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A Call Admission Control Scheme for Scheduled Priority
Arrivals in Wireless Communication Systems

by

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I. Introduction

With rapid proliferation of personal mobile computing and communication devices, future mass transportation vehicles such as trains may provide services via mobile LANS aboard the vehicle. Connectivity of onboard users to the world's communication networks would then depend on providing a high bandwidth link or links to the vehicle's LAN as the vehicle moves throughout a region. If the region in which such vehicles travel is served by a cellular type wireless infrastructure, it is natural to consider how connectivity for such platforms can be provided by the infrastructure. The traffic loading in a cell may change abruptly as such vehicles enter and leave cellular coverage areas. Ordinarily, communication systems are designed under the assumption that demands arrive randomly but more or less smoothly in time. But if there are likely to be abrupt and high demands for limited resources, there will be difficulty in accommodating communications needs unless the specific nature of these demands can be exploited. Simply increasing the number of channels in the cell to accommodate such events is unsatisfactory because resources will be wasted when the demand disappears.

However, mass transportation vehicles such as trains follow a more or less fixed schedule. If this is taken into consideration the cellular infrastructure might efficiently accommodate communication demands by using a call admission control policy that assigns resources in anticipation of *scheduled demand changes*. We consider strategies to accommodate such mass transportation vehicles.

For simplicity of engineering and practical implementation, we assume that a fixed number of wireless channels or a fixed bandwidth is required for the LAN to provide satisfactory

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QoS to all the mobile users on the train. Extension to cases for which other communication resources (in addition to bandwidth) are also required is deferred to future work. The essential characteristics of the train are that it has a more or less fixed schedule and requires a significant resource allocation during its sojourn in a cell.

In Section II, the problem statement and the system model are described and a strategy to accommodate mass transportation vehicles is briefly introduced. The call admission control scheme is described in Section III. In Section IV, equations for system state probabilities are formulated and solved by numerical methods. Additionally, appropriate performance metrics are defined. An optimization algorithm for call admission control is proposed in Section V. In Section VI, the strategy is described in detail for two typical scenarios: 1) a single train enters and leaves the cell, and 2) two trains enter and leave the cell. The performance of the strategy is also analyzed theoretically. The numerical results are presented in Section VII. Conclusions are drawn in Section VIII.

II. Problem Statement

Consider a region serviced by a cellular system using a fixed channel assignment. We assume that the base stations serve a large number of mobile subscribers with relatively modest resource needs in addition to the heavy and abrupt demands imposed by mass transportation platforms traversing the region. We refer to the large number of mobile subscribers that generate a statistically regular or stationary pattern of demand as the *local users*. The local user population generates a new (local) call origination process and a hand-off (local) call arrival process, each of which is assumed to be Poisson. Let λ_n denote the *known* new call origination rate. Let λ_h denote hand-off arrival rate when the cell is in the statistical *steady state*. That is, the state probabilities are not changing with time. The cell will be in the statistical steady state if the current train has left the cell for a sufficiently long time and the next train will enter the cell a sufficiently long time later. From previous work [3]-[5], we know that λ_h is an implicit function of λ_n and that λ_h is determined by the dynamics of the system. We assume that the duration of an individual session is a *ned* (negative exponential distributed) random variable with mean of $1/\mu$. We assume that the dwell time of a platform in a cell is also a *ned* random variable with a

mean of $1/\mu_D$. Let C be the number of channels in a cell and C_L be the fixed number of channels that are required by the service of the train.

In the proposed scheme, the service of the train has preemptive priority over the service of local users in each cell along the train's path. That is, when the train arrives at a cell in which the number of available channels is less than C_L, some local calls in progress will be terminated to guarantee the required C_L channels for service of the train. Because interruption of ongoing calls is undesirable to local mobile users we develop a strategy for the system to minimize such interruptions.

Let D_{cell} denote the time that a train spends in a cell. The value of D_{cell} is known to the train and announced to the BS. According to the speed of a train and the size of a regular cell, D_{cell} can be of several minutes in duration. In the proposed strategy, each train notifies the next base station (BS) that it will visit of its arrival time a *fixed* time interval before the actual arrival. (Notification of time to arrive at other base stations can also be considered). The fixed time *interval* (between the notification and actual arrival) is called the *notification interval* and is denoted by D_n. Suppose that the train notifies the BS at $t = T_n$ that it will *enter* the cell at $t = T_e$ and leave the cell at $t = T_l$, where $T_l = T_e + D_{cell}$. Then the notification interval D_n is $[T_n, T_e]$. The BS checks the state of the cell (i.e., the number of occupied channels in the cell) and takes appropriate call admission control action to control (restrict) the admission of new calls and hand-off calls beginning at some time $T_a \geq T_n$ in the notification interval. The time interval between T_a and T_e is denoted by D_a and is called the action interval. The value of D_a is a constant value that has to be determined by the analysis. A train will leave the cell D_{cell} time units after its arrival, and the (resources) channels that it uses during the sojourn will be released upon leaving. In the following sections we describe the details of the strategy.

III. Call Admission Control

We use a fractional guard channel policy for the purpose of call admission control. Generally in a fractional guard channel policy, at each state calls are admitted only with certain probability. Let α_i denote the probability that a new call arrival is admitted when there are i

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channels occupied in the cell, and β_i denote the probability that an arriving hand-off call is admitted when there are i channels occupied in the cell. New calls and hand-off calls are always rejected when all C channels are occupied. We have $0 \leq \alpha_i \leq 1$, and $0 \leq \beta_i \leq 1$, for $0 \leq i \leq C-1$, while $\alpha_i = 0$, $\beta_i = 0$, for $i = C$.

IV. Nonstationary State Probabilities and Performance Metrics

We assume that the arrival of the train has no influence on the statistics of local call origination. Thus, new call origination rates in the cell before the train arrives, while the train is in the cell and after the train leaves are the same. Also, in the model, blocked calls are cleared from the system so demand does not accumulate while the train is in the cell. In practice this means that blocked local calls may retry after a long time.

The cell in which we consider the accommodation of the train is called the target cell. As the train approaches the target cell, the two neighboring cells that the train will pass before and after the target cell will take call admission control to restrict new calls and hand-off calls. Therefore, the number of calls in progress in the two neighboring cells may be lower than the number of calls if the two cells were in statistical equilibrium. The result is that in the target cell, the hand-off arrival rate from these two neighboring cells may be lower than the hand-off arrival rate from the two cells when the two cells were in equilibrium. Thus, the hand-off arrival rate in the target cell is no greater than the steady state hand-off arrival rate λ_h. During the call admission control period, the hand-off arrival rate in the target cell is a time-varying variable and is very difficult to determine (track). For analytical convenience we use the steady state hand-off arrival rate λ_h as the upper bound of hand-off arrival rate during the call admission control period. Then, the hand-off failure probability that is computed by using the upper bound hand-off rate λ_h is an upper bound on the hand-off failure probability.

Let $P_i(t)$ denote the probability that there are i channels occupied in the cell at time t, where $t \geq T_a$. Developing the basic materials of [1], we can easily show that the state probabilities are governed by a birth-death process and satisfy the differential-difference equations

$$\frac{d}{dt}P_i(t) = (\alpha_{i-1}\lambda_n + \beta_{i-1}\lambda_h)P_{i-1}(t) + \mu P_{i+1}(t) - (\alpha_i\lambda_n + \beta_i\lambda_h + \mu)P_i(t) \qquad (1)$$

Because the duration of the action interval D_a is short, the system may not reach a steady state within D_a. We adapt the well-known Runge-Kutta algorithm [2] to this problem to calculate the numerical value of $P_i(t)$.

