Minimum Bandwidth Reservations for Periodic Streams in Wireless Real-Time Systems

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Abstract—Reservation-based (as opposed to contention-based) channel access in WLANs provides predictable and deterministic transmission and is therefore able to provide timeliness guarantees for wireless and embedded real-time applications. Also, reservation-based channel access is energy-efficient since a wireless adaptor is powered on only during its exclusive channel access times. While scheduling for Quality of Service at the central authority (e.g., base station) has received extensive attention, the problem of determining the actual resource requirements of an individual node in a wireless real-time system has been largely ignored. This work aims at finding the minimum channel bandwidth reservation that meets the real-time constraints of all periodic streams of a given node. Keeping the bandwidth reservation of a node to a minimum leads to reduced energy and resource requirements and leaves more bandwidth for future reservations by other nodes. To obtain a solution to the minimum bandwidth reservation problem, we transform it to a generic uniprocessor task schedulability problem, which is then addressed using a generic algorithm. This algorithm works for a subclass of priority-driven packet scheduling policies, including three common ones: fixed-priority, EDF, and FIFO. Moreover, we then specialize the generic algorithm to these three policies according to their specific characteristics. Their computation complexities and bandwidth reservation efficiencies are evaluated and guidelines for choosing scheduling policies and stream parameters are presented. Index Terms—Bandwidth reservation, schedulability test, earliest deadline first, fixed-priority, first-in-first-out, medium access control, real time, wireless.

1 INTRODUCTION

WIRELESS embedded real-time systems are becoming prevalent with the continuous increase in streaming applications such as video/audio communications, industrial automation, networked and embedded control systems, and wireless sensor and actuator networks. This has called for research efforts to enhance the support of timeliness and Quality of Service (QoS) in wirelessly networked embedded environments. Wireless networks are inherently broadcast and media-shared. Contention-based media accesses such as CSMA are nondeterministic and thus incapable of providing predictable QoS
support to periodic communications often found in wireless real-time systems. Moreover, multiple nodes are active simultaneously and continuously sense and contend for the shared media, leading to excessive energy consumption. Reservation-based channel management requires each node to negotiate its desired channel access duration for a given period based on its traffic constraints. However, the computation of such requirements has largely been ignored which has often resulted in poor real-time support, overprovisioning of valuable resources, and poor scalability. The goal of this work is to develop a strategy for the computation of the required channel access reservations for a given packet scheduling policy, such that 1) the real-time constraints of each node’s traffic are satisfied and 2) resource reservations are minimized.

To solve the minimum bandwidth reservation problem at a given node, we treat the complement of the periodic bandwidth reservation as a special periodic stream (the periodic sleep stream), i.e., the bandwidth reservation per channel access period is equal to the complement of the execution time (sleep time) of the sleep stream with period equal to the channel access period. We add the sleep stream to the original stream set to form an extended stream set. Accordingly, the scheduling policy for the extended stream set is extended from the original scheduling policy for the original stream set such that 1) the sleep stream always has the highest priority and is noninterruptible and 2) the priority relationship among the original stream set is unchanged. As a consequence, we transform the minimum bandwidth reservation problem to the maximum sleep time problem. In other words, there exists a schedule for the original stream set with a given scheduling policy if and only if there exists a schedule for the extended stream set using the extended scheduling policy. Therefore, minimizing the bandwidth reservation is equivalent to maximizing the sleep time of the sleep stream. The main contributions of this paper are:

1) the transformation of the problem of periodically reserving a time interval of minimum length to serve all real-time streams of a node (a problem in the network community) into a dual problem on a dedicated resource (a problem in the real-time scheduling community); and 2) present an alternative solution as in [3] to this problem by applying an augmented supply/demand analysis on the transformed problem in an efficient manner.

RELATED WORK
Scheduling and schedulability analysis have been extensively studied in previous work, particularly for processing resources. In networking environments, reservation-based mechanisms are becoming highly prominent in supporting latency-critical and energy-aware traffic. In this section, we discuss existing protocol standards and techniques related to resource and channel access reservations. The schedulability test scheme for the STSPP model in [3] can also be used to solve the problem, by iteratively executing the schedulability test algorithm proposed in [3] (similar to a binary search). Therefore, this approach would be very costly. It is particularly inefficient for the fixed-priority policy since the change of the resource supply and the change of job response times are nonlinear and irregular. Our algorithm augments the traditional timedemand analysis to compute the finished/unfinished portion before a job’s deadline, which avoids computing fixed-point equations iteratively. As a result, our solution to the reverse problem (the minimum resource requirement problem)
has the same complexity as the original problem (the exact schedulability test problem).

**BANDWIDTH RESERVATION MODEL**

This section presents our network access model, traffic model, and the problem statement. 3.1 Network Access Model We briefly discuss the concept of reservation-based channel access model (which corresponds to the single time slot periodic partition model introduced in [3]) since it forms the basis for the problem we intend to solve. Such a mechanism uses resource reservations to ensure contention-free accesses. This is achieved through a central authority at a BS that regulates the channel accesses of individual nodes. Here, the BS takes control of the channel and starts polling each of the nodes in a predetermined order (e.g., roundrobin). Upon reception of a polling frame, a node gains access to the channel. The HCCA mode defined in the IEEE 802.11e standard [2] is an example of a protocol which adopts the reservation-based channel access approach to enhance the QoS support for real-time applications in wireless environments.

