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Adaptive Distributed Fair Scheduling for Multiple Channels in Wireless Sensor Networks

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A novel adaptive and distributed fair scheduling (ADFS) scheme for wireless sensor networks (WSN) in the presence of multiple channels (MC-ADFS) is developed. The proposed MC-ADFS increases available network capacity and focuses on quality-of-service (QoS) issues. When nodes access a shared channel, the proposed MC-ADFS allocates the channel bandwidth proportionally to the packet's weight which indicates the priority of the packet's flow. The packets are dynamically assigned to channels based on the packet weight and current channel utilization. The dynamic assignment of channels is facilitated by use of receiver-based allocation and alternative routes. Moreover, MC-ADFS allows the dynamic allocation of network resources with little added overhead. Packet weights are initially assigned using user specified QoS criteria, and subsequently updated as a function of delay and queued packets. The back-off interval is also altered using the weight adaptation. The weight update and back-off interval selection ensure global fairness is attained even with variable service rates.

Keywords Fairness; Adaptive-Fair-Scheduling; Weight-Adaptation; Quality-of-Service; Embedded System

1. Introduction

Bandwidth is constrained in wireless sensor networks (WSN), thus effective and fair management of radio resources is crucial to guaranteeing the quality of service (QoS). The single-channel adaptive dynamic fair scheduling (ADFS) protocol was initially developed for ad-hoc networks [1]. In contrast, the primary focus of this work is to address challenges in packet scheduling, or flows, when nodes reside in a multi-channel network since multi-channel communication multiplies the bandwidth. This article focuses on the development of the multi-channel ADFS or MC-ADFS, which differs from other schemes [1] in that the scheduling protocol takes into account the state of the wireless channel while being fair and utilizes multiple channels. Due to multiple channels, a novel analytical development is necessary which is considerably different than a single channel scheduling protocol, for instance ADFS [1]. For the case of WSN, unlike ad-hoc networks, scheduling

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is required for both intra-cluster and inter-cluster levels resembling a multi-hop ad-hoc network. While multi-channel scheduling protocols exist in the literature [2, 3], many are intended for 802.11 networks or general ad-hoc networking. The proposed MC-ADFS protocol is scalable since it is capable of serving both 802.11, 802.15.4, and any other CSMA/CA enabled network while being in channel state and QoS aware. Other protocols have concentrated on energy aware [4–6], channel state aware [7], and QoS aware [8] scheduling methods. Next, the MC-ADFS is introduced.

2. Multi-Channel Adaptive and Distributed Fair Scheduling (MC-ADFS) Protocol

The main goal of the proposed MC-ADFS protocol is to achieve fair channel access over multiple channels. In other words, the protocol must accommodate dynamic channel states that affect available bandwidth. Channel dynamics include channel uncertainties such as shadowing and multi-path fading; weight adaptation is used to compensate for these changing channel states. ADFS employs an adaptive scheduling algorithm to provide fairness among local queues and a MAC protocol to provide the fair channel access via dynamic selection of the back-off interval. ADFS performance was previously evaluated in the NS-2 simulator [1]. To accommodate inclusion of multiple channels, the aggregate service is calculated over all channels and for a set of flows passing through a node. The aggregate service, W_f, for multiple channels is defined as

$$W_f = \sum_{c=0}^{C_{\max}} w_{f,c} \tag{1}$$

where $w_{f,c}$ is the aggregate service of flow f on channel c with $C_{\max}$ denoting the maximum number of channels. Through summation of the aggregate service over all channels, the evaluation of flow per-channel is performed. For this development, W_f is assumed to be an aggregate service for a flow over a multi-channel sensor network at a given ADFS node. The MC-ADFS differs significantly from ADFS [1], due to the inclusion of multiple channels and its impact on the analytical proofs as will be highlighted in the next few sections. In this section the service models, protocol implementation, and channel switching methodology for MC-ADFS is introduced.

