On Optimal Slot Allocation for Reservation TDMA MAC Protocol in Shadow Fading Environment

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***Abstract* — This paper investigates the problem of providing delay guarantees to time-sensitive users sharing an uplink channel. The channel is a time slotted joint AWGN and impulsive noise channel in a shadow fading environment. Guaranteeing delay in shadow fading and noisy environment requires the MAC layer to be aware of the application delay requirements and the physical layer characteristics of the wireless channel. One of the important components of the base station MAC is the slot allocation module that allocates time slots to users. Existing slot allocation schemes use linear proportional schemes based on the queue state and priority factor. We develop an optimal slot allocation scheme that bases its allocation decision on the buffer content, the traffic class factor and the wireless channel quality. We specify the wireless channel quality in terms of the probability of connectivity between users and the base station and develop a method of estimating this quantity. Instead of absolute no transmission during bad wireless link states our optimal slot allocation module allots fewer slots in bad link states. The slot allocation module is used in a reservation TDMA Base Station (BS) MAC to control queuing delay and improve throughput. The performance of the slot allocation scheme is evaluated using OPNET simulation.**

I. INTRODUCTION

There is growing interest in the potential use of embedded wireless sensors and actuator networks in the protection and decentralized control of critical infrastructures such as the power system [1] [2]. The idea is to integrate Intelligent Electronic Devices (IED) with radio and networked them to form a Local Smart Monitoring, Protection and Control (LSMPC) wireless system. Developing LSMPCs at the substation level and their appropriate integration into a multi-level hierarchical control is attracting attention of collaborative researchers. The LSMPC comprises a central intelligent controller, embedded sensors and actuators (IEDs). The intelligent controller senses its environment in real time, processes, and analyzes gathered information and makes local control decisions. As information is a valuable item that improves decision we focus on the timely delivery of information send to the central intelligent controller. The types of information needed by the central intelligent controller are the observed state of the subsystem, and the dependence information. The communication between the embedded sensors and the intelligent controller is modeled as a multi-access wireless communication system. One of the important issues in a multi-access wireless communication system is the allocation and coordination of access to the wireless link to fulfill user's quality of service (QoS) requirements [3] [4] [5]. This function is performed by the Media Access Control (MAC) protocol. The multi-access wireless environment presents unique challenges to timely delivery of data due to the time varying wireless channel [6] [7] [8]. The layout and the components in transmission substations obstruct the path of propagation. This leads to a path loss caused by a phenomenon called shadow fading [9]. The quality of the wireless channel in power system environment is impaired by shadow fading and joint AWGN and impulsive noise. Guaranteeing delay requires the MAC layer to be aware of the application delay requirements and the physical layer characteristics of the wireless channel.

There are lot of works on slot allocation schemes for delay sensitive support in wireless networks [10] [11-14] [15]. In [10] a survey on capacity allocation strategies is presented. The use of queue status in setting allocation priorities is proposed in [11, 12]. In [13] a scheme that allocates slots proportional to the buffer state is presented. Linear proportional scheme and its variations are used by many researchers because of their simplicity [14, 15]. However, these proportional schemes cannot be used in all operational environments. This is because these schemes do not take the channel quality into consideration in slot allocation decision making. We therefore propose a slot allocation scheme which in addition to buffer content and the traffic class factor uses wireless channel quality in slot allocation decision making.

The contribution of this work includes the estimation of the quality of the wireless link in terms of the probability of connectivity between users and the BS, and the development of an optimal slot allocation scheme. This work is different from previous once which consider the good and bad states as states of transmit and no transmit respectively. The performance of the propose slot allocation scheme is to linear proportional scheme using OPNET.

The remainder of the paper is organized as follows: An overview of reservation TDMA protocol is presented in section II. Section III presents slot allocation decision factors. In section IV slot allocation schemes are presented. Numerical results are presented in section V. The conclusion is given in VI.

II. OVERVIEW OF RESERVATION TDMA PROTOCOL

Reservation TDMA is a variation of TDMA protocol which provides slots on demand type of service. A user which has data packets to send but has no assigned data slots sends a reservation packet during the reservation period to the BS to request data slots. Access to the reservation minislots at the beginning of the uplink channel is either by contention or fixed assignment protocols.

