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ANNUAL REPORT

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Title: Discrete-Event-Dynamic-System-Based Approaches for Scheduling Transmissions in Multihop Packet Radio Networks

This is a summary of the research performed under this contract for the period 10/91 - 9/92. The main objective of this project was to investigate techniques from recent developments in the field of Discrete Event Dynamic Systems (DEDS) as they apply to the transmission scheduling problem in packet radio networks. This report is accompanied by four Technical Reports corresponding to the papers referenced as [1]-[4] in what follows.

In the classic transmission scheduling problem, the nodes of a Packed Radio Network (PRN) broadcast fixed-length packets over a common resource (the channel). Packet transmissions are subject to interference constraints; for example, if a node is transmitting a packet, then all adjacent (neighboring) nodes must refrain from transmission. One then adopts a slotted time model where every slot is allocated to a set of nodes which can simultaneously transmit without conflict. Thus, a node generally belongs to one or more of these sets (called *transmission sets*).

Our approach is based on viewing the transmission scheduling problem as a *single server multiclass polling problem with simultaneous resource possession*. Here, a class corresponds to a transmission set. The server corresponds to a channel operating with deterministic service times: a service time is equal to one time slot required for transmitting a packet. The scheduling problem is then equivalent to assigning the server (equivalently, each time slot) to a particular transmission set. The simultaneous resource possession feature arises because the server is assigned to a transmission set, i.e. it can simultaneously provide service to packets from all nodes which belong to that set. The construction of the transmission sets is dependent upon the topology and connectivity of the PRN and is equivalent to a graph partitioning problem. For our purposes, we assume M transmission sets have been specified. Finally, we allow for overlapping transmission sets, i.e. a node can belong to two or more difference transmissions sets.

We have adopted a simple *random polling* policy for this problem: the i th set is allocated a slot with probability θ_i . Our objective then is to determine the optimal probabilities by adjusting the variables $\theta_1, \dots, \theta_M$ on line in an adaptive manner so as to maximize some overall performance measure. For simplicity, we initially limited ourselves to a polling problem with non-overlapping transmission sets: each class (transmission set) is comprised of exactly one node. We assume that the performance of each class is measured through some function of the form $J_i(\theta_i)$. We can then formulate an optimization problem subject to the normalization constraint $\theta_1 + \dots + \theta_M = 1$.

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The constrained optimization problem can be solved using Lagrange multipliers, which gives rise to a set of Kuhn-Tucker optimality conditions. These conditions are expressed as linear relationships involving the partial derivatives (sensitivities) $\partial J / \partial \theta_i$ (for details, see [1]). Given these sensitivities, we use a stochastic gradient-based optimization algorithm to iteratively adjust the slot assignment probabilities $\theta_1, \dots, \theta_M$ until an optimal point is reached. For the simple non-overlapping system we initially considered, the optimality conditions are equivalent to setting all sensitivities equal to each other. This can be achieved through a variety of optimization schemes.

In our approach, the processes describing packet arrivals at various nodes are allowed to be completely arbitrary and no information about them is required. As a result, analytical expressions for the sensitivities $\partial J / \partial \theta_i$ are not available. Based on perturbation analysis techniques for DEDS, we were able to develop two novel unbiased estimators for these sensitivities. The estimation process is identical for each class, therefore we can consider the i th class in isolation and model the *schedule* (sequence of slot assignments) it observes as consisting of *transmission slots* (slots that are assigned to class i) and *vacation slots* (slots assigned to some other class). Let A and V be the set of slot indices corresponding to transmission and vacation slots respectively. The unbiased sensitivity estimators developed are given by:

$$\left[\frac{\partial J_i(\theta_i)}{\partial \theta_i} \right]_{est}^- = \frac{1}{\theta_i} \sum_{k \in A} [L(\theta_i) - L_{-k}(\theta_i)] \quad (1)$$

$$\left[\frac{\partial J_i(\theta_i)}{\partial \theta_i} \right]_{est}^+ = \frac{1}{1-\theta_i} \sum_{k \in V} [L_{+k}(\theta_i) - L(\theta_i)] \quad (2)$$

where $L(\theta_i)$ is the sample performance for class i ; $L_{-k}(\theta_i)$ and $L_{+k}(\theta_i)$ are the sample performance when the k th transmission slot is *marked* and *phantomized* respectively. Here, a *marked slot* is a transmission slot in the nominal schedule which becomes a vacation slot in a fictitious perturbed schedule. Similarly, a *phantom slot* is a vacation slot in the nominal schedule which becomes a transmission slot in the perturbed schedule. To obtain explicit expressions in (1) and (2), we developed two algorithms, termed *Marked Slot* and *Phantom Slot* algorithms respectively. These algorithms determine the effect of removing/adding transmission slots to an existing schedule on mean packet waiting times by directly observing the system (and without interfering with its operation). The estimators were then combined with a simple gradient-based optimization algorithm for adjusting a schedule on line so that the optimal slot assignment is reached [1] (some related sensitivity estimators were also developed as reported in [2]-[4]). A number of numerical results obtained through extensive simulation may be found in [1].