2.1. Service Models

Note that the service rate of flow-controlled, broadcast medium, and wireless links may fluctuate over time. Two service models, fluctuation constrained (FC) and the exponential bounded fluctuation (EBF) service model, are suitable for modeling many variable rate servers and have been introduced for computer networks. Similarly, variable rate service models for WSN can be defined to incorporate the channel and contention based protocols. An FC service model for WSN using channel c over a time interval $[t_1, t_2]$ has two parameters, average rate $\lambda(t_1, t_2, c)$ in bps and variations parameter, $\psi(\lambda, c)$, given by $\psi(\lambda, c) = \chi(\lambda, c) + \delta(\lambda, c) + \varpi(\lambda, c)$, where $\chi(\lambda, c)$ is the reduction channel capacity due to uncertainties, $\varpi(\lambda, c)$ is the variation due to the back-off interval, and $\delta(\lambda, c)$ is the burstiness in bits on channel c.

2.2. Protocol Implementation

To achieve fair scheduling across multiple channels, the MC-ADFS protocol implements the start-time fair queuing (SFQ) [9, 10] scheme, defined as follows:

i. On arrival, the j^{th} packet of flow f, defined as p_f^j and having length l_{fj} and weight ϕ_{fj}, is stamped with start tag $S(p_f^j)$, defined as $S(p_f^j) = \max\{v(A(p_f^j)), F(p_f^{j-1})\}$ where $F(p_f^j)$ is the finish tag of packet p_f^j, and is defined as $F(p_f^j) = S(p_f^j) + (l_{ff}/\phi_{ff})$ where $F(p_f^0) = 0$ and $j \geq 1$;
ii. Initially, the virtual time, $v(\circ)$, at a given wireless sensor node is set to zero. During transmission, the WSN node's virtual time at time t, $v(t)$, is set equal to the start tag of the packet being transmitted at time t. At the end of a transmission, $v(t)$ is set to the maximum of finish tag assigned to any packets that have been transmitted by time t;
iii. Packets are transmitted in the increasing order of the start tags.

2.2.1. Dynamic Weight Adaptation. To account for traffic dynamics, such as buffer availability, and channel states affecting fairness and end-to-end delay (E2E), packet weights are updated dynamically in contrast with a single channel ADFS [1]. Updating of the weights significantly improves the performance of the scheduling protocol. However, it adds complexity and convergence issues unless the packet weights are updated carefully. The actual weight for the j^{th} packet of the i^{th} flow, denoted $\hat{\phi}_{ij}$, is updated as

$$\hat{\phi}_{ij}(k+1) = \alpha\hat{\phi}_{ij}(k) + \beta E_{ij} \tag{2}$$

where $\hat{\phi}_{ij}(k)$ is the previous packet weight, $\{\alpha, \beta\} \in [-1, 1]$ are design constants and

$$E_{ij} = e_{ij,queue} + 1/e_{ij,delay} \tag{3}$$

is the network state where $e_{ij,queue}$ is the error between the expected length of the queue and the actual size of the queue and $e_{ij,delay}$ is the error between the expected delay and the delay experienced by the packet at the current time. According to (2) and (3), as queues grow, packet weights are increased clearing backlogs. Moreover, packets close to their E2E delay requirement are weighted heavier due to smaller values of $e_{ij,delay}$; however, overdue packets are dropped. Note that the term, E_{ij}, is bounded since the queue length and delay are finite values at each node. To calculate the back-off interval and implement MC-ADFS, the updated weights at each node are transmitted in the MAC data frame and updated dynamically using (2) at each node.

2.2.2. MAC Protocol - Dynamic Back-off Intervals. The proposed protocol uses the CSMA/CA scheme similar to the IEEE 802.11 and 802.15.4 protocols and is applicable to any network incorporating CSMA/CA. When multiple nodes of a WSN compete to access a shared channel, the selection of the back-off interval is crucial for fair access to the channel. Additionally, MC-ADFS is implemented at the MAC level to provide access to the shared channel through dynamic back-off intervals. The back-off interval, BI_{ij}, for i^{th} flow j^{th} packet with packet length l_{ij} and weight ϕ_{ij} is defined as $BI_{ij} = \rho \cdot SF \cdot (l_{ij}/\phi_{ij})$ where SF is a scaling factor and ρ is a random variable with mean 1. Since the weights are updated using (2), the back-off interval is also updated at each WSN node in the presence of multiple channels which is another major difference with a single channel ADFS. A collision handling mechanism is incorporated similar to [11], resulting in fair allocation of the bandwidth.