The reservation packet specifies the user's traffic characteristics, channel quality information and source buffer status. The base station uses the reservation information as input to the slot allocation scheme to allocate number of slots to the user. In many networking situations each user is allotted a number of time slots during each time frame. An important function of the Base Station (BS) MAC is to allot slots to the users based on their demands. This work focuses on the development of a slot allocation scheme that bases its allocation decision on the queue state, traffic priority factor and the channel quality. The frame structure used in the study is as shown in fig. 1.

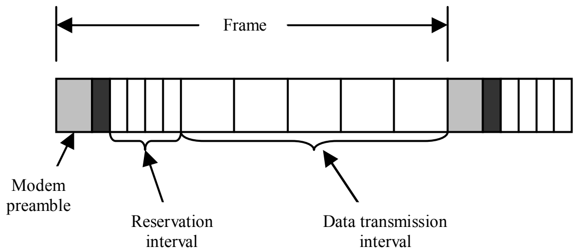

Fig. 1 Reservation TDMA frame structure

III. SLOT ALLOCATION DECISION FACTORS

This section presents the decision factors used by the optimal slot allocation module in its decision making.

A. Wireless Channel Quality Factor

We assume the random fluctuation of the quality of the wireless channel is due to shadow fading and noise. The shadowing effect is due to the blockage from objects on the path of the transmitted signal. This gives rise to random variations of the received power at a given distance. The signal attenuation is the difference in dB between the transmitted and received signal power and given by

$$\chi = 10\log_{10}\frac{p_t}{P_r}\ dB \qquad (1)$$

where p_t is the transmitted power and p_r the received power. In a shadow fading environment the signal attenuation is made up of two parts. The deterministic part given by [7] [8]

$$\chi_1 = \alpha 10\log_{10}(\frac{d}{d_0})\ dB \qquad (2)$$

where d_0 is a reference distance, d is the transmission distance and α is the path loss exponent.

The random component is chosen from a log-normal probability distribution function [7]

$$\chi_2 = p(\psi_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{dB}}}\exp[\frac{(\psi_{dB}-\mu_{dB})^2}{2\sigma^2_{\psi_{db}}}] \qquad (3)$$

The distribution of ψ_{dB} is Gaussian with mean $\mu_{\psi_{dB}}$ and standard deviation $\sigma_{\psi_{dB}}$

The total attenuation is given by

$$\chi = \chi_1 + \chi_2$$

In a wireless communication system there is typically a target minimum received power level $p_{\min}$ below which the performance of the wireless link is unacceptable [7] [8]. The attenuation value above which proper reception of data packet is impossible is described as the threshold attenuation. The signal attenuation of users varies due to shadowing. Proper reception of data packet is impossible when the attenuation is above the threshold value. Thus when

$$\chi > \chi_{th}$$

The threshold attenuation χ_{th} is a wireless system parameter. The quality of the wireless channel of a user depends on the extent to which its signal attenuation departs from the threshold value. The probability that the attenuation is greater than or equal to the threshold value is denoted as

$$P(\chi \geq \chi_{th})$$

Using (3) we can write

$$P(X \geq \chi_2) = \int_{\chi_2}^{\infty}\frac{1}{\sigma\sqrt{2\pi}}\exp[-\frac{(\chi-\mu)^2}{2\sigma^2}]d\chi \qquad (4)$$

The integral cannot be evaluated in a closed form and thus computed numerically using the Q function.

$$\text{Let } y = \frac{\chi-\mu}{\sigma}$$

$$P(y > \frac{\chi_2-\mu}{\sigma})\int_{\frac{\chi_2-\mu}{\sigma}}^{\infty}\frac{1}{\sqrt{2\pi}}\exp[-\frac{y^2}{2}]dy$$

$$P(y > \frac{\chi_2-\mu}{\sigma}) = Q(\frac{\chi_2-\mu}{\sigma})$$

But

$$\chi_2 = \chi_{th} - \chi_1$$

$$= \chi_{th} - 10\alpha\log_{10}(\frac{d}{d_0})$$

$$P(y > \frac{\chi_2}{\sigma}) = Q(\frac{\chi_{th} - 10\alpha\log_{10}(\frac{d}{d_0})}{\sigma}) \qquad (5)$$

Also

$$Q(z)=\frac{1}{2}[1-erf(\frac{z}{\sqrt{2}})]$$

Therefore the probability that attenuation is greater than the threshold attenuation is given by

$$P_{out}=\frac{1}{2}[1-erf\{\frac{\chi_{th}-10\alpha\log_{10}(\frac{d}{d_0})}{\sigma\sqrt{2}}\}] \qquad (6)$$

We use P_{out} as a measure of connectivity between users and the BS. This work is different from previous once which consider the good and bad states as states of transmit and no transmit. The connectivity measure is use to decide the number of data slots allocated to a node. Instead of absolute no transmission in bad states we develop an allocation scheme which allocates fewer slots in the bad state.

