An energy-efficient real-time scheduling scheme on dual-channel networks

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Abstract

The recent evolution of wireless sensor networks have yielded a demand to improve energy-efficient scheduling algorithms and energy-efficient medium access protocols. This paper proposes an energy-efficient real-time scheduling scheme that reduces power consumption and network errors on dual channel networks. The proposed scheme is based on a dynamic modulation scaling scheme which can scale the number of bits per symbol and a switching scheme which can swap the polling schedule between channels. Built on top of EDF scheduling policy, the proposed scheme enhances the power performance without violating the constraints of real-time streams. The simulation results show that the proposed scheme enhances fault-tolerance and reduces power consumption.

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1. Introduction

Power consumption is a critical design aspect in many applications such as mobile computing, wireless communications, information appliances, wearable computing as well as various industrial and military applications. As systems become more complex and incorporate more functionalities, they become more power-hungry [26]. Thus, reducing energy consumption and extending battery lifespan have become a critical aspect of designing battery-powered systems.

The IEEE 802.11 MAC (Medium Access Control), a contention-based medium access protocol, has been successfully deployed in WLAN (Wireless Local Area Network) and has also been implemented in many wireless testbeds and simulation packages for wireless multi-hop networks [12]. As both speed and capacity of wireless media increase, so does the demand for supporting time-sensitive high-bandwidth applications using a limited...
battery supply. One way to reduce the energy consumption is to use the power management included in the 802.11 standard [12]. According to the standard, an AP (Access Point) transmits a beacon every 100 ms, followed by a TIM (Traffic Indication Map). Each MS (Mobile Station) checks the TIM for its turn to send or receive data. When not communicating, the WLAN goes into the doze mode until the next beacon. Unfortunately, the protocol power management is not very effective because of multiple media access contention and delay imposed by sleep periods. These two issues should be resolved by carefully scheduling communication between units.

One of the promising techniques for scheduling of communication is DMS (Dynamic Modulation Scaling). The DMS technique uses the modulation level as an energy-speed control knob that can be fine-tuned to enable dynamic power-performance trade-offs in the communication system [24]. DMS reduces the radio’s RF power, therefore, it is applicable to medium and long range systems with transmit distances of at least 10 m such as WLANs. According to IEEE 802.11b standard, up to three channels can coexist under BSS (Basic Service Set). And each mobile station in WLAN can operate using dual channels [2,5]. In this system, each station may be equipped with transceiver that can tune to one of available channels, giving the flexibility to transmit and receive on both channels.

However, real-time scheduling for dual or multiple resource system is known to be an NP-hard problem [4]. On the other hand, Liu and Layland showed that the RM (Rate-Monotonic) algorithm is optimal for fixed priority-driven scheduling schemes. Also they showed that the deadline-driven algorithm, or termed elsewhere the EDF (Earliest-Deadline-First) algorithm, is optimal for dynamic priority-driven scheduling schemes [14]. Applying RM or EDF method to multiple resource system is not optimal in scheduling preemptable jobs due to its work conserving nature [15]. Wireless links generally possess characteristics that are quite different from those of wired links. They are subject to time- and location-dependent signal attenuation, fading, interference, and noise, which result in burst errors and time-varying channel capacities [1,29]. To apply such algorithms to wireless networks, fault-tolerant and energy-efficient scheduling scheme need to be provided.

To address these problems, this paper proposes an energy-efficient real-time scheduling scheme on dual-channel networks. In particular, this paper makes the following research contributions: First, our dynamic modulation scaling scheme can utilize bad or unused slots adaptively based on the channel status. Second, the proposed switching scheme can cope with network errors by swapping pre-scheduled messages of the dual channels when a specific station falls in a bad state. The rest of this paper is organized as follows. After introducing related works in Section 2, we present backgrounds of our work in Section 3. The proposed energy-efficient real-time scheduling scheme is described in detail in Section 4. The results of performance evaluation are presented in Section 5. Finally, we summarize and conclude in Section 6.