2.3. Multi-Channel Switching

To provide reliable allocation of packets across multiple channels, the MC-ADFS protocol assumes receiver-based allocation of channels where the nodes receive packets on an assigned channel and queue packets for scheduling. Next, for the duration of transmission, the channel is switched to that of the receiver for the next hop. Additionally, there are two scenarios considered for the sensor network's hardware layer. In the first scenario, the network is comprised of single-input-single-output radio frequency (RF) devices. In this case, the MC-ADFS protocol assumes that the nodes are capable of synchronizing their presence on a channel to send and receive packets. Synchronization can be accomplished by several methods, the simplest being an adaptation of time-slicing over channels. In the second scenario, nodes have a multi-input-multi-output (MIMO) capability, or multiple transceivers. This case is more ideal for the MC-ADFS protocol. For MIMO systems, MC-ADFS is assumed to have knowledge of the channels and a node is capable of sending and receiving based on routing information. This allows the proposed method to schedule packets for channels based on loading and QoS methods.

The main challenge in developing the MC-ADFS scheme is balancing loads between alternative channels/paths. Periodically, an MC-ADFS node communicates its service load to neighbors to provide feedback to the load balancing mechanism. When packets are scheduled the nodes select the next hop from available alternate channels/paths based on the current service load. The load balancing feature of MC-ADFS selects the next hop node with the lowest service loading ensuring that no individual MC-ADFS node is overloaded ensuring maximum QoS. Assumptions made include:

i. assignment of nodes to orthogonal channels is performed during route discovery and before packet scheduling begins;
ii. assignment of channels is receiver-based; and
iii. each node on a route is multi-channels capable of route discovery generating multiple routes.

For packet scheduling over multiple channels, ADFS dynamically selects relay nodes and channels used to transmit packets. Channel resources are scheduled on a packet-by-packet basis using the alternative routes available from a proactive routing protocol. As flows are added MC-ADFS balances the load based on relay-nodes' available capacity. When the packets are sent, the relay nodes evaluate the sum of the weights of transmitted packets for each channel. Next the feedback is sent to transmitting nodes, where they then allocate new packets to the least utilized channel and relay-node. Note that when a different channel is utilized, E2E delays can increase or decrease and the proposed MC-ADFS scheme will incorporate these as the weights are tuned. Load balancing and communication in multiple channels for scheduling purposes are other major differences with single channel ADFS [1].

2.4. MC-ADFS Performance Guarantee

To prove that MC-ADFS is fair, the bound on $|(W_f(t_1,t_2)/\phi_f) - (W_m(t_1,t_2)/\phi_m)|$ must be obtained for a sufficiently long interval $[t_1,t_2]$ over which both flows, f and m, are backlogged. In contrast to standard ADFS [1], MC-ADFS considers allocation of the channel and the bandwidth.

Lemma 1. The MC-ADFS node will fairly service all flows, Q, for a channel provided $\sum\limits_{n\in Q}\phi_{n,l} \le 1$.

To model the wireless channel as related to the upper bound of the service the channel the variations parameter from the FC and EBF service models is used. This additional term is included in the upper bound of the service over any interval $[t_1,t_2]$. In Lemma 1 we begin with the addition of the maximum variation term given as $\psi_f^{\max}(\lambda, c)$.

In order to proceed, the following assumption is needed.

Assumption. To arrive at a fair scheduling scheme, we assume that there exists a weight vector ϕ_{ij} for a i^{th} flow, j^{th} packet, at each WSN node $g$as $\phi_{ij} = [\,\phi_{ijg} \quad . \quad . \quad . \quad \phi_{ijm}\,]^{\,T}$

Remark 1. In fact, the weight update (2) ensures that the actual weight for the packet at each WSN node, at the cluster or cluster head (CH) level, converges close to its target value.

Remark 2. ϕ_{ij} is finite for each flow at each WSN node.

Lemma 2. If the weights are updated using (2) for a sufficiently long interval $[t_1,t_2]$, then the weight error $\tilde{\phi}_{ij}(k+1)$ is bounded, provided $|\alpha|$.