B. Traffic Class Factor

Multi-priority data transmission can be achieved by assigning different weight factor w_k to the different priority classes. The different traffic classes have diverse delay requirements and are queued in separate buffer. The messages are transmitted over a multi-access wireless channel as shown in fig. 2. The lower the traffic class the higher its weight factor. Three traffic classes are considered in this work. The arrival of each class of message is according to a Poisson process with rate λ_k. The inter-arrival time between messages is considered to be exponentially distributed. The traffic class information is contained in the reservation request message send to the BS. The traffic class factor is one of the information used by the BS in deciding the number of data slots allocated to a traffic class.

IV. SLOT ALLOCATION SCHEMES

This section presents two slot allocation schemes. The two schemes are the proposed optimal slot allocation scheme and the linear prioritized proportional scheme that we compare our scheme to.

A. Optimal Slot Allocation Module

The aim of the proposed scheme is to effectively use buffer state, traffic class factor and wireless link quality factor information in slot allocation decision. The function of the optimal slot allocation scheme is to allot slots so as to control queue delay and make efficient use of wireless capacity. In reservation TDMA protocol allocating time slots to meet user's delay requirement and taking into consideration the underlying physical impairments is a complex problem. The slot allocation problem is seen as a single server serving k traffic classes shown in fig. 2.

In this work we consider the slot allocation for only uplink transmissions. The slot allocation decision is made based on the traffic class, the buffer state and the channel quality information. The channel quality is specified in terms of connectivity between the transmitter and the receiver as described in section III.

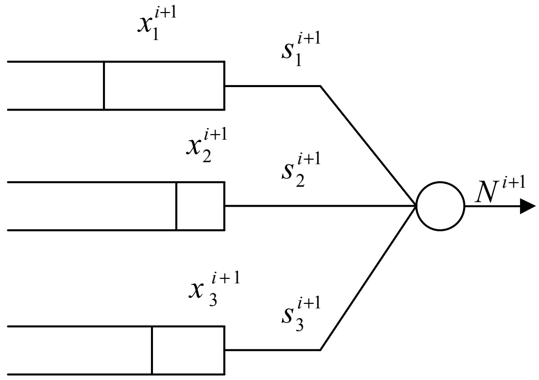

Fig. 2 Slot allocation model

Due to propagation and processing delays we assume that data slot requests made in a given frame are not granted in the same frame period. On frame by frame basis the slot allocation module uses the buffer content, the traffic class factor and the channel quality information to allot slots to (serve) 3 different queues

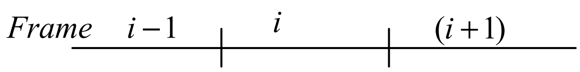

Fig. 3 Frame cycles

Let x_{jk}^{i} denote the estimated number of node j's traffic class k packets awaiting transmission at the beginning of frame i. Also let r_{jk}^{i} denote the expected number of node j's packets that arrive during frame i and s_{jk}^{i} the number of slots allotted to node j's traffic class k in frame i. The expected number of packet arrival r_{jk}^{i} is the product of the mean arrival rate and the frame duration. N^{i} is the available number of slots for use in frame i. The estimated number of packets awaiting transmission at the beginning of frame $i+1$ is given by

$$x_{jk}^{i+1}=x_{jk}^{i}+r_{jk}^{i}-s_{jk}^{i} \qquad (7)$$

For given x_{jk}^{i+1} and N^{i+1} the goal is to find an optimum slot allocation strategy based on the traffic class, and channel quality so that the quantity $\left(x_{jk}^{i+1}-s_{jk}^{i+1}\right)$ is minimized. We are of the view that reducing the expected number of packets awaiting transmission translates into reducing the queuing delay. The optimal slot allocation problem is posed as a constrained optimization problem. For node j the objective function for traffic class k is given by

$$\min_{s_{jk}^{i+1}} \sum_j \sum_k \left\{x_{jk}^{i+1} - s_{jk}^{i+1}\right\}^2 w_k cQ_{jk}$$

s.t. (8)

$$\sum_j \sum_k s_{jk}^{i+1} = N^{i+1}$$

where N^{i+1} is the number of available data transmission slots for use in frame $i+1$, w_k is the traffic class priority factor and cQ_{jk} is the channel quality factor of traffic class k of node j.