2. Related works

Reducing power and energy dissipation has long been addressed by several research groups [3,20,24]. PAMAS (Power Aware Multi-Access Protocol with Signalling for Ad-Hoc Networks) is one of the earliest contention-based protocols to address power efficiency in channel access which saves energy by attempting to avoid over-hearing among neighboring nodes. The Sensor MAC protocol, or S-MAC, is also in the contention-based protocol category but achieves energy efficiency by making use of low-power radio mode. Contention-based T-MAC introduces an adaptive duty cycle by dynamically ending the active part of it [6]. This reduces the amount of energy wasted on idle listening.

On the other hand, TRAMA (TRAffic-Adaptive Medium Access) protocol was introduced for energy-efficient collision-free channel access in wireless sensor networks [21]. It reduces energy consumption by ensuring that unicast, multicast, and broadcast transmissions have no collisions and by allowing nodes to switch to a low-power idle state whenever they do not transmit or receive. TRAMA assumes that time is slotted and uses a distributed election scheme based on traffic information at each node to determine which node can transmit at a particular time slot.

In energy-efficient multi-rate MAC scheme, the MAC calculates the proper transmit power and supplies it to the radio module, according to the desirable BER (Bit Error Rate) and the data rate required by the upper layer [28]. The MAC layer sets the transmit power supply value of the radio module. The transmit power supply value depends on the modulation scaling scheme and the required data rate. The calculation can be done quickly using a table lookup method.
Also, dual or multi channel schemes have been proposed to enhance energy efficiency and capacity. 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. In global scheduling, all eligible tasks are stored in a single priority-ordered queue, and the global scheduler selects the highest priority task for execution from this queue.

MUP (Multi-Ratio Unification Protocol) was proposed as a multiple NIC (Network Interface Card) architecture that increases capacity in a mesh network by optimizing the use of the available spectrum with standard-compliant IEEE 802.11 hardware [2]. However, power was not addressed in the protocol. MUP conceals multiple NICs from layers above it by presenting a single virtual interface. MUP, then, periodically monitors the channel quality on each interface, to each of its neighbors. Then, when it comes time to send a packet to a neighbor, it selects the right interface to forward the packet on. As for striping method over multiple IEEE 802.11 channels [27], when the device driver of the trunk interface receives packets, it will dispatch them to different interfaces using a round-robin scheme. When the IEEE 802.11 interface receives such a packet from the trunk driver, the interface will transmit it over its assigned frequency channel.

Multi-channel protocols require frequent interface switching. For interface switching, we need to design and implement a channel abstraction module that provides the requisite kernel support, and implementing a hybrid multi-channel protocol using the channel abstraction module [5]. A feature of the channel abstraction module is to export a single virtual interface to abstract multiple interfaces. This implementation of a channel abstraction module in the kernel simplifies the implementation of multi-channel protocols that require interface switching.

Energy harvesting has recently emerged as a feasible option to increase the operating time of sensor networks [17]. However, if each node of the network is powered by a limited energy source, power management solutions have to be reconsidered. This holds in particular if real-time responsiveness of a given application has to be guaranteed. Task scheduling at each node should consider the properties of the energy source as well as deadline of each task.

Data caching is used to improve the response time and the power consumption of a mobile client in a mobile computing environment. To replace an invalid data in a cache, a mobile client needs to access and download updated data item through wireless channel. Refreshing a cached invalid data item incurs large tuning time overhead [13].

Also, there is a problem of constructing an energy-efficient data aggregation for data gathering in wireless sensor networks [7]. We should consider a real-time scenario where the data aggregation must be performed within a specified latency constraint. The objective is to minimize the overall energy cost of the sensor nodes subject to the latency constraint. Energy minimization can be achieved by controlling the activities of wireless communications including transmitting, receiving, and scanning activities. Those wireless communication activities are known to consume most of the energy of wireless sensor nodes.

Some researchers have begun studying the problem of reducing power consumption on wireless interface [22,23]. One approach consists of reducing energy consumption for transmitting/receiving each bit and the other consists of reducing the amount of information exchanged over networks. Our work is unique in that it uses dynamic modulation scaling scheme to reduce energy consumption adaptively using dual channels. Besides, scheduling order is switchable between two slots or channels to cope with network errors based on the channel status.

