schedulable* if the total utilization does not exceed the maximum possible utilization in the network. Because of its extremely low runtime overhead, utilization-bound based schedulability test is considered one of most efficient and effective schedulability tests. Therefore, it has been extensively studied in CPU scheduling [7]. However, no work has been done yet on utilization based analysis of multi-hop wireless network. The key challenge arises from the fact that wireless networks are subject to transmission conflict and dynamics which are absent in CPU scheduling. We will address this challenge by bridging between wireless domain and non-preemptive CPU task scheduling where the behavior of transmission conflict is characterized as that of task blocking in traditional non-preemptive scheduling. Our technical approach for the utilization based analysis will divide

978-1-5090-5269-1/17/$31.00 ©2017 IEEE

the network into a hierarchical structure, and apply the analysis for each subnetwork.

II. BACKGROUND

For WSANs, there are two broad approaches for schedulability analysis. One approach is based on *end-to-end delay analysis*. The other approach is called *utilization bound analysis* that determines the maximum total utilization of all flows in the network and determines those as *schedulable* if the total utilization does not exceed the maximum possible utilization in the network. Because of its extremely low runtime overhead, utilization-bound based schedulability test is considered one of most efficient and effective schedulability tests. In contrast to the end-to-end delay bound based analysis [8], [9], [10], [11] that requires a separate schedulability test for each individual flow and that runs in *pseudo polynomial* time (i.e., *exponential* in the length of the input), utilization bound based analysis can provide a single closed-form expression that can run in polynomial time (usually in *linear* time). It thus greatly simplifies various scheduling-control optimization problems for which pseudo polynomial time delays bounds had been a major hurdle due to their non-linearity, non-convexity, non-differentiability, long execution time, and large number of constraints (at least n constraints for n flows) [4], [5]. In this research, we want to develop a schedulability analysis based on *utilization bound* which is a yet unexplored problem for multi-hop wireless networks.

A. System Model

Because of the world-wide adoption of WirelessHART in process control in challenging industrial environments, we consider a WSAN based on the WirelessHART standard [1]. This WSAN is a multi-hop mesh network of a Gateway, field devices, and access points. The *network manager* creates routes and transmission schedules. The *field devices* are wirelessly networked sensors and actuators. *Access points* provide redundant paths between the wireless network and the Gateway. Each node has a *half-duplex* omnidirectional radio transceiver, and hence cannot both transmit and receive at the same time, and can receive from at most one sender at a time.

WirelessHART [1] employs multi-channel TDMA (Time Division Multiple Access) for transmission. Each time slot is of fixed size (10 ms), and each transmission with its acknowledgement needs one time slot. For transmission between a receiver and its sender, a time slot can be either dedicated or shared for the link between the sender and the receiver, and the link is called a *dedicated link* or a *shared link*, respectively. In a time slot, when a link is used as a *dedicated link*, only one sender is allowed to transmit to the receiver. In a time slot, a *shared link* associated with a receiver indicates that multiple senders can attempt to send to the common receiver in that slot. Transmissions are scheduled based on *graph routing*. A *routing graph* is a directed list of paths that connect two devices. In the end-to-end communication between a source (sensor) and destination (actuator), on one path the scheduler allocates two dedicated slot for each link, followed by allocating a third shared slot on a separate path to handle another retry.

B. Problem Formulation

Each control loop, also called a *flow*, involves one or more sensors and one or more actuators. There are n control loops denoted as $F_1, F_2, \cdots, F_n$. The period (sampling period of sensors) and the deadline of F_i are denoted by T_i and D_i, respectively. The transmissions of the control loops are scheduled on m ($m \geq 1$) channels. The set of periodic flows F is called *schedulable* if there is a schedule of transmissions such that no deadline is missed. A schedulability test $\mathbb{S}$ is *sufficient* if any set of flows deemed to be schedulable by $\mathbb{S}$ is indeed schedulable. If flow F_i involves C_i transmissions, then its utilization u_i is defined as $\frac{C_i}{T_i}$. The total utilization of all n flows is $\sum_{i=1}^{n} \frac{C_i}{T_i}$. Our objective is to determine a sufficient schedulability analysis based on utilization bound.