Proof. Using (2) and the weight error defined as $\tilde{\phi}_{ij}$, given by $\tilde{\phi}_{ij} = \phi_{ij} - \hat{\phi}_{ij}$ the weight estimation error is expressed as

$$\tilde{\phi}_{ij}(k+1) = \alpha\,\tilde{\phi}_{ij}(k) + (1-\alpha)\,\phi_{ij} - \beta\,E_{ij}. \tag{4}$$

Choose a Lyapunov function $V = \tilde{\phi}_{ij}^2(k)$. taking the first difference, and using (4)

$$\begin{aligned}\Delta V = V(k+1) - V(k) &= \tilde{\phi}_{ij}^2(k+1) - \tilde{\phi}_{ij}^2(k)\\ &= [\alpha\,\tilde{\phi}_{ij}(k) + (1-\alpha)\,\phi_{ij} - \beta\,E_{ij}]^2 - \tilde{\phi}_{ij}^2(k)\end{aligned} \tag{5}$$

Eq. (5) can be rewritten as

$$\begin{aligned}\Delta V = &-(1-\alpha^2)\tilde{\phi}_{ij}^2 + (1-\alpha)^2\phi_{ij}^2 + \beta^2 E_{ij}^2 + 2\alpha\,\tilde{\phi}_{ij}(1-\alpha)\phi_{ij}\\ &- 2(1-\alpha)\phi_{ij}\beta E_{ij} - 2\alpha\,\tilde{\phi}_{ij}\beta E_{ij},\end{aligned} \tag{6}$$

This further implies that, $|\Delta V| \le -(1-\alpha^2)\Big[\big|\tilde{\phi}_{ij}\big|^2 - \big(2\alpha/(1-\alpha^2)\big)\big|\tilde{\phi}_{ij}\big|\,a - (b/(1-\alpha^2))\Big]$ where $a = \big|[(1-\alpha)\phi_{ij} - \beta E_{ij}]\big|$ and $b = \Big|(1-\alpha)^2\phi_{ij}^2 + \beta^2 E_{ij}^2 - 2(1-\alpha)\phi_{ij}\beta E_{ij}\Big|$; and $|\Delta V| \le 0$ implies that $\big|\tilde{\phi}_{ij}\big| \ge B_{ij,\phi}$ where $B_{ij,\phi}$ is the upper bound on the weight error and is given by

$$B_{ij,\phi} = \alpha\, a + \sqrt{\alpha^2 a^2 + b(1-\alpha^2)} \Big/ (1-\alpha^2) \tag{7}$$

For $\left|\tilde{\phi}_{ij}\right| \geq B_{ij,\phi}\ \Delta V$. Therefore (7) can be treated as the upper bound on the weight error. Since $\left|\tilde{\phi}_{ij}\right| \geq B_{ij,\phi}$, from $\tilde{\phi}_{ij} = \phi_{ij} - \hat{\phi}_{ij}$ we get $\hat{\phi}_{ij} \leq \sigma\, \phi_{ij}$ for some positive constant σ.

Note. The weight of a packet of flow *f* at node *g* is denoted as $\phi_{f,g}$ and given by $\phi_{f,g} = \sigma_f \phi_f$

Lemma 3. The actual weights $\hat{\phi}_{ij}$ at each node using (2) converge close to their target values in a finite time.

Proof. Since $|\alpha|$, define $\tilde{\phi}_{ij}(k) = x(k)$, then (4) can be expressed as

$$x(k+1) = c\, x(k) + d\, u(k) \tag{8}$$

where $c = \alpha$, $d = [\,(1-\alpha) \quad -\beta\,]$, and $u(k) = [\,\phi_{ij} \quad E_{ij}\,]^T$. Equation (8) is a stable linear system [12], driven by a bounded input $u(k)$ (see Remark 2). According to the linear system theory [12], $x(k)$ converges close to its target value in a finite time.