3. Backgrounds

WLAN divides its time axis into CFP (Contention Free Period) and CP (Contention Period), which are mapped into PCF (Point Coordination Function) and DCF (Distributed Coordination Function), respectively. To provide the deterministic access to each station during CFP, AP polls each station according to a predefined order, and only the polled station can transmit its frame. In the DCF interval, every station including AP contends the medium via the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocol. The AP periodically initiates CFP by broadcasting a beacon frame that has the precedence in transmission via SIFS (Shorter InterFrame Space). Since random access is not appropriate for real-time periodic traffic, a scheduling technique called PCF can be implemented on top of DCF to support real-time traffic, based on polling that is controlled by a centralized point coordinator [12].
This paper exploits the contention-free TDMA style access policy as in [1] for the real-time guarantee. Slotted systems require a mechanism for maintaining slot synchronization. In the infrastructure mode, there is a central base station generating a periodic signal in order for mobile stations associated with this base station to synchronize to it. On the other hand, there is no centralized coordinator like the base station in mobile ad-hoc networks. However, the GPS (Global Positioning System) can be used as a global time signal source, making it possible to implement a slotted scheme for mobile ad-hoc networks. The network time is divided into a series of equally sized slots to eliminate the unpredictability stemmed from access contention. Then, the allocation scheme assigns each slot to real-time streams to meet their time constraints. The slot is the basic unit of wireless data transmission. Therefore, a preemption occurs only at the slot boundary.

The traffic of sensor data is typically synchronous, consisting of message streams that are generated by their sources and delivered to their respective destinations, on a continuing basis [15]. This paper follows the general real-time message model which has \(n\) streams, and each stream, \(R_i\), generates a message whose duration is less than or equal to worst-case communication time, \(C_i\), at the beginning of its period, \(P_i\). The communication time of each task is usually less than its worst case, and the actual utilization at run time is usually lower than the worst-case utilization. Each packet must be delivered to its destination within \(D_i\) time units from the start of the period. Otherwise, the packet is considered to be lost. Generally, \(D_i\) coincides with \(P_i\) to make the transmission complete before the generation of the next message. A schedule of a task set is called feasible if the deadline of each task is satisfied at all times.

In IEEE 802.11 standard, RTS/CTS is used in DCF mode to prevent collisions and the maximum MAC retransmission number is set to 7 [8,12]. During PCF operation, the AP is able to acquire the channel. Therefore, there is no need to use RTS/CTS to prevent collisions. However, this RTS/CTS mechanism can be used to verify the state of the channel [9,11]. CSDPS (Channel-State Dependent Packet Scheduling) models the actual links by expressing link state through parameter. However, this scheme causes a discrepancy between the actual channel state and the estimation because it does not monitor each link continuously.

In our channel status estimation scheme, the probing process is performed once or twice per time slot. Channel estimator sends a short probing RTS packet to the designated receivers on dual channels before the start of packet transmission. The receiving device responds by sending a CTS packet as an acknowledgement to the RTS. If the CTS packet is received intact, the state of the channel is assumed to be good. If the CTS is not received after a given timeout, the channel state is considered to be bad. Also, the channel estimator tries to send the RTS packet again after switching the channels. Therefore the maximum number of probe is 2.

However, channel measurement and estimation also incur unnegligible overhead. The probing cost varies between channels, depending on both the probing time and the interference caused to other users. Let us denote by \(\Delta\) the overhead originated from the network management such as polling/probing overhead, beacon packet broadcast, interframe space, and so on. As \(\Delta\) is fixed for a stream set, we can calculate per-slot overhead and merge it into \(C_i\).

4. Proposed scheduling scheme

Real-time schedules are designed for time-critical multimedia applications and tasks sets [29]. They can perform well in an ideal network with predictable workload. However, in a realistic network with shared bandwidth and unpredictable workloads, their performance may be poor. As an example, EDF algorithm is one of the most widely used online scheduling policies and it is proven to be optimal in deterministic environment [10]. To cope with network errors at run-time, the polling order on one channel needs to be re-ordered so that the probability of successful transmission of the streams can be maximized when a probed channel status is bad at run-time. The overhead of calculating the candidate set of the re-ordering of polling sequence is too high to be used at run-time, which is the motivation of our off-line and on-line scheduling technique.