We divide the duration of the action interval, D_a, into many equal-size intervals. Let S denote the number of intervals and Δt denote the duration of each interval. We have

$$S \cdot \Delta t = D_a = T_e - T_a \qquad (2)$$

If the interval Δt is small enough, equation (1) can be written as

$$\frac{P_i(t + \Delta t) - P_i(t)}{\Delta t} = (\alpha_{i-1}\lambda_n + \beta_{i-1}\lambda_h)P_{i-1}(t) + \mu P_{i+1}(t) - (\alpha_i\lambda_n + \beta_i\lambda_h + \mu)P_i(t) \qquad (3)$$

Thus, $P_i(t + \Delta t)$ can be expressed as

$$P_i(t + \Delta t) = [(\alpha_{i-1}\lambda_n + \beta_{i-1}\lambda_h)P_{i-1}(t) + \mu P_{i+1}(t) - (\alpha_i\lambda_n + \beta_i\lambda_h + \mu)P_i(t)] \cdot \Delta t + P_i(t) \qquad (4)$$

In this way, $P_i(t)$ at $t = T_a + n\Delta t$ ($n=1, 2, ..., S$) can calculated given $P_i(t)$ at $t = T_a$. Let k denote the index of the iteration. Let $S^{(k)}$ denote the number of small intervals in the kth iteration, and $\Delta t^{(k)}$ denote the duration of small intervals in the kth iteration. The numerical algorithm is shown in Fig. 2 and described as follows:

Algorithm:

Step 1: Let $k=1$. Begin the iteration with the number of small intervals $S^{(1)}$ each interval having a duration, $\Delta t^{(1)}$, where $S^{(1)}\Delta t^{(1)} = D_a$. Let $P_i^{(k)}(t)$ denote state probability of i at the kth iteration. Then, $P_i^{(k)}(t)$ at $t = T_a + n\Delta t$ ($n=1, 2, ..., S^{(k)}$) is calculated by applying the Runge-Kutta method with equation (4). For details of the Runge-Kutta method, readers are referred to [2].

Step 2: Let $k=k+1$. Double the number of small intervals, S, that is $S^{(k)} = 2 \cdot S^{(k-1)}$ and $\Delta t^{(k)} = \frac{1}{2}\Delta t^{(k-1)}$. Using the Runge-Kutta method with equation (4) again, we get $P_i^{(k)}(t)$ at

$t = T_a + n\Delta t^{(k)}$ ($n=1, 2, \ldots, S^{(k)}$). Define ε_{in} ($n=1, 2, \ldots, S^{(k-1)}$) as the relative error

between $P_i^{(k-1)}(T_a + n\Delta t^{(k-1)})$ and $P_i^{(k)}(T_a + 2n\Delta t^{(k)})$. This is given by

$$\varepsilon_{in} = |\, P_i^{(k)}(T_a + 2n\Delta t^{(k)}) - P_i^{(k-1)}(T_a + n\Delta t^{(k-1)})\,| \,/\, P_i^{(k-1)}(T_a + n\Delta t^{(k-1)}) \qquad (5)$$

Step 3: If each ε_{in} ($i=0, 1, \ldots, C, n=1, 2, \ldots, S^{(k-1)}$) is less than a very small number ζ, the

iteration is stopped. Then each $P_i^{(k-1)}(t)$ at $t = T_a + n\Delta t$ ($n=1, 2, \ldots, S^{(k-1)}$) is taken as the

value of $P_i(t)$ at our desired accuracy. We also get the duration of interval $\Delta t = \Delta t^{(k-1)}$ that is

sufficiently small to yield the desired accuracy. (If we take $\zeta = 1 \times 10^{-4}$, the solution will be

correct to within roughly four significant figures.) If the test for ANY of the quantities, ε_{in}, is

not satisfied the iteration is continued by returning to step 2.

There are two important performance measures that result from the call admission control
scheme. One is the probability that a local call that is in progress is preempted at the time of the
train's arrival. This is called the *preemption probability*. The other is the *hand-off failure
probability* during the action interval. Define the state when the BS begins to take call admission
control as the *initial state* of call admission control. Let $P_{pt}(l, D_a)$ denote conditional
preemption probability *given* that the initial state is l and the duration of the action interval is
D_a. This conditional preemption probability is defined as the expectation of the ratio of the
number of preempted calls to the number of calls in progress at the time the train enters the cell.
The expectation counts only those ratios when at least one call is preempted. Let G denote the
maximum number of local calls in the cell so that no local calls will be preempted when the train
enters. In the case under discussion we have, $G = C - C_L$. Then, $P_{pt}(l, D_a)$ is given by

$$P_{pt}(l, D_a) = \sum_{i=G+1}^{C} \frac{i-G}{i} \cdot P_i(T_e) \qquad (6)$$

To provide satisfactory Quality-of-Service to local users, it is required that the preemption

probability, $P_{pt}(l, D_a)$ not exceed some given threshold, say θ.

During the action interval D_a the admission of new calls and hand-off calls will be restricted to accommodate the scheduled arrival. Because of the non-stationarity induced by the train arrival and the onset of admission control, the hand-off failure probability changes with time. Since the failure of hand-off calls is undesirable for local users, our call admission control scheme will keep the *time average* hand-off failure probability (that is, averaged over the action interval) as low as possible and meet the preemption probability requirement. Let P_{ij} denote the probability that the cell of interest is in state i in the jth time interval $[T_a + j\Delta t, T_a + (j+1)\Delta t)$. If we use piecewise linear interpolation to get the value of $P_i(t)$ during the jth interval, P_{ij} is given by

$$P_{ij} = \frac{P_i(T_a + j\Delta t) + P_i(T_a + (j+1)\Delta t)}{2} \tag{7}$$

If the cell is in state i, an arriving hand-off call will fail with a probability of $(1 - \beta_i)$. Let $P_h(j \mid l, D_a)$ denote the conditional hand-off failure probability during the jth interval *given* that the initial state is l and the duration of action interval is D_a. The probability is given by

$$P_h(j \mid l, D_a) = \sum_{i=0}^{C} P_{ij} \cdot (1 - \beta_i) \tag{8}$$

The *time averaged* hand-off failure probability $< P_h(l, D_a) >$ is given by

$$< P_h(l, D_a) > = \frac{1}{S} \sum_{j=0}^{j=S-1} P_h(j \mid l, D_a) \tag{9}$$

(Note: The time average is over the action interval with the given condition that the initial state is l).

V. Optimum Call Admission Control

A. Optimization Goal and Expression

From equation (4), we see that the new call and hand-off arrival rates, λ_n and λ_h respectively, influence the state probabilities only through the weighted sum, Λ_i, given by

$$\Lambda_i = \alpha_i \lambda_n + \beta_i \lambda_h \tag{10}$$

where α_i and β_i are the admission probabilities for new calls and hand-off calls respectively as defined in Section III. So (4) can be written as

$$P_i(t + \Delta t) = [\Lambda_{i-1} P_{i-1}(t) + \mu P_{i+1}(t) - (\Lambda_i + \mu) P_i(t)] \cdot \Delta t + P_i(t) \tag{11}$$

We can see that

$$0 \leq \Lambda_i \leq \lambda_n + \lambda_h, \qquad \text{if } 0 \leq i \leq C - 1 \tag{12}$$

From (11), it can be seen that the state probabilities are determined only by $\Lambda_i = \alpha_i \lambda_n + \beta_i \lambda_h$ (and not α_i and β_i separately). In order to keep the hand-off failure probability as low as possible, (intuitively) hand-off calls should be accommodated as much as possible. So β_i should take the highest possible value. This can be seen from (10) and (11). Let $\alpha_{i\_opt}(\Lambda_i)$ and $\beta_{i\_opt}(\Lambda_i)$ denote the optimal value of α_i and β_i that minimize the hand-off failure probability for a given Λ_i respectively. They are given by

$$\alpha_{i\_opt}(\Lambda_i) = \begin{cases} 0 & \text{if } \Lambda_i \leq \lambda_h \\ (\Lambda_i - \lambda_h)/\lambda_n & \text{if } \Lambda_i > \lambda_h \end{cases} \tag{13}$$

$$\beta_{i\_opt}(\Lambda_i) = \begin{cases} \Lambda_i / \lambda_h & \text{if } \Lambda_i \leq \lambda_h \\ 1 & \text{if } \Lambda_i > \lambda_h \end{cases} \tag{14}$$

For a given initial state l and a given action interval D_a, the admission control policy is to minimize the hand-off failure probability $< P_h(l, D_a) >$ (with respect to $\Lambda_i (0 \leq i \leq C - 1)$) while at the same time keeping the value of preemption probability $P_{pt}(l, D_a)$ below the prescribed constant, θ. Then, the optimization problem can be stated mathematically as follows:

$$\min_{\substack{\Lambda_i \\ 0 \leq i \leq C-1}} \quad < P_h(l, D_a) > \text{ and also assure } P_{pt}(l, D_a) \leq \theta,$$

where $\Lambda_i \in R$ and $0 \leq \Lambda_i \leq \lambda_n + \lambda_h$, $\alpha_i = \alpha_{i\_opt}(\Lambda_i)$ and $\beta_i = \beta_{i\_opt}(\Lambda_i)$ (15)