C. Related Work

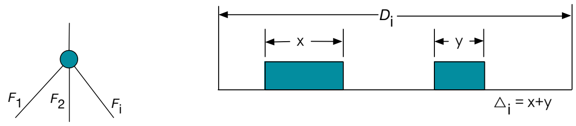
Real-time scheduling for wireless networks was studied in [12], [13], [14], [15] without any schedulability analysis. For wireless sensor networks, schedulability analysis was studied in [16], [17], [18], [16], [17], [19] but only for data collection and without considering multi-channel and route diversity that are crucial in WirelessHART. Real-time scheduling for WirelessHART networks was studied in [20], [21], [8], [6], [22], [4], [23], [24]. Among these, only [8], [9], [10] considered schedulability analysis based on delay bounds. In contrast, we propose utilization based approach for schedulability analysis which provides the simplicity and efficiency in application. Utilization based analysis has been studied in [25] for single hop wireless network. In contract, we focus on multi-hop WSAN in which scheduling and analysis is significantly different and challenging as it has to deal with multiple concurrent transmissions on different channels, interferences, and transmission conflicts.

III. UTILIZATION BASED SCHEDULABILITY ANALYSIS

We first propose an approach for determining a schedulability analysis where transmission conflict of WSAN are characterized by task blocking in traditional non-preemptive scheduling. We then organize the network into a hierarchical structure, and apply the derived analysis for each subnetwork. We propose analysis for both fixed-priority and dynamic priority scheduling.

A. Establishing a Utilization Bound Analysis

In a WSAN, there are two sources that contribute to the delay of a flow. A lower priority flow can be delayed by higher priority flows (a) due to ***channel contention*** (when all channels are assigned to transmissions of higher priority flows in a time slot), and (b) due to ***transmission conflicts*** arising from the fact that a node cannot both transmit and receive at the same time and can receive from at most one sender (due to single half-duplex radio). Transmission conflict poses additional challenge in wireless domain which is absent in



(a) Transmission conflict (b) Time loss (cyan color) due to conflict

Fig. 1. Time loss due to transmission conflict

CPU scheduling. Our technical approach leverages the bridge between multiprocessor scheduling and wireless transmission scheduling.

We first review the results on preemptive and non-preemptive scheduling on multiprocessors. In *preemptive scheduling*, a task upon start can be preempted by any higher priority task any time. In *non-preemptive scheduling*, a task once started can never be preempted by any other task. In non-preemptive scheduling, a higher priority task thus can be *blocked* by a lower priority task (as it cannot preempt if the lower priority task has already started). EDF (Earliest Deadline First) is a dynamic priority scheduling policy where, at any time, the task having the shortest absolute deadline is scheduled first. Any constrained deadline (i.e. $D_i \leq T_i$) set of n real-time tasks is schedulable using preemptive EDF scheduling on m processors [26] if

$$\sum_{i=1}^{n} \frac{C_i}{D_i} \leq m - (m-1)\left(\max\left\{\frac{C_i}{D_i}|1 \leq i \leq n\right\}\right) \quad (1)$$

Deadline monotonic (DM) scheduling is a fixed priority scheduling policy where tasks are prioritized based on their relative deadlines. Any constrained deadline (i.e. $D_i \leq T_i$) set of n real-time tasks is schedulable using preemptive DM scheduling on m processors [27] if

$$\sum_{i=1}^{n} \frac{C_i}{D_i} \leq \frac{m}{2}\left(1 - \max\left\{\frac{C_i}{D_i}|1 \leq i \leq n\right\}\right) + \max\left\{\frac{C_i}{D_i}|1 \leq i \leq n\right\} \quad (2)$$

For non-preemptive scheduling the corresponding conditions are derived by taking into account the maximum blocking time. To adopt the similar results for WSANs, we present our ideas as follows. In absence of transmission conflict and when every transmission happens on a separate channel in a time slot (allowing at most m concurrent transmission per time slot) and considering every time slot as time unit, we can use the above two analyses for WSAN. Then, to take into account the effects of transmission conflict, the additional delay caused by transmission conflict can be considered as blocking time in non-preemptive scheduling. Let Δ_i denote the delay caused on control loop F_i by all higher priority flows. In our analysis, we consider utilization loss due to transmission conflict delay. Thus F_i will have only $D_i - \Delta_i$ time slots to complete end-to-end communication. For example, in Figure 1(a), the transmission of F_i cannot be scheduled until other 4 transmissions of higher priority flows F_1 and F_2 (due to transmission conflict at the node shown in the figure) are scheduled causing a delay of 4 slots on F_i even if there are channels available. We can hence consider a time loss of 4 slots from its relative deadline (Figure 1(b)). Namely, from deadline D_i (which is the total quanta for F_i), the flow F_i loses at most Δ_i slots, and hence its effective utilization μ_i becomes (Figure 1(b)) $\mu_i = \frac{C_i}{D_i - \Delta_i}$. Let us define

$$\mu_{\max} = \max\{\mu_i | 1 \leq i \leq n\}; \qquad \mu_{\text{sum}} = \sum_{i=1}^{n} \mu_i$$

