A Real-Time Message Scheduling Scheme Based on Optimal Earliest Deadline First Policy for Dual Channel Wireless Networks[*]

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Abstract. This paper addresses the problem of scheduling time sensitive messages on dual channel wireless sensor networks. Besides the bandwidth expansion, partitioning evenly the transmission time makes it possible to inherit the optimality of EDF scheduling scheme on the dual channels based on fixed-size time slots synchronized across the two channels. Slot rearrangement also maximizes the number of switchable pairs, so the allocation can be switched dynamically between the channels according to the current channel status, enhancing the reliability of timely message delivery. Simulation results show that the rearrangement scheme can generate 70 % of switchable pairs even when the utilization reaches the saturation point, improving the ratio of successful transmission by up to 18 % when the packet error rate exceeds 0.4, compared with global EDF or NCASP.

1 Introduction

Wireless media such as WLAN (Wireless Local Area Network) have become increasingly important in today's computer and communications industry [1]. In addition to traditional data services, WLAN is creating new opportunities for the deployment of advanced multimedia services such as broadband VoD (Video on Demand). Meanwhile, one of the promising application areas of wireless technology is the wireless sensor network, where the periodically sampled data are delivered to the appropriate station within a reasonable deadline to produce meaningful data [2]. The message of sampled data has a real-time constraint that it should be transmitted within a bounded delay as long as the channel stays in good state. Otherwise, the data are considered to be lost, and

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the loss of a real-time message may jeopardize the correctness of execution result or system itself. Accordingly, a real-time message stream strongly demands the guarantee from the underlying network that its time constraints are always met in advance of the system operation or connection setup.

However, the guarantee scheme is not sufficient to satisfy such time constraints as the wireless network is subject to unpredictable location-dependent and bursty errors, which make a real-time traffic application fail to send or receive some of its real-time packets [3]. In the mean time, the wireless network has an advantage that it can be easily duplicated, or a cell is able to operate dual channels, as a cell can have up to 3 channels according to the IEEE 802.11 standard. In this system, each sensor station may be equipped with a transmitter and a receiver that can tune to either channel, giving the flexibility to transmit and receive on both channels. After all, the dual channel system enables various ways to improve the reliability of the message delivery.

The dual network architecture is analogous to the dual processor system in that both network and processor can be considered as an active resource. However, real-time scheduling for dual or multiple resource system is known to be an NP-hard problem [4], while the uniprocessor system has an optimal scheduling solutions such as RM (Rate Monotonic) for static scheduling as well as EDF (Earliest Deadline First) for dynamic scheduling. Applying RM or EDF method to multiple resource system is not optimal in scheduling preemptable jobs due to its work conserving nature [5]. Existing multichannel scheduling schemes such as MULTI-FIT cannot be applied directly to the real-time communication, as they didn't directly take into account the timeliness requirement [4].

In wireless sensor network, each message usually has no data dependency, so the optimality of EDF scheme can be sustained also for the dual networks by evenly partitioning each stream rather than grouping streams into two sets. Moreover, the dual channels can efficiently cope with network errors without violating the time constraints of messages, if the transmission order is rearranged lest the same stream should be scheduled on the concurrent time slots of two channels. Then, the allocation can be switched dynamically between the channels according to the current channel status. With these assertions, we are to propose and analyze the performance of a bandwidth allocation scheme for real-time sensor messages on the dual channel wireless networks, aiming at keeping the optimality of EDF scheduling scheme as well as maximizing the capability of coping with wireless channel errors. In this paper, the infrastructure mode IEEE 802.11 WLAN is assumed to be the target communication architecture [6].

The rest of this paper is organized as follows: Section 2 will introduce backgrounds and related works on real-time message scheduling for multiple networks, and then Section 3 explains the scope of this paper and basic assumptions on network, message, and error models. Section 4 will describe the proposed scheduling scheme in detail along with a relevant example. After exhibiting the performance measurement result in Section 5, Section 6 concludes this paper and briefly describes future works.