To provide run-time adaptability and energy conscious scheduling in a realistic network and unpredictable workloads, we propose a scheduling technique which is divided into off-line and on-line parts. At off-line, a static scheduling is set up using a normal real-time scheduling technique. We can use any real-time scheduling techniques to setup the initial off-line schedule at this stage. In this paper, we use EDF as an example. Since we assume a fixed set of network streams, a schedule within LCM (Least Common Multiple) of the periods of the streams is fixed. And then, the static modulation scaling scheme is applied to the off-line schedule to reduce the
number of BPS (Bits Per Symbol) using DMS. Then, the stream set is distributed into two channels according to the real-time scheduler used to setup the initial off-line schedule. Here, we treat the two channels as if they were a single channel with double capacity. Then, we apply DMS technique to both channels such that energy usage is reduced but latency is increased. Now, we rearrange the scheduling of the streams on one channel such that the probability of successful transmission of a stream increases within their deadlines. To do that, we make a schedule of the streams within the LCM of the periods of the streams. When indeterministic situations such as temporary channel failures happen, our technique rearranges the schedule on-line, which is as simple as a table lookup. Also at run-time, the dynamic modulation scaling scheme is applied to reduce both the number of BPS adaptively according to the channel status and the number of empty slots. The proposed scheduling operation based on these concepts is shown in Figs. 1, 3 and 4.

4.1. Off-line scheduling scheme

The description of proposed off-line scheduling operation on AP is as follows: First, $b_{\text{max}}$ is denoted by maximum modulation scaling factors as shown in line 1 of Fig. 1. Likewise, $b_{\text{min}}$ is denoted as minimum modulation scaling factors. These factors are only bounded by implementation constraints. In our work, we choose $b_{\text{max}}$ and $b_{\text{min}}$ equal to 8 and 2, respectively, for QAM (Quadrature Amplitude Modulation), as it is both efficient and easy to implement [19,24]. These maximum and minimum modulation scaling factors are the possible values which can be encoded into 4 bits for 4-QAM ($2^2$-QAM) [25]. The maximum modulation factor is only bounded by implementation choices and maximum transmit power. For QAM, $b_{\text{min}}$ is equal to 2 (2 bits/symbol) and $b_{\text{max}}$ is frequently set to 8 as in [19,25].

Second, as shown in line 2 of Fig. 1, the worst-case utilization is calculated by $U = \sum_{i=1}^{n} \frac{C_i}{P_i}$. If the number of BPS can be lowered, the transmission time can be also stretched by $X_{st} = \left\lceil \frac{P}{b_{\text{min}}} \right\rceil$, and then $b^*$ can be reduced to $\text{max}(\lceil \frac{P_{\text{max}}}{X_{st}} \rceil, 2)$. Third, we partition the stream set into two channels as shown in line 3. So, the modified modulation scaling factor, $b^*$, can be set to $\text{max}(\lceil \frac{P}{X_{st}} \rceil, 2)$. By using the lowest value of $b^*$, the power consumption is reduced.

An example set and the algorithm are shown in Fig. 2. There are three streams, $A(6,6,1)$, $B(8,8,1)$, and $C(12,12,2)$. Each stream is represented by a tuple $(P_i, D_i, C_i)$, where $P_i$ is its period, $D_i$ is its deadline, and $C_i$ is its WCET (Worst-Case Execution Time). Their utilization ratio is 0.458 and hyper-period is 24. A typical EDF schedule assumes that tasks run at their worst-case communication times, as shown in Fig. 2a. Thus, the static number of BPS, $b^*$, can be reduced to $\text{max}(\lceil \frac{P}{X_{st}} \rceil, 2) = 4$ and the transmission time is increased by $X_{st} = \left\lceil \frac{4}{0.458} \right\rceil = 2$, as shown in Fig. 2b. Then, $b^*$ of each channel is set to $\text{max}(\lceil \frac{P}{X_{st}} \rceil, 2) = 2$, as shown in Fig. 2c.

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, for the sake of both real-time guarantee and power saving. On WLAN, network access can be implemented by making AP poll each station according to the predefined schedule during the CFP. To describe the goal of slot assignment, let $(S^1_i, S^2_i)$ be the $i$th slot assignments of channel1 and channel2. If $S^1_i$ and $S^2_i$ are allocated to different streams, say $A$ and $B$, respectively, switching their transmission channels does not violate their time constraints. We define a pair $(S^1_i, S^2_i)$ as a switchable pair if $S^1_i$ and $S^2_i$ are allocated to different streams, or any one of $S^1_i$ and $S^2_i$ is left unassigned. The purpose of slot assignment is to maximize the number of switchable pairs, as it can overcome slot failure due to transient channel errors.