Many optimization methods require knowledge of the derivative(s) of the objective function or at least numerical evaluation of the derivative(s). However, these methods are not applicable in this case because the expressions for $P_{pt}(l, D_a)$ and $< P_h(l, D_a) >$ contain $P_i(t)$, which may not be expressible in closed-form. Thus, expressions for derivatives of $P_{pt}(l, D_a)$ and $< P_h(l, D_a) >$ are unavailable and even the numerical evaluation of the derivatives

of $P_{pt}(l,D_a)$ and $<P_h(l,D_a)>$ are difficult to obtain. In order to solve the optimization problem to a given accuracy, at first we quantize the value of Λ_i into small steps. Then, the optimization problem in (15) can be converted into a nonlinear integer programming problem. The nonlinear programming problem can be solved using a step-by-step increment method that does not require the knowledge of the derivative of objective functions. In this way, we can circumvent the difficulty of finding the derivative of the objective function. The details are given below:

Suppose that M is a large integer. Let m_i denote the quantization level for Λ_i, where m_i is an integer and $0 \leq m_i \leq M$. Let $\Lambda_i(m_i)$ denote the quantized value of Λ_i. Since $0 \leq \Lambda_i \leq \lambda_n + \lambda_h$, we can express $\Lambda_i(m_i)$ as

$$\Lambda_i(m_i) = \frac{m_i}{M}(\lambda_n + \lambda_h) \tag{16}$$

If M is sufficiently large, the optimization problem in (15) can be written as the following nonlinear integer-programming problem

$$\min_{\substack{m_i \\ 0 \leq i \leq C-1}} P_h(l,D_a) \text{ and also assure that } P_{pt}(l,D_a) \leq \theta,$$

where $m_i \in I$ and $0 \leq m_i \leq M$, $\alpha_i = \alpha_{i\_opt}(\frac{m_i}{M}(\lambda_n + \lambda_h))$, $\hat{a}_i = \beta_{i\_opt}(\frac{m_i}{M}(\lambda_n + \lambda_h))$ (17)

Let $\overline{m}$ be a vector whose components are $(m_0, m_1, ..., m_{C-1})$. It is called the admission decision vector. Let $\overline{m}^0$ denote the initial guess vector and $\overline{m}^1, \overline{m}^2, ..., \overline{m}^m$ denote the subsequent refined vectors. Let $P_h(\overline{m}^k)$ and $P_{pt}(\overline{m}^k)$ denote the hand-off failure probability and the preemption probability respectively when the admission decision vector is $\overline{m}^k$. Here arguments of initial state l and the duration of action interval D_a are omitted as default to make the expression concise. Let $\overline{e(i)}$ denote the ith unit vector.

$$\overline{e(i)} = (e_0, e_1, ..., e_{C-1}) \tag{18}$$

where $e_n = 1$ only if $n = i$, otherwise $e_n = 0$. The optimization algorithm diagram is shown in Fig. 3 and described as follows.

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B. Optimization Algorithm

A benchmark policy of the call admission control scheme is $m_i = 0$ ($0 \leq i \leq C-1$), which we call the "closed-gate" policy. This policy corresponds to the call admission control policy for which no new or hand-off calls are admitted during the admission control period. The benchmark policy is used in the optimization algorithm to test whether the optimization objective is achievable for specific initial state and action time interval D_a.

Step 1: If the preemption probability when the closed-gate policy is used is greater than the preemption probability requirement θ, then optimization constraint can not be met and the admission parameters $\alpha_i = \beta_i = 0$, $0 \leq i \leq C-1$ are taken as the optimized parameters in this case. Otherwise, there exists a set of m_i ($0 \leq i \leq C-1$) that can achieve the optimization objective function in (17) and the algorithm proceeds with step 2.

Step 2: Select an M that is sufficiently large (for example, $M = 1 \times 10^4$). Set $m_i^0 = 0$ ($0 \leq i \leq C-1$). Let $k=0$.

Step 3: Search through $0 \leq i \leq C-1$ and determine the index i that maximizes $[P_h(\vec{m}^k) - P_h(\vec{m}^k + \overrightarrow{e(i)})]$ while at the same time the constraint $P_{pt}(\vec{m}^k + \overrightarrow{e(i)}) \leq \theta$ is still met. Then, update the admission decision vector as $\vec{m}^{k+1} = \vec{m}^k + \overrightarrow{e(i)}$. Then, increment the index k by 1.

Step 4: If the index i that satisfies the requirement $P_{pt}(\vec{m}^k + \overrightarrow{e(i)}) \leq \theta$ and $P_h(\vec{m}^k) > P_h(\vec{m}^k + \overrightarrow{e(i)})$ can not be found for $0 \leq i \leq C-1$, the search terminates and the optimal admission decision vector is found to be $\vec{m}^k$. We denote the optimal admission decision vector by $\vec{m}_{opt}$. Otherwise, go back to step 3 and continue the search.

VI. Strategies for Two Typical Scenarios of Scheduled Priority Arrival

A. Scenario 1: A single train enters and leaves the cell

At D_a time units before the arrival (i.e., at the beginning of the action interval), the BS checks the state of the cell. Suppose that the initial state is i. Recall from Section II that the value of D_a is known. If the state i is among the states G, $G+1$, ..., C, the BS will take call admission control that is optimized in Section V with initial state i and action interval D_a. Remember that $P_{pt}(i, D_a)$ and $< P_h(i, D_a) >$ are respectively, the resulting preemption probability and hand-off failure probability given the initial state i and the duration of the action interval D_a. The value of $P_{pt}(i, D_a)$ and $< P_h(i, D_a) >$ are given in (6) and (9) in Section IV.

If the state i is among 0 to G-1, the BS will wait until the state of the cell increases to G to initiate call admission control. But with some corresponding probability, the state may increase to G at any time instant. This requires the BS to be able to compute the optimized call admission parameters in real time at any time instant. The computation of the optimized parameters is time-consuming. It may be difficult for the BS to finish the computation in real time. Therefore, we propose a simplified method in which the BS checks the state of the cell after every period. Let D_m denote the duration of one period. The value of D_m is a design parameter and should be chosen properly so that the probability that the state increases to higher than G in the duration of one period is low. We assume that

$$D_a = L \cdot D_m, \; L \text{ is an integer} \tag{19}$$

The optimized call admission control parameters for states G, $G+1$, ..., C and possible remaining time $D_a - kD_m$ $(1 \leq k \leq L-1)$ can be calculated beforehand and stored in the BS. So the BS does not need to calculate the optimized control parameters in real time when call admission control is initiated.

Then, if the initial state i is less than G, the BS will check the state of the cell after D_m time units to see if the state is in G or higher at that time. If after D_m time units the state is in G or higher, the BS will initiate call admission control with optimized parameters. Otherwise, the

BS will check the state another D_m time units later. The same procedure is repeated for each following period until either the state is in G or higher at the end of some period or the train enters the cell.

Let s_k ($k=1, 2, ..., L$) denote the state of the cell after the kth period on condition that the call admission control was not initiated after the $(k-1)$th period. Let $P_s(j \mid h, D_m)$ denote the probability that the state of the cell increases from h to j after D_m time units. For simplicity of presentation, we categorize the states into two more general states. If the number of calls in progress in the cell is less than G, the cell is in the *light* state. Otherwise, the cell is in the *heavy* state. Suppose that the state of the cell *first* comes into a *heavy* state after k periods (each of duration D_m time units). For a particular state s_k ($s_k \geq G$), the BS will take call admission control with the state s_k and the remaining time $D_a - kD_m$. The resulting preemption probability and hand-off probability are $P_{pt}(s_k, D_a - kD_m)$ and $< P_h(s_k, D_a - kD_m) >$ respectively. These can be calculated by using the numerical method given in Section IV. Let $p_{pt}(k)$ and $p_h(k)$ denote the weighted resulting preemption probability and hand-off failure probability respectively for the case that the cell is in heavy state at the end of the kth period.