Lemma 4. If flow *f* is backlogged over the interval $[t_1, t_2]$, then at a MC-ADFS WSN node $\phi_{f,g}.(v_2 - v_1) - l_f^{\max} - \psi_f^{\max}(\lambda, c) \leq W_f(t_1, t_2)$, where $v_1 = v(t_1)$ and $v_2 = v(t_2)$ are virtual times. The term $\psi_f^{\max}(\lambda, c)$ accounts for the channel number and state in a multi-channel network.

Proof. Refer to [13] for proof.

Lemma 5. In a MC-ADFS-based WSN node, during any interval $[t_1, t_2]$ $W_f(t_1, t_2) \leq \ \phi_{f,g}(v_2 - v_1) + l_f^{\max} + \psi_f^{\max}(\lambda, c)$.

Proof. Refer to [13] for proof.

Theorem 1. For any interval $[t_1, t_2]$ were flows *f* and *m* are backlogged over the entire interval, the difference in service received by two flows at a MC-ADFS WSN node is given as

$$\begin{aligned} \left|(W_f(t_1,t_2)/\phi_{f,l}) - W_m(t_1,t_2)/\phi_{m,g}\right| &\leq ((l_f^{\max} + \psi_f^{\max}(\lambda,c)) \Big/ \phi_{f,g}) \\ &\quad + ((l_m^{\max} + \psi_m^{\max}(\lambda,c))/\phi_{m,g}) \end{aligned}$$

.

Remark 3. If $E_{ij} = 0$ at each node and no channel variations, then the proposed MC-ADFS will become a DFS scheme [11]. Here a single channel is utilized at the ADFS node.

Remark 4. No assumption on the service rate of the wireless node was made to establish Theorem 1. Hence, Theorem 1 holds regardless of the service rate of the WSN node. This demonstrates that MC-ADFS achieves fair allocation of bandwidth and thus meets a fundamental requirement of fair scheduling algorithms for integrated services networks.

Remark 5. The addition of the wireless variations parameters $\psi_f^{\max}(\lambda, c)$ and $\psi_m^{\max}(\lambda, c)$ for flows f and m respectively account for the state of the wireless channel over each time interval. Using the $\psi^{\max}(\lambda, c)$ the maximum aggregate service delay is included in the bound of the service error. The new bound accommodates the variation in a wireless channel and provides innovation in that the ADFS method is extended to accommodate channel conditions.

2.5. Throughput Guarantee

The following theorem provides the guarantee of flow throughput by a MC-ADFS FC and EBF service model. This theorem is a version of throughput guarantees based on computer networks as applied to WSN. Consequently, the throughput and end-to-end delay bounds are a function of the node service rate, channel state, and back-off interval in contrast to computer networks where they do not exist.

Theorem 2. If Q is the set of flows served by a MC-ADFS node following FC service model with parameters $(\lambda(t_1, t_2), \psi(\lambda, c)$, and $\sum_{n\in Q} \phi_{n,g} \leq \lambda(t_1, t_2, c)$, then for all intervals $[t_1, t_2]$ in which flow f is backlogged throughout the interval, $W_f(t_1, t_2)$ is given as

$$\begin{aligned} W_f(t_1, t_2) \geq\ & \phi_{f,g}(t_2 - t_1) - \phi_{f,g}\Big(\sum_{n\in Q} l_n^{\max} \Big/ \lambda(t_1, t_2, c)\Big) \\ & - \phi_{f,g}(\psi(\lambda, c)/\lambda(t_1, t_2, c)) - l_f^{\max} - \psi_f^{\max}(\lambda, c) \end{aligned}$$

Proof. The proof follows that of ad-hoc networks [1] based on computer networks [9].