1. $b^* = b_{\text{max}}$ /* $b^*$ is maximum of BPS
2. $b^* = \text{max}(\lceil \frac{b_{\text{max}}}{\sum_{i=1}^{n} \frac{C_i}{P_i}} \rceil, 2)$
   //Reduce the number of bits per symbol equally for all stream set
3. Partition the stream set into two channels, Ch1 and Ch2
   //Reduce the number of bits per symbol if possible

Fig. 1. Off-line scheduling operation.
The allocation scheme first partitions the given stream set into two identical sets so that each of them has the same period and communication time but the number of BPS is reduced. And then, the allocation on channel 2 is rearranged to maximize the number of switchable pairs.

At the arrival time of message at slot time \( t \), and the laxity time before its deadline is denoted as \( L_t \), as shown in Fig. 2c. From the first slot, \( S^1_t \) and \( S^2_t \) are investigated whether or not they are equal, i.e., they are allocated to the same stream. If they are the same, the rearrangement procedure attempts to change \( S^2_t \) using the procedure described in Fig. 3. That is, the stream whose slot time is less than or equal to deadline of stream \( S^2_t \) and which has already arrived, is swapped with

![Diagram](image-url)

**Fig. 2.** Off-line schedule result for the example set. (a) Typical EDF schedule based on \( b_{\text{max}} \), (b) schedule after scaling BPS, (c) schedule after partitioning schedule (b) into two channels, (d) schedule after maximizing # of switchable pairs between two channels.

The allocation scheme first partitions the given stream set into two identical sets so that each of them has the same period and communication time but the number of BPS is reduced. And then, the allocation on channel 2 is rearranged to maximize the number of switchable pairs. \( A_t \) is the arrival time of message at slot time \( t \), and the laxity time before its deadline is denoted as \( L_t \), as shown in Fig. 2c. From the first slot, \( S^1_t \) and \( S^2_t \) are investigated whether or not they are equal, i.e., they are allocated to the same stream. If they are the same, the rearrangement procedure attempts to change \( S^2_t \) using the procedure described in Fig. 3. That is, the stream whose slot time is less than or equal to deadline of stream \( S^2_t \) and which has already arrived, is swapped with

```
For slot i from t + L_t to t + 1 // current slot time t
If (S^2_i == S^2_t) continue; // same station
If (A_i > t) continue; // cannot be deferred
Else exchange S^2_t and S^2_i and break;
```

**Fig. 3.** Rearrangement procedure on channel2.
The goal of this process is to maximize the number of switchable pairs. This is good because switchable pairs may have another chance by switching channels when channel status is bad. The switchable pairs are shown in the arrow indication of Fig. 2d.

4.2. On-line scheduling scheme

At run-time, if AP cannot poll the stream because the channel between itself and the station has fallen to a bad state, the existing poll is invalidated. This slot is idle and simply wasted when it is not used by other stations. Also, some task instances may complete earlier than their worst-case communication times. A station may have no pending message when it receives a poll, in which case it responds with a null frame containing no payload. These idle slots obtained dynamically can be used to enhance fault-tolerance and to improve throughputs.

The dynamic modulation scheme based on fixed-size slot can utilize the unassigned or empty slots as reserved space for the messages assigned at bad slots. Because the minimum granularity of a transmission time is a slot, flooring and ceiling operations are used to properly calculate the number of slots to send a message. Our on-line scheme increases the probability of servicing the message assigned to a bad slot. As a result, we can improve throughput of real-time streams by giving up the reduction of energy consumption slightly.

In our proposed scheme, AP checks the network errors with the probing packet and then reclaims the slots to retransmit the messages of bad slots or swaps slots of the two channels at run-time. If the slot becomes unassigned, we can retransmit the message of bad slot or reduce the number of BPS adaptively between slots or channels as shown in lines 2–8 of Fig. 4. With the unused slots, we can extend the transmission time. We denote by d the number of extendable slots. Extendable slots may come from the next time slot of the current channel or from the time slot of the other channel. When there are extendable slots available, the number of BPS can be reduced to save energy.