Therefore, from (1) and (2), any constrained deadline set of real-time flows is schedulable on m channels in a WSAN that allows at most m concurrent transmissions under EDF scheduling if

$$\mu_{\text{sum}} \leq m - (m-1)\mu_{\max} \quad (3)$$

and under DM scheduling if

$$\mu_{\text{sum}} \leq \frac{m}{2}(1 - \mu_{\max}) + \mu_{\max} \quad (4)$$

To handle retransmissions upon transmission failures, we need to consider ETX (Expected number of transmissions) of every link. We need to reserve a time slot for every retransmission. Thus, if ETX_j indicates the ETX of link j and there are a total of ℓ_i links on flow F_i's route, then we can update C_i as follows $C_i = \sum_{j=1}^{\ell_i} \text{ETX}_j$.

Our preliminary work in [9] shows the basic idea of calculating a value of Δ_i. Based on that, we will determine a tight bound on the value of Δ_i to make the above results effective and efficient.

B. Adopting the Utilization Based Analysis through Hierarchical Networking

Because we derived the above results considering at most m concurrent transmissions in the network, we now propose a hierarchical network based analysis where this constraint will be relaxed for the global network. Namely, the network is considered as a collection of subnetworks, each subnetwork having its own subnetwork manager will adopt the above result at subnetwork level. A global network manager will coordinate with the subnetwork managers to manage the entire network in a hierarchical fashion. Every subnetwork will involve unique channel for every transmission in a time slot. Thus if there are $m'(\leq m)$ channels used in a subnetwork, then there will be at most m' concurrent transmissions in the subnetwork. Therefore, we can use the results of (3) and (4) in each subnetwork directly. We will prove our claims mathematically in this research.

An important technical challenge in our proposed hierarchical architecture is to deal with the interdependencies among the subnetworks. For example, if the subnetwork manager of a subnetwork needs to create a local TDMA schedule (i.e., for the links inside the subnetwork), it may need to wait after its neighboring subnetworks (or some of the neighboring subnetworks) finish their schedule. This happens because any packet that needs to be routed through multiple subnetworks, needs to be scheduled in the earlier subnetworks first. Because feedback control loops involve both upwards and downward communication in the WSAN, such dependencies can be cyclic. For example, let us consider 2 packets p and q such that p needs to be scheduled first in subnetwork C_1 and then in subnetwork C_2, and that q needs to be scheduled first in subnetwork C_2 and then in subnetwork C_1. In such a scenario, C_1 needs to create a schedule after C_2 creates, and C_2 needs to create a schedule after C_1 creates, thereby creating a cyclic dependency. We propose to address this challenge by efficiently removing the dependencies. Our proposed method to remove these dependencies is to assign subdealines and release offsets for each control loop among the subnetworks. Specifically, for every control loop F_i that passes through a subnetwork C_j, we will assign a release offset $r_{i,j}$ and a subdeadline $d_{i,j}$ in the subnetwork. The release offset $r_{i,j}$ is equal to the subdeadline of F_i in the subnetwork where it needs to be scheduled immediately before C_j. Thus, subnetwork C_j needs to schedule F_i within the time window $[r_{i,j}, d_{i,j}]$, thereby requiring no knowledge of the schedule (for F_i) in other subnetworks. Note that, if the control loops are schedulable in subnetworks, they are schedulable (considering the complete network), but the reverse may not be true always. Hence, the global network manager must assign the subdeadlines effectively. We will develop efficient methods to determine subdeadlines by extending existing real-time scheduling approaches to distributed real-time systems with end-to-end tasks [28] to wireless networks. Once proper subdeadlines are determined, we will leverage the results derived in (3) and (4) for utilization based schedulability analysis in each subnetwork.

IV. Conclusion and Future Work

We develop a schedulability analysis based on *utilization bound* which is a yet unexplored problem for multi-hop wireless networks. This approach determines the maximum total utilization of all flows in the network and determine those as *schedulable* if the total utilization does not exceed the maximum possible utilization in the network. Because of its extremely low runtime overhead, utilization-bound based schedulability test is considered one of most efficient and effective schedulability tests.

This work is the inception of a new horizon on utilization based analysis for WSANs which can direct the wireless community in the same way the real-time systems research today evolved from Liu and Layland's utilization bound. Our result will trigger many research directions in the line of real-time scheduling, scheduling-control codesign, control performance optimization, routing, priority assignment, and mixed-criticality real-time WSANs. Our future work involves analyzing the effects of deadlines miss, packet loss, and the tradeoffs among various control performance metrics in WSANs.

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