When $k=1$, for a particular state $s_1(s_1 \geq G)$, $P_s(s_1 \mid i, D_m)$ is the probability that the state of the cell increases from i to s_1 after D_m time units and $P_{pt}(s_1, D_a - D_m)$ is the resulting preemption probability. Therefore, the weighted resulting preemption probability for the case that the cell is in heavy state after the first period, $p_{pt}(1)$, is given by

$$p_{pt}(1) = \sum_{s_1=G}^{C} P_s(s_1 \mid i, D_m) \cdot P_{pt}(s_1, D_a - D_m) \tag{20}$$

When $1 < k < L$, it means that the cell was not at heavy state at the end of 1st, 2nd, ... and $(k-1)$th periods but the cell is in the heavy state after the kth period. For a particular state s_k, the corresponding probability is $\sum_{s_1=0}^{G-1} P_s(s_1 \mid i, D_m) \cdot \sum_{s_2=0}^{G-1} P_s(s_2 \mid s_1, D_m) \cdots \sum_{s_{k-1}=0}^{G-1} P_s(s_{k-1} \mid s_{k-2}, D_m) \cdot P_s(s_k \mid s_{k-1}, D_m)$ and resulting preemption probability is $P_{pt}(s_k, D_a - kD_m)$. Therefore, the weighted resulting

preemption probability for the case that the cell is in heavy state at the end of the kth period, $p_{pt}(k)$, is given by

$$p_{pt}(k) = \sum_{s_1=0}^{G-1} P_s(s_1|i,D_m) \cdot \sum_{s_2=0}^{G-1} P_s(s_2|s_1,D_m) \cdots \sum_{s_{k-1}=0}^{G-1} P_s(s_{k-1}|s_{k-2},D_m) \cdot \sum_{s_k=G}^{C} P_s(s_k|s_{k-1},D_m) \cdot P_p(s_k,D_a-kD_m) \quad (21)$$

When $k=L$, the BS does not need to check the state of the cell after the Lth period, because the train enters the cell at this time. For a particular state s_L ($s_L \geq G$), the resulting preemption probability is $\dfrac{s_L-G}{s_L}$. Therefore, $p_{pt}(L)$ is given by

$$p_{pt}(L) = \sum_{s_1=0}^{G-1} P_s(s_1|i,D_m) \cdot \sum_{s_2=0}^{G-1} P_s(s_2|s_1,D_m) \cdots \sum_{s_{L-1}=0}^{G-1} P_s(s_{L-1}|s_{L-2},D_m) \cdot \sum_{s_L=G}^{C} P_s(s_L|s_{L-1},D_m) \cdot \left(\frac{s_L-G}{s_L}\right) (22)$$

Similarly, we can find the weighted hand-off probability (i.e., $p_h(k)$) for the case in which the cell is in a heavy state at the end of the kth period. When $k=1$, $p_h(1)$ is given by

$$p_h(1) = \sum_{s_1=G}^{C} P_s(s_1|i,D_m) \cdot <P_h(s_1,D_a-D_m)> \quad (23)$$

When $1<k<L$, $p_h(k)$ is given by

$$p_h(k) = \sum_{s_1=0}^{G-1} P_s(s_1|i,D_m) \cdot \sum_{s_2=0}^{G-1} P_s(s_2|s_1,D_m) \cdots \sum_{s_{k-1}=0}^{G-1} P_s(s_{k-1}|s_{k-2},D_m) \cdot \sum_{s_k=G}^{C} P_s(s_k|s_{k-1},D_m) \cdot <P_h(s_k,D_a-kD_m)> (24)$$

When $k=L$, it means that the BS did not take any call admission control during the action interval D_a. Let P_{sh} denote hand-off failure probability when the cell is in steady states. The value of P_{sh} can be calculated by using our previous work [3-5]. In this case, the resulting hand-off failure probability will take the value of P_{sh}. Therefore, $p_h(L)$ is given by

$$p_h(L) = \sum_{s_1=0}^{G-1} P_s(s_1|i,D_m) \cdot \sum_{s_2=0}^{G-1} P_s(s_2|s_1,D_m) \cdots \sum_{s_{k-1}=0}^{G-1} P_s(s_{k-1}|s_{k-2},D_m) \cdot \sum_{s_k=G}^{C} P_s(s_k|s_{k-1},D_m) \cdot P_{sh} \quad (25)$$

Remember that in the Section IV, $P_{pt}(i,D_a)$ and $<P_h(i,D_a)>$ are defined only for $G \leq i \leq C$ because the BS will begin call admission control at D_a time units before the arrival only if the initial state i is among G and C. Here, we use the notations $P_{pt}(i,D_a)$ and $<P_h(i,D_a)>$, $0 \leq i \leq G-1$, denote the resulting average preemption probability and hand-off

probability respectively if the state of the cell is i ($0 \le i \le G-1$) at D_a time units before the arrival. $P_{pt}(i, D_a)$ and $< P_h(i, D_a) >, 0 \le i \le G-1$, are the sum of the weighted preemption probability and hand-off probability for every possible case respectively. They are given by

$$P_{pt}(i, D_a) = \sum_{k=1}^{L} p_{pt}(k), \ 0 \le i \le G-1 \tag{26}$$

$$< P_h(i, D_a) >= \sum_{k=1}^{L} p_h(k), \ 0 \le i \le G-1 \tag{27}$$

When the train leaves the cell, the C_L channels that the train uses during the time that it is in the cell will be released and made available for use of local calls. After some time, the cell will reach statistical equilibrium as before. (The case that the arrival of trains is sufficiently frequent so that the cell may never reach statistical equilibrium is included in the scenario 2).

B. Scenario 2: Two trains enter and leave the cell

We consider the scenario that a single train enters a cell and another train enters the cell before the first train departs from the cell. We assume that each train will notify its arrival to the BS D_n time units before its arrival and spend D_{cell} time units in the cell. Let D_d denote the time difference between the arrivals (or notifications) of the first train and the second train. The following cases with regard of the difference of the arrival times are considered:

Case 1: The second train enters the cell more than D_n time units after the first train leaves.

In this case, $D_d > D_n + D_{cell}$ and the timing is shown in Fig. 5. This case is equivalent to that in which two single trains enter and leave a cell separately as in scenario 1. The BS will take call admission control for the two trains respectively as in the scenario 1.

Although the cell may not be in the statistical equilibrium state when the second train arrives, but the performance analysis of the arrival of the second train is not affected. The reason is that performance of the call admission control is determined only by the action interval and the initial state (NOT state probability). The system performance analysis for the arrival of both trains is exactly the same as the performance analysis for a single train as in the scenario 1.

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Case 2: The second train is scheduled to enter the cell within D_n time units after the first train leaves the cell.

In this case $D_{cell} \leq D_d \leq D_n + D_{cell}$ and the timing is shown in Fig. 6. At first, the BS controls the incoming traffic in the cell using the strategy for scenario 1 as if there is only one train (the first train) arrival until the first train leaves the cell. Upon the first train's leaving, all the channels used by the LAN on the train will be released and the number of channels occupied by local users is at most G. If $D_d > D_a + D_{cell}$, the BS will wait until D_a time units before the arrival of the second train then check the state of the cell and take proper control action according to the state as in scenario 1. If $D_d \leq D_a + D_{cell}$, the BS will immediately check the state of cell. If the state is G, the BS will take call admission control that is optimized in Section V with the initial state G and the duration of the action interval D_a. If the state is between 0 and G-1, the BS will check the state of the cell every D_m time units and take optimized call admission control as in the scenario 1.

The performance analysis of the first train is exactly the same as the performance analysis of a single train. If $D_d > D_a + D_{cell}$, the performance analysis of the second train is also the same as the performance analysis of a single train. If $D_d \leq D_a + D_{cell}$, the performance analysis of the second train is similar to the performance analysis of a single train except that in (6), (9) and (20-27) $D_d - D_{cell}$ will replace D_a and in (6) and (9) l will only take the value of G.

Case 3: The second train is scheduled to enter the cell before the first train leaves. At the time that the second train notifies the BS of its arrival, the BS has not yet initiated any call admission control action.

In this case, $D_d < D_{cell}$ and $D_d < D_n - D_a$. The timing is shown in Fig. 7. During the interval of $D_{cell} - D_d$ time units, two trains are simultaneously present in the cell of interest. So $2C_L$ channels will be required to support the LANS on the trains in this time interval. Let G' denote the maximum number of local calls in the cell so that no local calls will be preempted when the second train enters. Here, G' equals to $C - 2C_L$. After receiving the notification of the second train, beginning a suitable time interval, denoted by D_a', before the arrival of the first

train, the BS will check the state of the cell and take proper call admission control for both trains. It is obvious that the notification time D_n should be no less than $D_a' + D_d$.