It is important to emphasize that these sensitivity estimation algorithms are *not* based on explicitly constructing perturbed sample paths of the observed PRN in operation. Rather, we conduct "thought experiments" using information directly available from the nominal system in order to determine changes in various sample path quantities (specifically, $L_{-k}(\theta_i)$ and $L_{+k}(\theta_i)$ in (1) and (2) above). Moreover, these estimators are applicable to a wide range of performance measures (e.g., waiting times, throughputs, probability of exceeding deadlines). In what follows, we describe the salient features of the marked and phantom slot algorithms when the performance measure is the mean waiting time. For this performance measure, the quantity of interest is the change in the cumulative waiting time due to marking/phantomizing a slot.

In the *Marked Slot* algorithm, the effect due to marking a transmission slot in a given busy period (e.g., the j th busy period) can propagate to subsequent busy periods. This results in the coalescence of busy periods in the perturbed sample path. A little thought reveals that the end of a

resulting busy period in the perturbed system coincides with the end of the *first idle transmission slot following a busy period in the nominal system*. In fact, the implementation of the marked slot algorithm is based on checking for idle transmission slots immediately following busy periods in the nominal system. This algorithm is easy to implement (see [1]).

In the *Phantom Slot* algorithm, the effect of phantomizing a slot is localized to the busy period in which this (vacation) slot is phantomized. This allows us to easily specify a stopping rule for the algorithm in terms of a number of observed busy periods on the nominal path. From an implementation standpoint, the phantom slot algorithm requires the storage of arrival and transmission epochs for the duration of the current busy period, in addition to performing various comparison operations.

We were subsequently able to extend our approach to the general case of transmission sets with multiple nodes and with nodes possibly belonging to more than one such set. In this case, we can still formulate a similar optimization problem by introducing auxiliary variables ϕ_i , where ϕ_i is the total probability (over multiple transmission sets) that node i is assigned the current slot. The optimality conditions are now more complex, but always in the form of linear relationships involving the partial derivatives (sensitivities) $\partial J / \partial \phi_i$. Moreover, the sensitivities are calculated with respect to the auxiliary variables ϕ_i ; therefore an additional step is needed to determine the actual control parameters θ_i at every iteration step. Extensive numerical results based on simulations were reported during a presentation at NRL in June 1992 (some also included in [1]).

Note that although we have focused on the broadcast scheduling problem, our analysis can be extended to incorporate static (fixed source/destination pair) routing. The effect of routing is to redefine the transmission sets in the polling model. In addition, the methodology can be extended to consider periodic polling policies. Here the underlying assumption is that there is a *frame* consisting of f slots which is repeated in time. The frame is constructed probabilistically so that a slot is assigned to class i with probability θ_i . The control objective is to select the optimal probabilities θ_i and construct a frame based on these probabilities. Marked/Phantom slot estimates can be developed for sensitivities of blocking probabilities with respect to the slot assignment probabilities. The frame-based scheduling model can be applied to minimize blocking in tandem networks with homogeneous resource capacities.

The essence of our approach (which can be used in several other problems related to packet radio networks) is to bypass the computational complexity involved in scheduling problems through a randomization process; we then determine the best policy within this class. We believe that there are several advantages in this approach: (a) As already mentioned, it provides one means for bypassing computational complexity, (b) It leads to scheduling policies which do not require state information (typically not available in practice), and (c) We have found that this approach can be used to ultimately design *deterministic* frames where each slot in a frame is allocated to a specific transmission set. In particular, once the optimal values of the parameters θ_i are determined, we can adopt various schemes (e.g. the "golden ratio") to design such frames. Moreover, as operating conditions change, we maintain the ability to adjust the frame based on the sensitivities estimated on line. We have performed extensive simulation experiments to substantiate these observations.

Our work to date also suggests several issues for further research. First, implicit in our approach is the existence of a central controller, that is a node which receives local sensitivity estimates from each node in the network, performs all control parameter adjustments, and then broadcasts the new schedule to each node. Clearly, we would like to obtain a distributed implementation of the algorithm. Secondly, as pointed out, for the case of overlapping transmission sets the optimality conditions are usually complex. The design of the actual optimization algorithm, in particular convergence issues, need to be further addressed.

Finally, towards the end of this project, we began to explore the possibility of using similar techniques for more general performance measures and integrated service networks (e.g. controlling slot allocation so as to minimize voice call blocking probabilities, while also ensuring satisfactory performance for data traffic). Our preliminary results in the area of voice/data integration indicate that this is indeed feasible, and have helped us identify some key issues to be further investigated.

References

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