To reduce the number of BPS, we calculated two adjusted modulation factors as $b_H = \lceil \frac{b}{d} \rceil$ and $b_L = \lfloor \frac{b}{d} \rfloor$. For example, if there is no message to transmit in current slot, and if the message in the next slot can be advanced or the message of other channel can be divided into two channels, then $d$ is set to 2. We can select $b_H$ bits per symbol for $k = \frac{[b - b_L d]}{b_H - b_L}$ slots and $b_L$ bits per symbol for $(d - k)$ slots. If the minimum value, $b_L$, is

```
1 For all slots, t
2   If $S_1 = \text{NULL}$ or $S_2 = \text{NULL}$ //if the slot is unassigned
3       If $Q$ is not empty //Q: retransmission queue
4           Transmit an $S \in Q$
5   Else
6       Probe the channel status of $S_{t+1}$ or $S_{t+1}$
7       Probe the channel status of $S_i$ or $S_i$
8       Reduce the number of bits adaptively between slots or channels;
9           $b^* \leftarrow \lceil \frac{b}{2} \rceil$ for $k = (b^* - \lfloor \frac{b}{2} \rfloor) \times d$ slots,
10          $b^* \leftarrow \lfloor \frac{b}{2} \rfloor$ for $(d - k)$ slots
11   Else
12       Probe the channel status between AP and the stations
13       Probe the channel status after switching channels
14       Select the optimal slot assignments of two channels
15   Reduce the number of bits adaptively between slots or channels
```

Fig. 4. Run-time scheduling operation.
less than $b_{\text{min}}$, the number of BPS is set to $b_{\text{min}}$. For example, when the current modulation scaling factor, $b^*$ is 8 bits/symbol and the number of extendable slots is 3, $b^*$ for the first and second slots are 3 bits/symbol, and that for the third slot is 2 bits/symbol ($3 + 3 + 2 = 8$). On the other hand, if the slot is assigned, we should probe the channel status of the pre-assigned and switched cases between AP and the stations as shown in lines 9–13 in Fig. 4.

An example scenario is shown in Fig. 5. The table of Fig. 5 shows the slot time (column 1), original assignments of $Ch_1$ and $Ch_2$ (columns 2–3), channel status of original assignments and switched cases (columns 4–7), optimal assignments (columns 8–9), and the number of saved transmissions through channel switching (column 10). According to the channel status between AP and the assignments as shown in the fourth column through seventh column, we can select the optimal slot assignments of two channels.

Our technique saves power by switching polls when a channel status turns out bad. As shown in Fig. 5a, if we switch polls between two channels, then AP saves one transmission that might fail in ordinary schedule. In Fig. 5b, if only $C$ can transmit using $Ch_1$ and $Ch_2$, the power consumption can be reduced by dividing the stream into two channels and transmitting simultaneously. If the current number of BPS is 4, it can be reduced to 2. Fig. 5c shows the case that unused null slot is utilized by retransmitting the message $A$ of bad slot 9 in Fig. 5b. In Fig. 5d, if only $Ch_2$ is good, the slot of $Ch_1$ would be wasted without further rearrangement. However, if the message on the next slot of $Ch_2$ is same as current message of $Ch_2$ and it is ready to transmit, then our scheme increases the number of BPS twice to utilize the next slot of $Ch_2$ for the assigned message at $Ch_1$. Therefore the messages ($B$) of two slots are transmitted within one slot, and remaining slot can be used by the message ($C$) that might fail on $Ch_1$. As a result, if a transmission which would fail has another chance to succeed, then the success ratio of real-time traffics is enhanced.

5. Performance evaluation

This section presents the performance of the proposed scheduling scheme in terms of the energy consumption and the success ratio as a function of the error rate estimated using an SMPL event scheduler. SMPL (Simple Message Passing Library) is a software composed of a set of C functions for building event-driven, discrete-event simulation models [16]. The success ratio means the ratio of the number of successfully transmitted packets within their deadlines to the total number of generated packets. It is assumed that the communication time...
of each instance of a task is drawn from a random gaussian distribution. For the target stream sets, we fixed the length of a planning cycle to 24, and the number of streams to 3, and generated every possible 7256 stream sets whose utilization ranges from 13% to 100%.