Remember that Δt is the duration of interval that is sufficiently small to get desired accuracy of state probabilities $P_i(t)$. Let S' denote the number of intervals in the duration of $D_a' + D_d$. It is given by

$$S' = (D_a' + D_d) / \Delta t \tag{28}$$

Let T_a' denote the time instant that the BS begins to check the state of the cell and take control. State probability $P_i(T_a' + j\Delta t), j=0, 1, 2, \ldots, S'$ can be calculated by using the numerical solution in the Section IV. Remember that the first train will enter the cell at $t=T_e$ and the second train will enter the cell at $t=T_e + D_d$. Let $P_{pt1}(l, D_a')$ and $P_{pt2}(l, D_a')$ denote the preemption probabilities at the first train's arrival and second train's arrival respectively given that the initial state is l and the duration of the action interval is D_a'. Similar to preemption probability given in (6), they are given by

$$P_{pt1}(l, D_a') = \sum_{i=G+1}^{C} \frac{i-G}{i} \cdot P_i(T_e) \tag{29}$$

$$P_{pt2}(l, D_a') = \sum_{i=G+1}^{C} \frac{i-G}{i} \cdot P_i(T_e + D_d) \tag{30}$$

Let P_{ij}' denote the value of $P_i(t)$ during the interval $[T_a' + j\Delta t, T_a' + (j+1)\Delta t)$. If the piecewise linear interpolation is used, P_{ij}' is given by P_{ij}'

$$P_{ij}' = \frac{P_i(T_a' + j\Delta t) + P_i(T_a' + (j+1)\Delta t)}{2} \tag{31}$$

Let $P_h'(j|l, D_a')$ denote the hand-off failure during the interval $[T_a' + j\Delta t, T_a' + (j+1)\Delta t)$ given that the initial state is l and the duration of the action interval is D_a'. It is given by

$$P_h'(j|l, D_a') = \sum_{i=0}^{C} P_{ij}' \cdot (1 - \beta_i) \tag{32}$$

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The time average hand-off failure probability given that the initial state is l and the duration of the action interval is $D_a{}'$, $<P_h{}'(l,D_a{}')>$, is expressed as

$$<P_h{}'(l,D_a{}')>=\frac{1}{S'}\sum_{j=0}^{j=S'-1}P_h{}'(j\,|\,l,D_a)\qquad(33)$$

Then the optimization problem is equivalent to finding a suitable set of m_i ($0\le i\le C-1$) to meet the following goal:

$$\min_{\substack{d_i\\G\le i\le C-1}} <P_h{}'(l,D_a{}')> \text{ and also assure } P_{pt1}(l,D_a{}')\le\theta \text{ and } P_{pt2}(l,D_a{}')\le\theta$$

where $m_i\in I$ and $0\le m_i\le M$, $\alpha_i=\alpha_{i\_opt}(\frac{m_i}{M}(\lambda_n+\lambda_h))$, $\hat{a}_i=\beta_{i\_opt}(\frac{m_i}{M}(\lambda_n+\lambda_h))$ (34)

The detailed optimization procedure is the same as in Section V.

After receiving the notification of the second train, the BS will check the state of the cell beginning $D_a{}'$ time units before the arrival of the first train. If the initial state i is among the states G', $G'+1$, ..., C, the BS will take call admission control that is optimized with the constraints and objective functions in (34) and with the initial state i and the duration of the action interval $D_a{}'$.

If the BS finds that the current state is between 0 and $G'-1$, it will check the state of the cell after every D_m time units until at the end of some period the number of occupied channels in the cell becomes no less than G'. Suppose that at the end of the kth D_m time units the state of the cell increases to s_k ($s_k\ge G$). Then the BS will take call admission control that is optimized in (34) with the initial state s_k and the duration of the action interval D_a-kD_m.

The performances of the arrival of the two trains are analyzed in terms of $P_{pt1}(l,D_a{}')$, $P_{pt2}(l,D_a{}')$ and $<P_h{}'(l,D_a{}')>$ which are defined in (29-30) and (33). The analysis is carried out similarly as in the performance analysis of the scenario 1. The only differences are that here parameter G' will replace G, S' will replace S and $D_a{}'$ will replace D_a in the scenario 1.

Case 4: The second train is scheduled to enter the cell before the first train leaves. At the time that the second train notifies the BS of its arrival, the BS has already initiated call admission control for the first train.

In this case, the interval durations are related by $D_n - D_a < D_d < D_{cell}$ and the timing is shown in Fig. 8. Upon receiving notification of the second train, the BS will stop the call admission control for the first train, check the state of the cell, and then apply corresponding admission control according to *exactly the same* criteria as in case 3. However, as we discussed in order to meet the performance requirement, D_n has to be chosen greater than D_a'. Remember that D_a' is the action interval to accommodate the arrival of two trains and is much larger than D_a, (the action interval to accommodate the arrival of a single train). Since D_{cell} is small, we have $D_n > D_a' > D_a + D_{cell}$. Later on in numerical results, this will be verified. This case will not happen in practical systems at all. So the performance of this case is not analyzed at all.

In all the four cases, when the trains leave the cell the channels that it uses during the stay will be released and available for use of other train or local calls. After sufficiently long time, the cell will go to statistically equilibrium state as before.

VII. Numerical Results

The selection of suitable fixed action time D_a, D_a' and a suitable fixed notification time, D_n, is very important to the overall performance of the system. In this section, we examine the performance of different scenarios of the system with different D_a, D_a' and D_n. In the calculations, we take the total number of channels in a cell, C, to be 25, and the number of channels that are required by the service of a single train, C_L, to be 7. We take the mean duration of an unencumbered session, $1/\mu$, to be 180 sec, the mean dwell time of a platform in a cell, $1/\mu_D$, to be 500 sec, and the new call origination rate in the cell, λ_n, to be 0.11 calls/sec.

Using our previous framework, we can calculate the value of the hand-off arrival rate in a cell, λ_h. It is 0.01873 calls/sec. For the details for calculation of λ_h, readers are referred to [3]-[5]. We assume that the train will stay in the cell for 2 minutes, that means D_{cell} is 120 sec.

A. Scenario 1: A single train enters and leaves the cell

For the scenario that a single train enters and leaves the cell, we calculate the preemption probability and *average* hand-off failure probability for the cell with different action interval D_a and different initial states. The preemption probabilities and average hand-off failure probabilities for different initial states are plotted as functions of action interval D_a in Figs. 9 and 10 respectively. In the figures, *IS* denotes initial state. We can see that in Figs. 9 and 10 for a given initial state, the preemption probability and the *average* hand-off failure probability decrease as the action interval D_a increases. We can also see that for a given action interval, the larger the initial state is, the larger the preemption probability and *average* hand-off failure probability are. This is because that for larger initial state and shorter action interval duration the BS needs to take more stricter call admission control to make sure the preemption probability meets the requirement θ. Stricter call admission control will result in a larger preemption probability and a larger *average* hand-off failure probability.

We also noticed that if the action interval is too short the requirement of preemption probability may not be met and the *average* hand-off failure probability will be unacceptably high. For example, we consider the performance of the system when the initial state is 25 and the action interval is 100 seconds. From Figs. 9 and 10 we can see that the preemption probability is 1.05%, which exceeds the maximum allowed value of 1%, and he average hand-off failure probability is 86.59%, which is unacceptably high.

Choice of an appropriate action interval duration D_a considers two aspects. First, we require that the preemption probability cannot exceed the requirement of 1% and the average hand-off failure probability should be as low as possible. Second, we require that the action interval duration should be as short as possible. Owing to the trade-off between the average hand-off failure probability and the action interval duration, a compromise between the two factors was made. We chose D_a to be 300 sec.

B. Scenario 2: Two trains enter and leave the cell

As discussed in the Section VI, in case 1 the performance of both trains are the same as in the scenario that a single train enters and leaves the cell. Therefore, the performance plotted in Fig. 9 and 10 are also the performance for the case 1.

In the case 2, the performance when the first train enters and leaves the cell is the same as the scenario of a single train. If $D_d > D_a + D_{cell}$, the performance when the second train enters and leaves the cell is also the same as the scenario of a single train. If $D_d \leq D_a + D_{cell}$, the performance when the second train enters and leaves the cell is similar to the performance of the scenario of a single train except that the *actual* action interval $D_d - D_{cell}$ is less than D_a and initial state is at most G. This means that the performance of this case corresponds to the curves where action interval is less than 300 seconds and initial state is no more than 18 in Fig. 9 and 10. Because the initial state is at most G, no matter how small $D_d - D_{cell}$ is, the requirement of preemption probability can always be met.