2   Background and Related Works

The IEEE 802.11 was developed as a MAC (Medium Access Control) standard for WLAN, and the standard consists of both an essential DCF (Distributed Coordination Function) and an optional PCF (Point Coordination Function) [6]. The DCF exploits collision-based CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocol for non-real-time messages, aiming at enhancing not only their average delivery time but also overall network throughput. However, packet collisions, intrinsic to CSMA and its variants, make it impossible for a node to predictably access the network. In the other hand, PCF mode makes one AP (Access Point) take the initiative of the traffic flow from all stations onto the network medium. The AP polls all stations to determine which station has the right to transmit during a given time slice, and it can prioritize traffic from specific stations, as well as guarantee the bounded latency for data transmission. In addition, the available wireless spectrum is divided into several channels. The IEEE 802.11b standard specifies 11 channels operating in the 2.4 GHz band with 80 MHz of reusable spectrum. Even though the number of simultaneous channels in a cell is limited to 3 due to the channel overlap problem, it is possible to create multiple channels from the wireless spectrum in a cell.

As the most prominent dynamic priority scheduling mechanism for the uniresource real-time system, EDF algorithm assigns priorities to individual jobs in the tasks according to their absolute deadlines. M. Caccamo et al. have proposed a MAC that supports deterministic real-time scheduling via the implementation of TDMA (Time Division Multiple Access) to apply the EDF scheme to the WLAN [7]. Referred as *implicit contention*, their scheme makes every station concurrently run the common real-time scheduling algorithm to determine which message can access the medium. Each message implicitly contends for the medium through the scheduling algorithm, for example, with priorities, rather than explicitly on the physical medium, thus it can save power and time.

Traditionally, there have been two approaches for scheduling periodic tasks in dual or multiprocessors, namely, *partitioning* and *global scheduling* [4]. The partitioning scheme assigns each stream to a single network, on which messages are scheduled independently. The main advantage of partitioning approaches is that they reduce a multiprocessor scheduling problem to a set of uniprocessor ones. However, finding an optimal assignment to networks is a bin-packing problem, which is NP-hard in the strong sense. For another example, Lee et al. have proposed a bandwidth allocation scheme for real-time traffic on dual channel WLANs, which decides the polling vector based on the weighted round robin policy for CFP (Contention Free Period) [8]. Though their scheme can efficiently overcome the deferred beacon problem that significantly deteriorates the schedulability of WLAN for real-time messages, it did not consider how to cope with the channel error at all.

In global scheduling, all eligible tasks are stored in a single priority-ordered queue while the global scheduler selects the highest priority task for execution from this queue. For example, CASP (Contiguous Algorithm for Single Priority) maintains an allocation vector V, where V_i represents the partial sum of slots

currently allocated to channel i [9]. For a given request, the scheduling algorithm allocates the request contiguously on the channel which has the least partial sum of allocation. In contrast, NCASP (Non-continuous Algorithm for Single Priority) defines an overflow amount Φ, and if an assignment makes V_i exceed Φ, it is split and then the overflown part is assigned to another resource. However, how to decide Φ brings another complex case-sensitive problem.

3   Basic Assumptions

3.1   Network and Error Models

To begin with, each cell is assumed to consist of an AP and multiple (mobile) SSs (sensor stations) as shown in Fig. 1. Each member of a cell has interfaces to two respective channels, and transmits or receives data on two channels in parallel. AP may be linked to a wired backbone or other wireless channel. In a cell, every station shares medium on the common frequency band and accesses according to the predefined MAC protocol. Whether each flow is ether an uplink (SS to AP) or downlink (AP to SS), AP coordinates the overall network operations. This paper exploits the contention-free polling-based access policy as in most of previous works [3,4,10], for the real-time guarantee cannot be provided without developing a deterministic access schedule, as well as the contention resolution via packet collisions consumes the precious communication energy. Moreover, the mobility of sensor station can be reinforced by an appropriate hand-off mechanism [11].
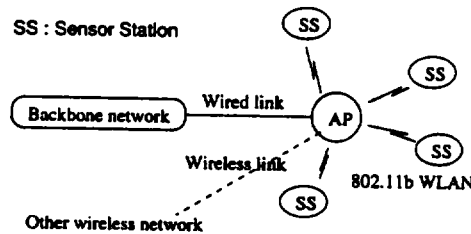