We solve (8) using the Lagrange method for constrained optimization. Thus

$$L(s_{jk}^{i+1},\lambda) = \sum_j \sum_k \left\{x_{jk}^{i+1} - s_{jk}^{i+1}\right\}^2 w_k cQ_{jk} + \lambda\left(N^{i+1} - \sum_j \sum_k s_{jk}^{i+1}\right) \quad (9)$$

$$\frac{\partial L\left(s_{jk}^{i+1},\lambda\right)}{\partial s_{jk}^{i+1}} = 2\left(x_{jk}^{i+1} - s_{jk}^{i+1}\right) w_k cQ_{jk} - \lambda = 0 \quad (10)$$

$$\frac{\partial L\left(s_{jk}^{i+1},\lambda\right)}{\partial \lambda} = N^{i+1} - \sum_j \sum_k s_{jk}^{i+1} = 0 \quad (11)$$

$$s_{jk}^{i+1} = x_{jk}^{i+1} + \frac{\lambda}{2 w_k cQ_{jk}} \quad (12)$$

Substituting (12) in (11) we have

$$\sum_j \sum_k \left(x_{jk}^{i+1} + \frac{\lambda}{2 w_k cQ_{jk}}\right) = N^{i+1}$$

$$s_{jk}^{i+1} = x_{jk}^{i+1} - \frac{\left\{\left(\sum_j \sum_k x_{jk}^{i+1}\right) - N^{i+1}\right\}}{w_k cQ_{jk}\left(\sum_j \sum_k \frac{1}{w_k cQ_{jk}}\right)} \quad (13)$$

It is seen from (13) that there would be no need for the optimization if the total number of packets awaiting transmission at the beginning of a frame is equal to the total number of slots available. This is because $\{(\sum_j \sum_k x_{jk}^{i+1}) - N^{i+1}\} = 0$ and all the requested slots can be honored. Also the higher the priority factor w_k and the wireless channel quality cQ_{jk} the higher the allocated number of slots s_{jk}^{i+1}. The link connectivity between users and the BS is specified in terms of the link outage probability and given by

$$cQ_{jk} = 1 - P_{outjk} \quad (14)$$

B. Prioritized Proportional Allocation Scheme

Linear proportional scheme and its variations are used by many researchers because of their simplicity. However, these proportional schemes cannot be used in all operational environments. This is because these schemes do not take the channel quality into consideration in slot allocation decision making. The linear prioritized proportional slot allocation is based on

$$s_{jk}^{i+1} = \frac{w_k x_{jk}^{i+1}}{\sum_j \sum_k w_k x_{jk}^{i+1}} N^{i+1} \quad (15)$$

x_{jk}^{i+1} is the estimated number of node j 's traffic stream k packets at the beginning of frame $i+1$.

V. NUMERICAL RESULTS

The outage probability is estimated for attenuation scenarios of path loss exponent 2.5, and 4.0. The shadowing cases considered are standard deviation of 4, 8 and 12. The results using (6) are shown in fig. 4 and 5.

The traffic-class factors used in this work are 0.6, 0.3 and 0.1 for classes 1, 2, and 3 respectively. Assuming perfect channel conditions during each frame when there are traffic class k packets to send, class k is guaranteed to receive a fraction of available slots based on its weight. The OPNET setup comprises traffic source, a buffer and a server. We generate 3 traffic classes using standard OPNET source generators. The traffic parameters configured are the average data rate, the packet size and the function of the interarrival distribution. The buffer is modeled as a passive queue and forwards packets only upon receiving a request from the server.