In the calculation for case 3, we found that the preemption probability at the first train's arrival is very small and negligible when the preemption probability at the second train's arrival meet the requirement of 1%. When the second train enters the cell, the number of channels required by the trains is $2C_L$. When the first train enters the cell, only C_L channels are required by the train. The admission parameters are optimized to make the preemption probabilities at both the first and second train's arrival meet the requirement. Because the arrival time difference between the trains is small, the optimized result is that the preemption probability at the arrival of the first train is very small and the preemption probability at the arrival of the second train meet the requirement of 1%.

Thus, we only consider the preemption probability at the arrival of the second train and plot the preemption probability at the arrival of the second train and average hand-off probability as functions of initial states in Figs. 11 and 12 respectively. We observe the similar trends as in Figs. 9 and 10. The reason is that because preemption probability at the arrival of the first train is very small and negligible then the case 3 is similar to the case that a single train with a demand of $2C_L$ channels enters the cell.

The criteria of choosing the action interval duration for arrival of two trains, $D_a{}'$, is the same as the criteria for a single train. We compromise between factors of the preemption probability, the hand-off failure probability and the action interval duration, and choose $D_a{}'$ to be 540 sec. Because the system is a causal system, the notification interval D_n has to be larger than $D_a{}'$. The value of $D_a + D_{cell}$ equals 420 sec. Therefore, D_n satisfies the condition that $D_n > D_a{}' > D_a + D_{cell}$. This means that the case 4 in the scenario 2 can not happen in such a system, which verifies our discussion of the case 4 of the scenario 2 in the Section VI.

VIII. Conclusions

We have considered strategies to accommodate *scheduled demand changes* brought by mass transportation vehicles in wireless communication systems. We modeled the system by a birth-death process and proposed a strategy in which the BS uses call admission control that assigns resources in anticipation of these *scheduled demand changes*. We defined the preemption probability at the arrival of the train and the *average* hand-off failure probability during the call admission control as the performance measures of the accommodation strategy. The call admission control parameters are optimized with the preemption probability as the constraint and the *average* hand-off failure probability as the object function. In the scenario that a single train enters and leaves the cell, the BS will take call admission control *immediately* if the initial state is *heavy*. If the initial state is *light*, the BS will check the state of the cell every D_m time units and take control if (and when) it finds that the state is *heavy*. In the scenario that two trains enter and leave the cell, the BS will take different actions according to the time difference between of the arrivals of the two trains. If the two trains will not be simultaneously present in the cell, the BS will take the same call admission control for each of the two trains as in the scenario of a single train — but in some cases the range of initial state and action interval will respectively differ from the single train case. If the two trains will be present simultaneously, the BS will take similar call admission control action as in the scenario of a single train. However, the BS will begin to check the state of cell earlier than in the single train scenario and the call

admission parameters are optimized using an objective function that is based on the traffic load of two trains instead of a single train.

The performance of the accommodation strategy was analyzed and numerical results were calculated for illustrative scenarios. From the numerical results, we can see that by using the proposed accommodation strategy the BS can accommodate *scheduled traffic load increase* caused by mass transportation vehicles and at the same time guarantee performance requirement of the local users. Thus, we conclude that the accommodation strategy can accommodate *scheduled demand changes* brought by mass transportation vehicles into wireless communication systems successfully.