Fig. 1. Network model

Each station is associated with a channel link which has either of two states, namely, *error state* and *error-free state* at any time instant. A channel link is defined between each mobile and the AP, and it can be modeled as a Gilbert channel [12]. We can denote the transition probability from state *good* to state *bad* by p and the probability from state *bad* to state *good* by q, as shown in Fig. 2. The pair of p and q representing a range of channel link conditions, has been obtained by using the trace-based channel link estimation. The average error probability and the average length of a burst of errors are derived as $\frac{p}{p+q}$ and $\frac{1}{q}$, respectively. A packet is received correctly if the channel link remains in state *good* for the whole duration of packet transmission. Otherwise, it is received in error. Channel links between the AP and respective stations are independent
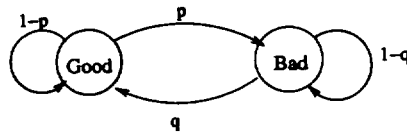
Fig. 2. Error model

of one another in their error characteristics. Correspondingly, while error-free transmission may be possible between a given host and the AP, transmission between another host and the AP may be corrupted by errors.

3.2   Message Model

A station, currently inactive, can be activated by an upper layer query command that wants to monitor or process the data flow from the sensor station [13]. The query may also specify sampling period as well as precision level of needed data to determine the message length. In case of a change in the active flow set, the network schedule should be regenerated [5]. The destination of a message can be either within a cell or outside a cell, and the outbound messages are first sent to the AP and then forwarded to the remote destination, while internal messages are also relayed by the AP. Hence, AP also acts as another source of message stream and is treated as such with an exception that it is just virtually polled. In addition, WLAN mandates the ACK from the receiver for every unicast transmission, but it consumes not a little network time and is meaningless, as the retransmission is only possible upon the polling from AP, not a sender station. Accordingly, even for the point-to-point streaming, multicast mode transmitting is assumed to deactivate the mandatory ACK.

   The traffic of sensory data is typically *isochronous* (or synchronous), consisting of message streams that are generated by their sources on a continuing basis and delivered to their respective destinations also on a continuing basis [5]. This paper follows the general real-time message model which has n streams, namely, S_1, S_2, ..., S_n, and each S_i generates a message not more than C_i at each beginning of its period P_i, while the first message of each stream arrives at time 0. Each packet must be delivered to its destination within D_i time unit from its generation or arrival at the source, otherwise, the packet is considered to be lost. D_i usually coincides with P_i to ensure that the transmission completes before the generation of the next message. However, sometimes, D_i is larger than P_i, and in this case, more errors can be recovered within message deadline. Finally, each stream belongs to a specific station, so if a slot is assigned to a stream, it means that AP should poll that station at the slot time.

4   Dual Channel Operation

4.1   Bandwidth Management

The network time is divided into a series of fixed-size slots, and each of them is exclusively assigned to a real-time station, completely removing a contention

procedure such as CSMA/CA, for the sake of both real-time guarantee and power saving, as mentioned earlier. The slot length, say L, is as large as the basic unit of wireless data transmission and every traffic is also segmented to fit the slot size. On WLAN, such network access can be implemented by making AP poll each station according to the predefined schedule during the CFP, while each station transmits for as long as L. To describe the goal of slot assignment, let $< f_i^1, f_i^2 >$ be the i-th slots of channel 1 and channel 2. If f_i^1 and f_i^2 are allocated to different streams, say A and B, respectively, switching their transmission channels does not violate their time constraints. We define a *switchable pair* if f_i^1 and f_i^2 are allocated to different streams, or any one of f_i^1 and f_i^2 is left unassigned. The purpose of bandwidth allocation, or slot assignment is to maximize the number of switchable pairs, as it can overcome channel errors as already explained in Section 1.