![Fig. 1. A wireless device's bandwidth profile (SP; SI). Shaded intervals c(S_i) are the exclusive access periods for a node, which are repeated every SI time units.](image)

3.2 Traffic Model We consider a set of wireless nodes with applications on each node generating one or more periodic real-time streams. Nodes connect wirelessly to a common BS to access an external network. We denote the set of periodic streams generated by a node as $S \equiv fS_1; \ldots ; S_n g$. Each stream $S_i$ periodically generates a certain number (worst case or average case) of bytes (called a datagram) for a given period $p_i$ for transmission. The datagram generated at the beginning of the $j$th period of $S_i$ for transmission is denoted as $J_{i;j}$. Wireless channel conditions are time-varying and error-prone. The worst-case estimation (denoted as $e_i$) of the transmission time of a datagram of $S_i$ is needed, which has been the focus of many prior efforts (e.g., in [5] and [24]). Each datagram of $S_i$ has a relative transmission completion deadline $D_i$. The release time and deadline of $J_{i;j}$ are denoted as $r_{i;j}$ and $d_{i;j} = r_{i;j} + D_i$, respectively. Our framework requires no specific relationship between stream periods and datagram deadlines, i.e., $D_i$ can be less than, equal to, or greater than $p_i$. Due to the similarity between the concept of tasks in the literature and the concept of streams in this paper, we will use stream and task interchangeably in this paper. Similarly, the terms datagram and job are also used interchangeably.

![Fig. 2. Transformation of the bandwidth profile and the sleep stream.](image)

**Definition 4.1 (Sleep Stream).** Given a bandwidth profile $(SP; SI)$, the corresponding sleep stream $S_0$ is defined with $p_0 = \frac{1}{4} SI$ and $D_0 = e_0 = 0\frac{1}{4} SI \_ SP$, i.e., its period is equal to the service interval $SI$; its execution time and deadline are invariantly equal and both are equal to the complement portion of the allocated access interval $SP$, i.e., $SI \_ SP$. Furthermore, the sleep stream cannot be interrupted (i.e., its nonpreemption portion is equal to the execution time).
5.1 Generic Framework

In this section, we develop a generic algorithmic framework (Algorithm 1) to solve the MET problem, based on an augmented time-demand analysis. In the following description, we distinguish between the finished portion and the unfinished portion of execution before a given deadline. This concept allows us to conservatively reduce the sleep time of the sleep stream to approach its minimum value, assuming that the reduced sleep time (equal to the unfinished portion) is solely utilized by the job missing its deadline. To compute the finished/unfinished portions of a job, we define a generic time-demand function at every job release event point. The available time at a job release event point for lower priority jobs is equal to the dedicated time supply minus the generic time demand. As a result, the finished portion of a job before its deadline is equal to, provided it has not finished, the maximum available time over all job release event points between its release time and its deadline. Our approach avoids iterative computations of fixed-point equations (which are usually found in existing response time computations).

![Algorithm 1](image)

**Fig. 4.** An illustration of the augmented time-demand analysis to compute the finished portion.
Theorem 5.1. For any periodic stream set and any job-level static scheduling policy under which the scenario of the worst-case response time is the synchronous busy interval, the bandwidth minBW computed by Algorithm 1, if successfully terminated, is the exact minimum bandwidth requirement of the stream set.

\[ w_{i,j} = \sum_{0 \leq k \leq n} \left( \frac{r_{i,j}}{p_k} \right) e_k + \theta, \]

\[ e_{i,j}^+ = \min \{ e_{i,j}, \max \{ 0, w_{i,j} - d_{i,j} \} \}, \]

\[ f_{i,j} = w_{i,j}. \]

**CONCLUSIONS AND FUTURE WORK**

The benefits of reservation-based channel accesses are twofold: 1) they provide contention-free access within allocated/reserved channel access intervals to meet timing constraints predictably and 2) they allow a wireless radio to be powered down when the channel is not needed. Careless resource allocations may lead to poor support for real-time traffic or overprovisioning of scarce network resources. This paper solves the minimum bandwidth reservation problem to allow all streams to meet their timing constraints. To obtain a solution to the minimum bandwidth reservation problem, we transform it to a generic uniprocessor task schedulability problem, which is then addressed using a generic algorithm based on time-demand analysis. The generic minimum bandwidth reservation algorithm works for a subclass of priority-driven packet scheduling policies, including three common ones: fixed-priority (e.g., RM and DM), EDF, and FIFO. Refinements of the generic solution to these three types of policies are presented and discussed as well. The simulation results show that the generic algorithm is correct and practical in terms of computation complexity. The proposed bandwidth reservation scheme leads to minimal amounts of bandwidth waste if appropriate scheduling policies and stream parameters are selected for a given stream set. However, it also leads to potentially large energy savings, while being simple to implement and deploy. In our future work, we will address 1) how the base station chooses the optimal SI value to minimize the bandwidth/energy consumption of the entire wireless local area network, 2) how different client nodes use an SI which is a multiple of the beacon interval of the base station, and 3) how reservations (SPs) of nodes with different SIs can be composed efficiently to form a superframe.