Let $v_1 = v(t_1)$ and let $\hat{L}(v_1, v_2)$ denote the aggregate length of packets served by the wireless node in the virtual time interval $[v_1, v_2]$. Then, from Lemma 4 we conclude $\hat{L}(v_1, v_2) \leq \sum_{n\in Q} \phi_{n,g}(v_2 - v_1) + \sum_{n\in Q} l_n^{\max}$. Since $\sum_{n\in Q} \phi_{n,g} \leq \lambda(t_1, t_2, c)$,

$$\hat{L}(v_1, v_2) \leq \lambda(t_1, t_2, c)(v_2 - v_1) + \sum_{n\in Q} l_n^{\max} \tag{9}$$

Define v_2 as

$$v_2 = v_1 + t_2 - t_1 - \Big(\sum\nolimits_{n\in Q} l_n^{\max} \Big/ \lambda(t_1, t_2, c)\Big) - (\psi(\lambda, c)/\lambda(t_1, t_2, c)) \tag{10}$$

Then from (9) it can be concluded that

$\hat{L}(v_1, v_2) \leq \lambda(t_1, t_2, c)(v_2 - v_1) + \sum_{n\in Q} l_n^{\max} \leq \lambda(t_1, t_2, c)(t_2 - t_1) - \psi(\lambda, c)$ Let $\hat{t}_2$ be such that $v(\hat{t}_2) = v_2$. Also let $T(w)$ be the time taken by a WSN node to serve packets with aggregate length w in its busy period. Then,

$$\hat{t}_2 \leq t_1 + \mathrm{T}(\hat{L}(v_1, v_2)) \leq t_1 + \mathrm{T}(\lambda(t_1, t_2, c)(t_2 - t_1) - \psi(\lambda, c)) \tag{11}$$

from the definition of FC service model, we get

$$T(w) \leq (w/\lambda(t_1,t_2,c)) + (\psi(\lambda,c)/\lambda(t_1,t_2,c)) \tag{12}$$

From (11) and (12) it can be shown that

$$\hat{t}_2 \leq [t_1 + [(\lambda(t_1,t_2,c)(t_2 - t_1) - \psi(\lambda,c))/\lambda(t_1,t_2,c)] + (\psi(\lambda,c)/\lambda(t_1,t_2,c))] \leq t_2$$

From Lemma 4 $W_f(t_1,\hat{t}_2) \geq \phi_{f,g}(v_2 - v_1) - l_f^{\max} - \psi_f^{\max}(\lambda,c)$. Since $\hat{t}_2 \leq t_2$, using (10) to get:

$$W_f(t_1,t_2) \geq \phi_{f,g}(t_2 - t_1) - \phi_{f,g}\Big(\sum\nolimits_{n\in Q} l_n^{\max} \Big/ \lambda(t_1,t_2,c)\Big) \\ - \phi_{f,g}(\psi(\lambda,c)/\lambda(t_1,t_2,c)) - l_f^{\max} - \psi_f^{\max}(\lambda,c) \tag{13}$$

Remark 6. Since $\psi(\lambda,c)$ is dependent on bandwidth changes due to the channel number and state, and the back-off interval during contention, Eq. (13) clearly indicates that MC-ADFS throughput depends upon the channel, channel state, and the back-off intervals in contrast to [1].

2.6. Performance Evaluation Metric

Evaluation of performance is carried out using a fairness index (FI) which illustrates the weighted fairness among the flows is maintained independent of network dynamics. The FI [14] of the network is calculated by $FI = \left(\sum_f (T_f/\phi_f)\right)^2 \Big/ \eta * \sum_f (T_f/\phi_f)^2$ and is used as a metric to further evaluate the performance of the MC-ADFS protocol where for flow f, T_f is the throughput, ϕ_f is the initial weight, and η is the number of flows.

3. Conclusions

The proposed protocol, MC-ADFS, introduces a new metric for the upper bound of the service for a flow and the upper bound for the error in service for two contending flows. The introduction of MC-ADFS for WSN allows for increased capabilities and transmission capacity allowing dynamic scheduling of packets over multiple channels, thereby facilitating an increased network capacity, reduction of congestion, and efficient packet scheduling. Analytical assurance of the QoS level in terms of throughput provides confidence that the rate of the packet transfer is guaranteed for each source and due to the distributed adaptive nature of ADFS allows implementation with a low packet overhead.

About the Authors

James Fonda received his Ph.D. in Electrical Engineering from Missouri University of Science and Technology in 2008. His interests include sustainable manufacturing, embedded systems design, nonlinear and neural network controls, condition based maintenance, and wireless sensor networks. He has been an intern at Continental AG in Hannover, Germany, is a member of Eta Kappa Nu and IEEE, and received the 2003

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