For AP to decide the polling order for a stream set, each stream S_i submits tuple of (P_i, C_i) information to AP. For simplicity, we assume that every P_i as well as C_i is an integer multiple of L. The bandwidth allocation consists of 3 steps, namely, stream partition, EDF based reservation, and slot rearrangement. At Step 1, to inherit the optimality of EDF in a single resource system, the allocation scheme first partitions the given stream set into two identical sets so that each of them has the same period but the transmission time of every stream is reduced by half. Namely,

$$\Theta : \{(P_i, C_i)\} \to \Theta_1 : \{(P_i, \frac{C_i}{2})\}, \Theta_2 : \{(P_i, \frac{C_i}{2})\} \qquad .$$

Then, the schedulability of message streams is tested by the following sufficient condition [5]:

$$\sum_{i=1}^n \frac{C_i}{P_i} + \Delta \le 1.0,$$

which assumes that there are n streams and that all the messages are sorted by increasing relative deadlines, while Δ denotes the overhead term originated from the network management such as polling/probing overhead, beacon packet broadcast, interframe space, and so on. As Δ is fixed for a stream set, we can calculate per-slot overhead, and merge it into C_i. Hence, Δ can be assumed to be 0, enabling us to concentrate on the problem of slot allocation.

Next at Step 2, the transmission is reserved for a fixed number of time slots by a station. The AP should create a polling table for the entire polling sequence. For S_i, every message arrival is estimated at 0, P_i, $2P_i$, and so on, while each invocation needs $\lceil \frac{C_i}{L} \rceil$ slots. Based on these estimations, the scheduling is virtually performed at each slot boundary to build a polling order table. The scheduler selects the message whose deadline is closest and allocates the next slot to it. If no slot request is pending at a slot boundary, the scheduler leaves the slot unassigned. The schedule for Θ_1 and Θ_2 is determined by EDF policy, both schedules being identical. The table-driven reservation scheme seems to demand a lot of memory space to store the polling order information. However, since the invocation behavior for a set of periodic tasks repeats itself once every T time units, where T, called the *planning cycle* of the task set, is the least common

does not receive the probing control packet correctly from the station, the channel is estimated to be bad. Even though the probing indicates the channel is good, the ensuing transmission can fail if a state transits to the bad state during the transmission. Let's assume that AP is to start slot i which is originally allocated to A on channel 1 as well as B on channel 2, namely, $< A, B >$. AP first probes the channel condition from itself to A and B on all two channels. Thus each slot should inevitably contain two probing latencies. Table 1 shows the probing result and corresponding actions. As shown in row 1, AP can reach A on channel 1 and also B on channel 2, AP polls each station as scheduled. In row 2, all connections from AP are good except the one to B through channel 2. If we switch $< A, B >$ to $< B, A >$, both streams can successfully send their messages. Otherwise, only A can send on channel 1, so in this case, we can save one transmission loss. Row 8 describes the situation that AP can reversely reach A only on channel 2 while B on channel 1. By switching polls between the two channels, AP can save the 2 transmissions that might fail on ordinary schedule.

Table 1. Channel status and transmission

No.	Ch1–A	Ch2–B	Ch1–B	Ch2–A	Ch1	Ch2	save
1	Good	Good	X	X	A	B	0
2	Good	Bad	Good	Good	B	A	1
3	Good	Bad	Good	Bad	A	–	0
4	Good	Bad	Bad	X	A	–	0
5	Bad	Good	Good	Good	B	A	1
6	Bad	Good	Good	Bad	–	B	0
7	Bad	Good	Bad	X	–	B	0
8	Bad	Bad	Good	Good	B	A	2
9	Bad	Bad	Good	Bad	B	–	1
10	Bad	Bad	Bad	Good	–	A	1
11	Bad	Bad	Bad	Bad	–	–	0