IX. References

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[5] S. S. Rappaport, and C. Purzynski, "Prioritized resource assignment for mobile cellular systems with mixed services and platform types," *IEEE Trans. Veh. Technol.*, Vol. 45, No. 3, Aug. 1996.
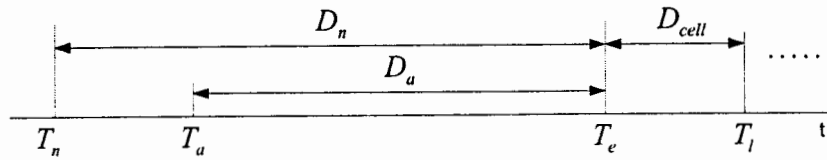
Fig. 1: Timing of the call admission strategy.
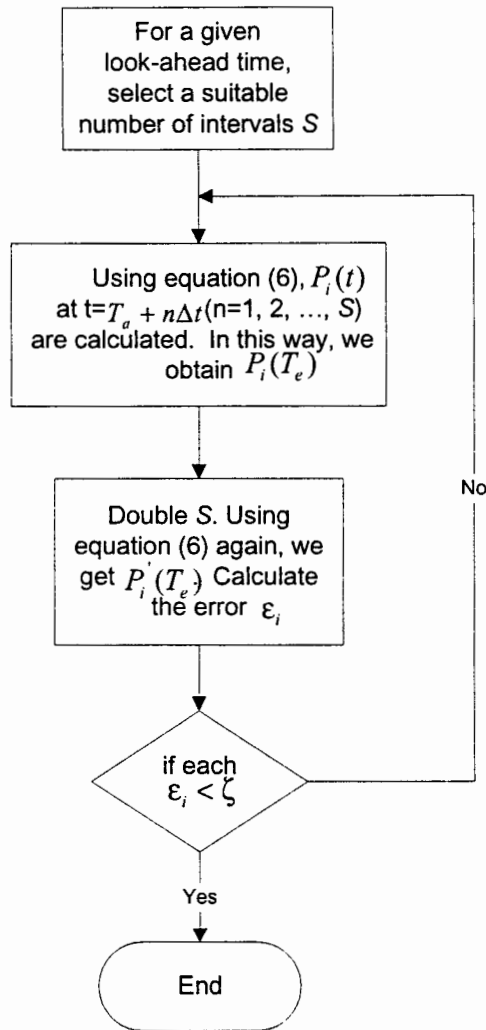
Fig. 2: Algorithm to calculate the numerical solution of state probabilities.
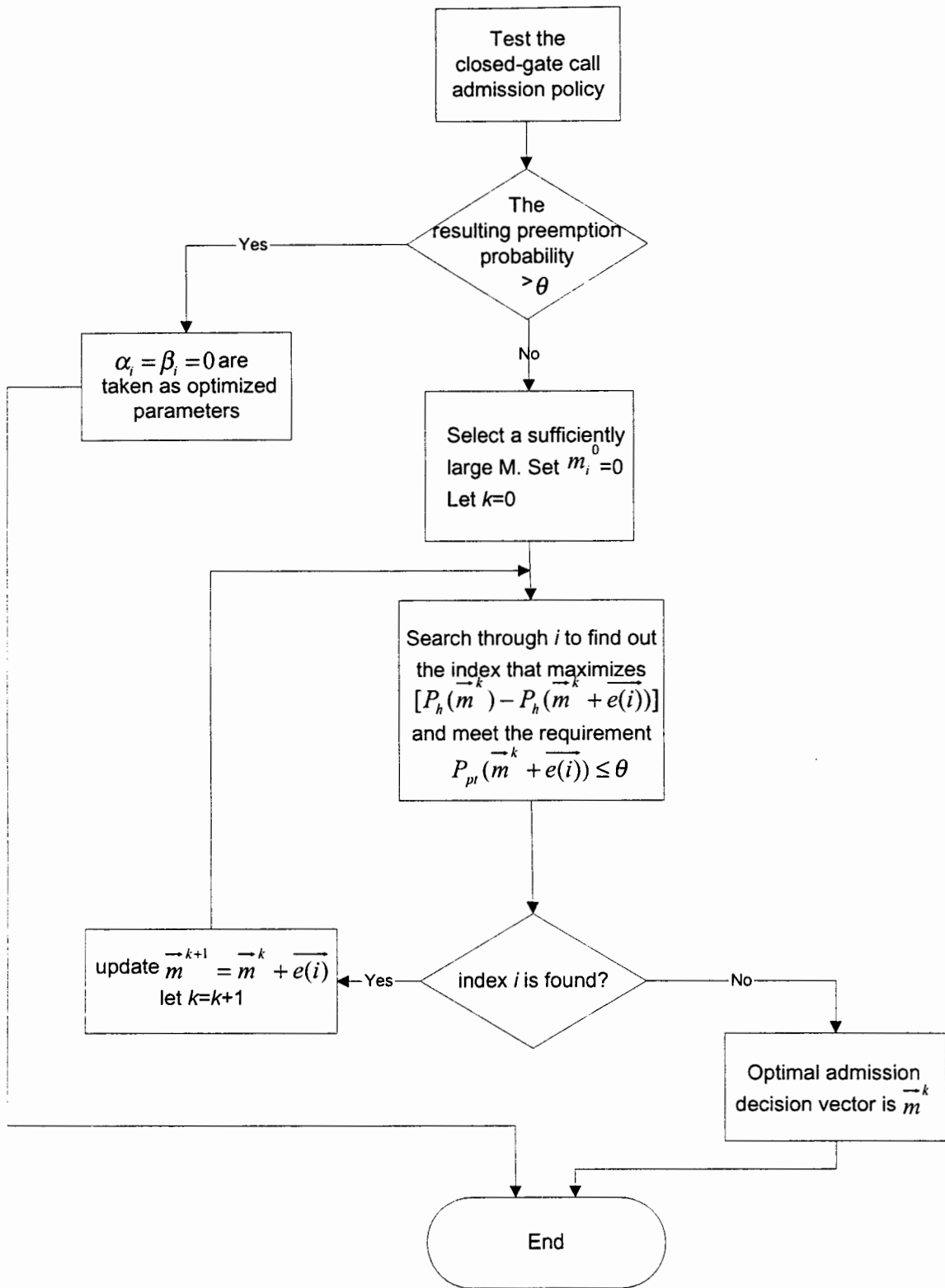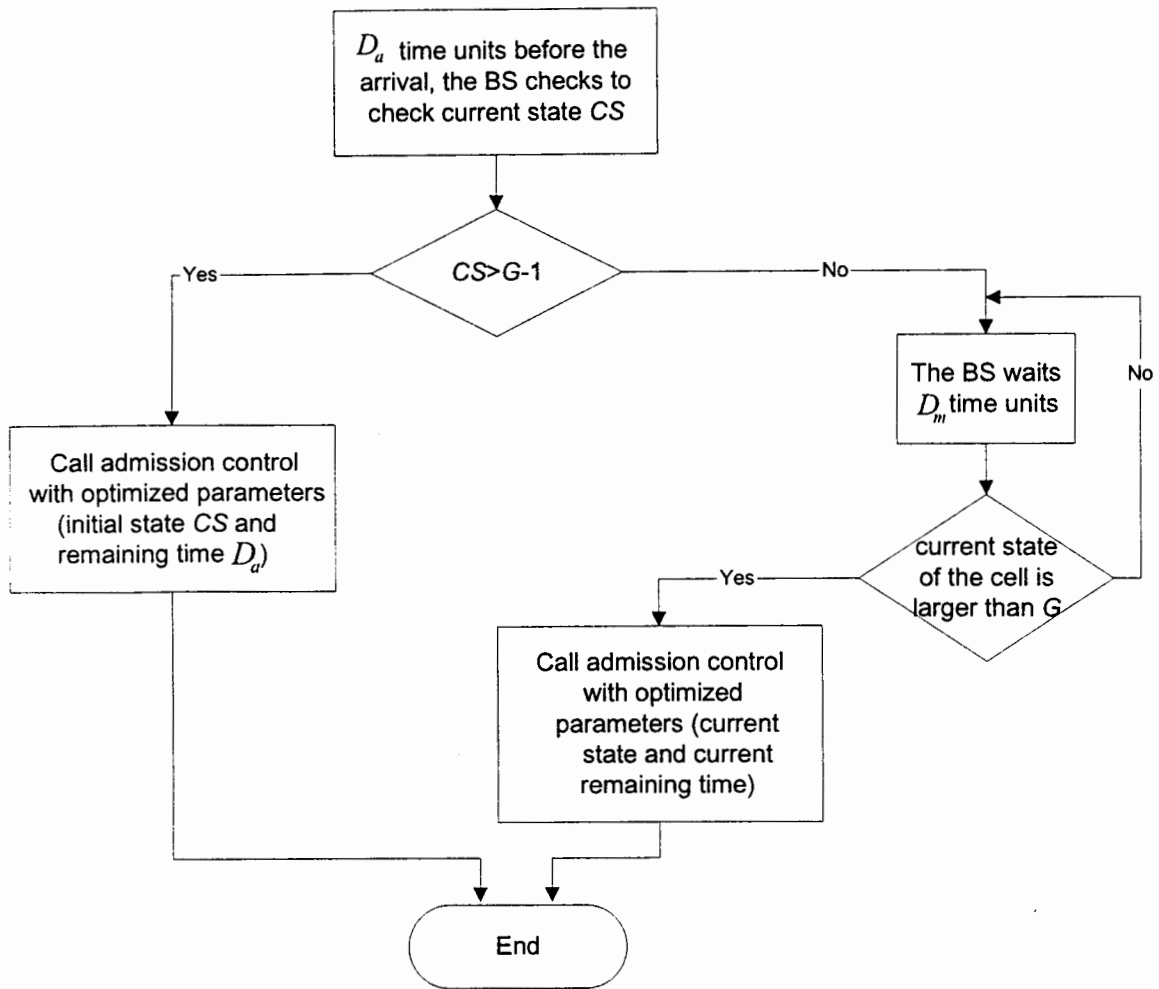
Fig. 3: Optimization Algorithm Diagram.

Fig. 4: The monitoring process and corresponding control actions.
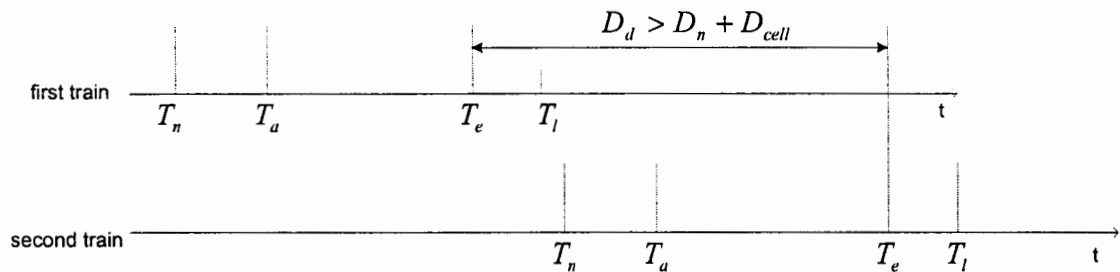

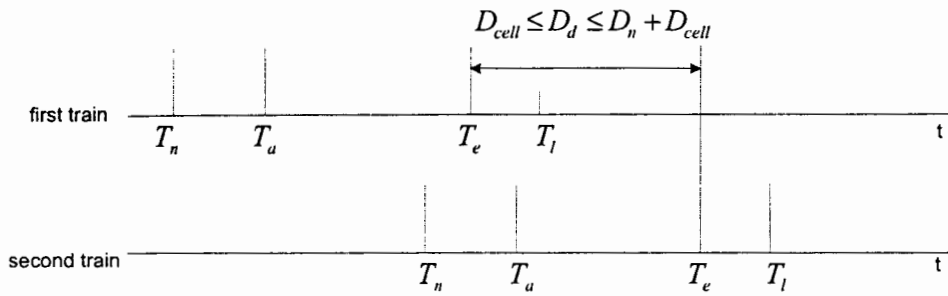Fig. 5: Timing of case 1 in scenario 2.
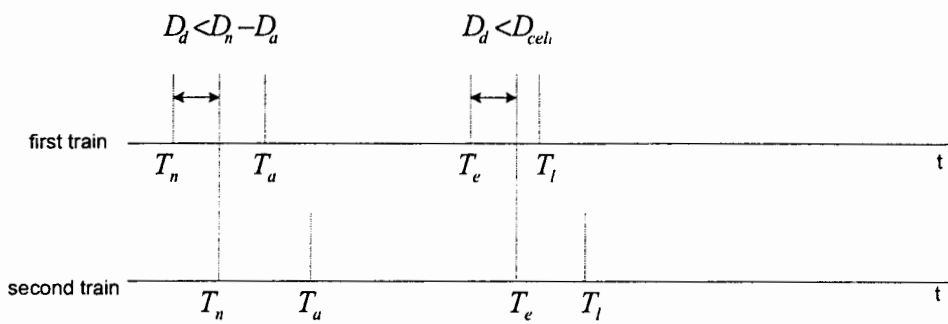
Fig. 6: Timing of case 2 in scenario 2.
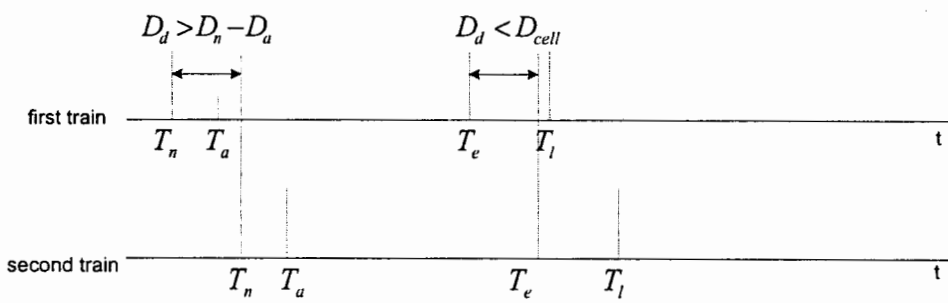