The average time to transmit one bit is given by $T_{\text{bit}} = \frac{1}{R_S}$, where $R_S$ is the symbol rate in the number of symbols sent over the channel per second. The energy consumed for transmitting one bit is given by $E_{\text{bit}} = \frac{C_S}{R_S} + C_E \times \frac{1}{P}$ [19,24]. Parameter $C_S$ is an implementation constant, which depends on the bit error rate and the noise power spectral density. $C_E$ is a constant that results from losses from electronic devices and does not depend on $b^*$ or the transmission power. Therefore we assume them to be constant ($C_S = 10^{-7}$ J, $C_E = 1.8 \times 10^{-8}$ J, $R_S = 1$ MHz). When data rate is changed from 8 Mbps to 4 Mbps, the corresponding transmit power can be reduced by up to $12\%$ [28]. If dynamic modulation scaling is used along with this static modulation scaling, the energy consumption can be reduced further.

Fig. 6 plots the relative energy consumption ratio as a function of the packet error rate, when the error control scheme is applied. $DMS_{\text{Dual}}$ and $DMS_{\text{Single}}$ curves represent the results of single and dual network schemes, respectively, based on dynamic modulation scaling scheme. This ratio is based on $NoDMS_{\text{Single}}$ scheme that does not consider DMS and uses single channel. Simulation result shows that $DMS_{\text{Dual}}$ provides the best performance because of the dual-channel network scheme and the adaptive modulation scaling scheme. Energy consumption of $DMS$ schemes is usually under $8\%$ compared with $NoDMS$ cases, and $DMS_{\text{Dual}}$ scheme can reduce the consumption up to $29.6\%$ on average, compared with $DMS_{\text{Single}}$ case.

Fig. 7 plots the success ratio according to the error rate. $NoDMS_{\text{Single_EC}}$, $DMS_{\text{Single_EC}}$, and $DMS_{\text{Dual_EC}}$ mean the same EC(Error Control) cases with Fig. 6, while $NoDMS_{\text{Single_NoEC}}$ case does
not consider error control scheme. We measured how many errors can be recovered by swapping the polling schedule between channels or slots, for the error rate of 0.0 through 0.5. As shown in Fig. 7, DMS_Dual_EC scheme shows enhancement up to 12.2% and 6.5% compared with NoDMS_Single_EC and DMS_Single_EC, respectively, and thus, it considerably relieves the problem of error-prone WLAN and poor utilization of PCF operation. NoDMS_Dual_EC scheme provides the better performance than DMS_Single_EC scheme when the error rate is under 0.25, but the performance degrades as the error rate goes high. NoDMS_Dual scheme divides stream into two channels and reduces the number of BPS, but it is different from the static modulation scheme in that NoDMS_Dual scheme does not consider empty slots. Also, NoEC schemes (DMS_Dual_NoEC, DMS_Single_NoEC, NoDMS_Dual_NoEC, NoDMS_Single_NoEC) have similar success ratio.

6. Conclusion

Wireless sensor networks – consisting of numerous tiny sensors that are pervasively embedded in their environment – have been the subject of intensive research. As for many other battery-operated embedded systems, a sensor’s operating time is a crucial design parameter. Research continues to develop higher energy-density batteries and supercapacity, but efficient usage of the limited energy always leads to longer system lifespan.

In this paper, we have proposed an energy-efficient real-time scheduling scheme that reduces power consumption and network errors on dual-channel networks. The proposed scheme is based on the dynamic modulation scaling scheme and the switching scheme between channels. It makes it possible to utilize the bad or unused slots adaptively and cope with network errors based on the channel status and the pre-assigned schedule. The simulation results show that the proposed scheme enhances success ratio up to 12.2% and reduces power consumption up to 29.6% on average.

As a future work, we plan to apply the power management scheme to the bandwidth allocation scheme based on fixed/variable size slot transmission combined with a fault tolerant mechanism. Using the Linux based PASTA (Power Aware Sensing Tracking and Analysis) nodes that were developed by University of Southern California – Information Sciences Institute [18], transmission evaluation of the real-time traffic is currently in progress. We also expect that these schemes can enhance the real-time throughput and success ratio based on this embedded system.

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