X : don't care

5 Performance Evaluation

This section measures the performance of the proposed scheme in terms of switchable pairs and corresponding success ratio according to the packet error rate via simulation using ns-2 event scheduler [14]. For the first experiment, we fixed the length of planning cycle to 24 as well as the number of streams to 3, and generated every possible stream sets whose utilization ranges from 0.2 to 2.0, aiming at measuring how many the rearrangement scheme can generate switchable pairs. Fig. 4 plots the measurement result sorted by the utilization of stream sets. Even when the utilization is 2.0, 17 out of 24 slots are rearranged to switchable pairs on average. As the utilization gets lower, the number of switchable pairs increases, since the number of unassigned slots also grows. Global EDF generates the switchable pair only by unassigned slots, so the number of

switchable pairs proportionally decreases as the utilization increases. The gap
between the two schemes becomes large on the higher utilization.

Fig. 5 shows the success ratio according to the packet error rate along with
utilization to demonstrate the effect of slot rearrangement. The success ratio
means the ratio of timely delivered real-time packets to all generated packets.
The packet error rate is the function of packet length and bit error rate, and it
ranges from 0.0 to 0.4, considering the error-prone wireless channel characteris-
tics. This experiment compared the success ratio of the proposed scheme with
those of global EDF and NCASP. The value of Φ is ideally chosen to 12. As
shown in Fig. 5, first of all, when the packet error rate is 0.0, every transmission
succeeds both in our scheme and in global EDF regardless of utilization. How-
ever, NCASP misses some deadlines because it cannot optimally schedule the
real-time packets when utilization exceeds 1.3. The proposed scheme outperforms
the global EDF by around 18 % at maximum due to the difference in the number
of switchable pairs when the packet error rate is over 0.4. The performance gap
gets larger according to the increase of packet error rate. On lower utilization,
NCASP shows almost same performance as the proposed scheme since it assigns
a series of slots to stream, maximizing the number of switchable pairs. However,
the limitation of real-time scheduling capability causes performance degradation
on high utilization.

Actually, we have also measured the effect of deadline length to the success
ratio. However, even in the case the deadline is longer than the period, the
rearrangement within a planning cycle did not result in a significant performance
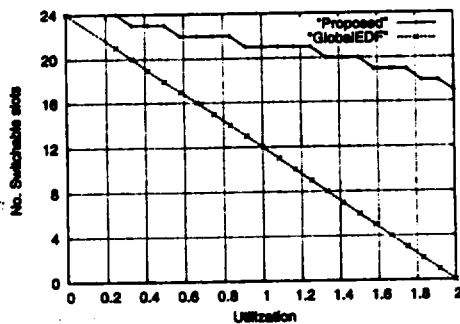improvement. The rearrangement across the planning cylce will bring another
difficult problem.

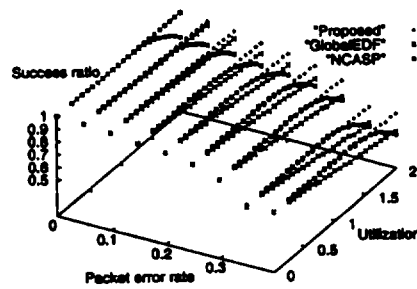

Fig. 4. Number of switchable slots

Fig. 5. Success ratio

6   Conclusion

This paper has proposed and analyzed the performance of real-time message
scheduling scheme for dual channel wireless sensor networks. The proposed
scheme solves NP-hard complexity of multiple resource scheduling by evenly
partitioning the stream set into two identical sets to apply EDF policy that
is optimal under uniprocessor environment for dynamic preemptive real-time

scheduling. In addition, slot rearrangement maximizes the number of switchable pairs, so the AP can dynamically select the error-free channel for two streams. Simulation results show that the proposed scheme can generate 70 % of switchable pairs even when the utilization reaches the saturation point, improving the ratio of timely delivery by up to 18 % when the packet error rate exceeds 0.4.

As a future work, we will extend the allocation scheme to combine the error control functions such as the retransmission of damaged packets as well as reclaim the unused slot to reassign to other reachable stations. For example, the polling table in Table 1 has some entries marked as '-', which means AP cannot poll A or B. In this case, it seems better to poll another station. and the way to select this station is to be investigated.

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