The slot allocation module which acts as the server allots packets to the respective classes as described in section IV.For all traffic classes the mean delay performance of the linear proportional scheme is better than that of the optimal slot allocation scheme as seen in fig. 6 to 8. This in our view is due to the fact the linear proportional scheme does not consider the wireless channel quality in its decision making. The optimal slot allocation scheme therefore gives a more realistic result.

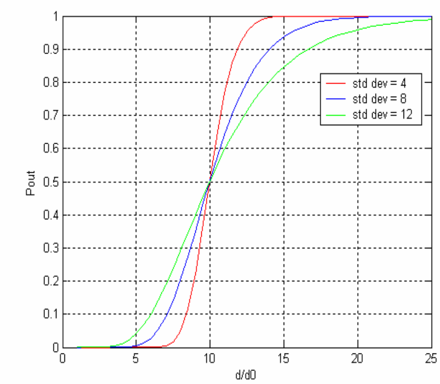

Fig. 4 Outage Probability for path exponent of 2.5

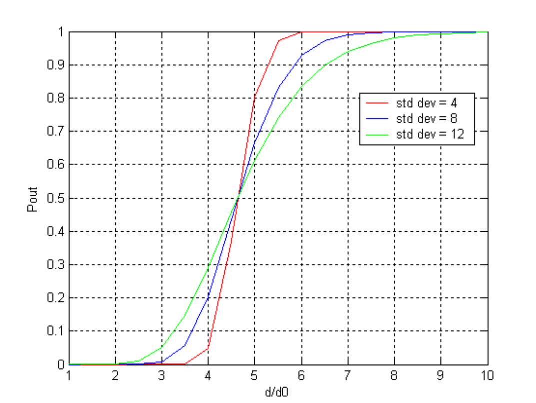

Fig. 5 Outage Probability for path exponent of 4.0

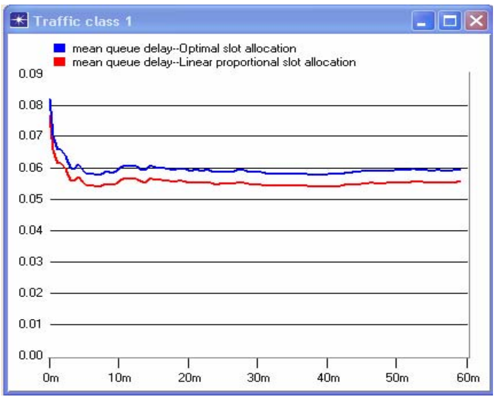

Fig. 6 Mean delay for traffic class 1

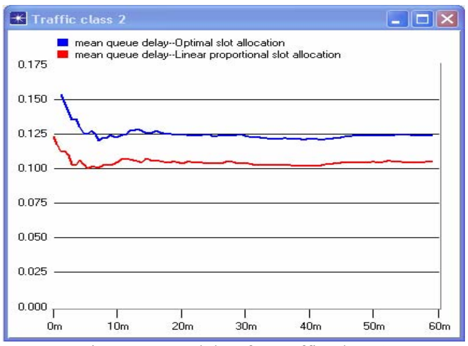

Fig. 7 Mean delay for traffic class 2

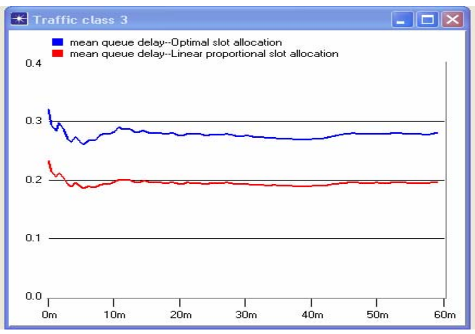

Fig. 8 Mean delay for traffic class 3

VI. CONCLUSIONS

We develop an optimal slot allocation scheme that bases its allocation decision on the buffer content, the traffic class factor and the wireless channel quality. We specify the wireless channel quality in terms of the probability of connectivity between users and the base station and develop a method of estimating this quantity Instead of absolute no transmission in bad wireless link states our optimal slot allocation module allots fewer slots during bad link states. The mean delay performance of the linear proportional scheme is better than that of the optimal slot allocation scheme. This in our view is due to the fact the linear proportional scheme does not consider the wireless channel quality in its slot allocation decision making. The optimal slot allocation scheme therefore gives a more realistic result.

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