Fig. 7: Timing of case 3 in scenario 2.
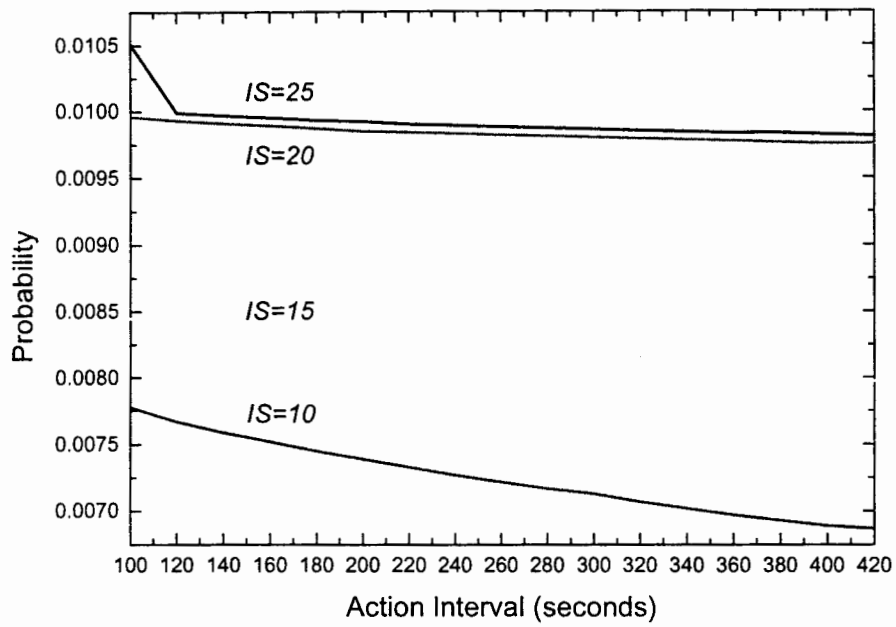

Fig. 8: Timing of case 4 in scenario 2.
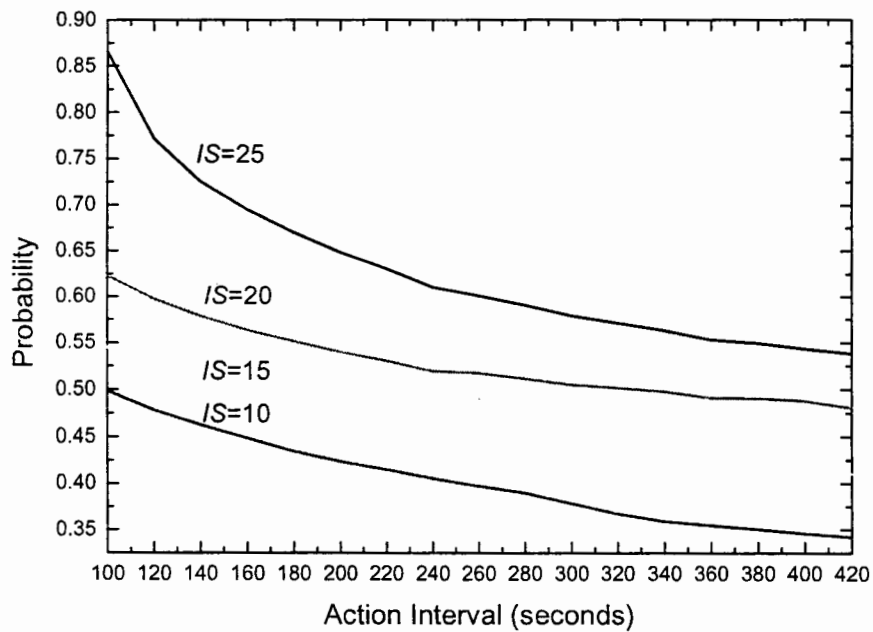
Fig. 9: Preemption probability for scenario 1.

Fig. 10: Average hand-off failure probability for scenario 1.
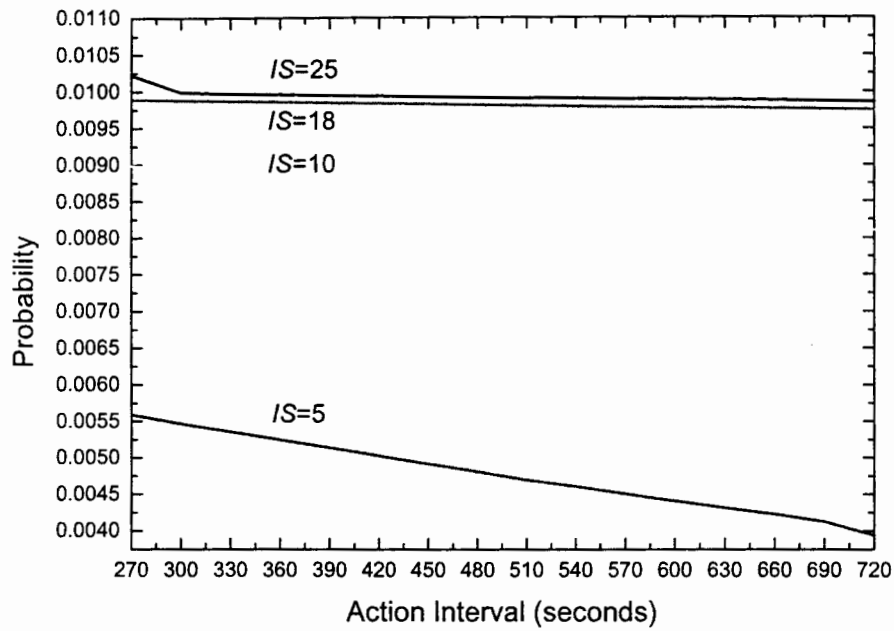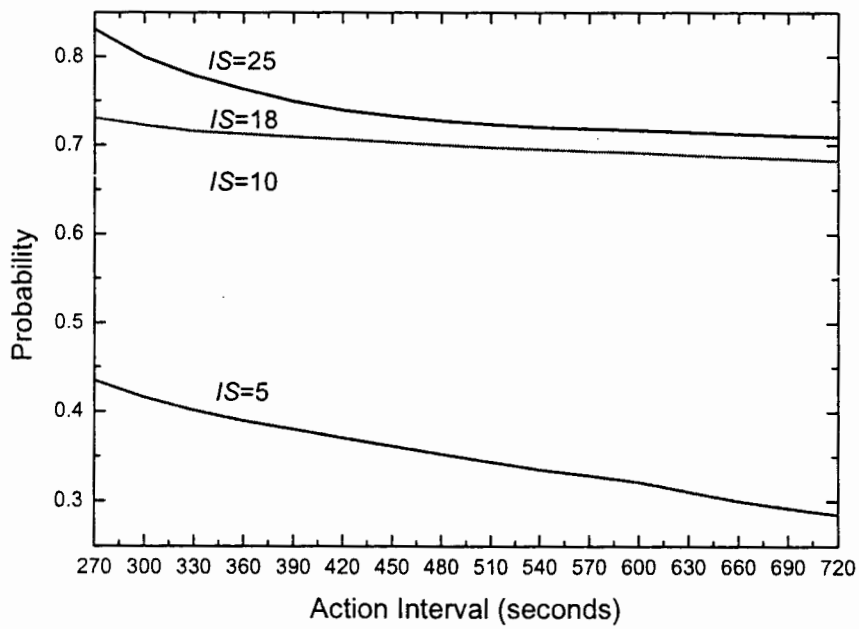
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Fig. 11: Preemption probability for case 3 of scenario 2.

Fig. 12: Average hand-off failure probability for case 3 of scenario 2.