# TECHNICAL RESEARCH REPORT

## Optimization of Connection-Oriented, Mobile, Hybrid Network Systems

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# OPTIMIZATION OF CONNECTION-ORIENTED, MOBILE, HYBRID NETWORK SYSTEMS

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## Abstract

*In this paper we consider the extension of a cellular system by means of satellite channels. Specifically, we consider an area covered by a number of cells, that is also covered by a number of spot-beams. We consider connection-oriented service, and call durations are assumed to be exponentially distributed. Also, users are mobile and, as such, they may cross cell and/or spot-beam boundaries, thus necessitating hand-offs. We incorporate the possibility of call-dropping due to unsuccessful hand-off attempts, in addition to satellite propagation delays along with the probability of new call blocking and formulate a specific cost function that must be ultimately minimized. The minimization is to be carried out by choosing (i) the optimal split of the total number of channels between the cellular and the satellite systems, and (ii) the call admission and assignment policy, subject to the constraints of a demand vector that consists of an exogenous (new-call) generation process and an internal (hand-off-based) process that results from the mobility model. This complex optimization problem is solved by means of both numerical and standard clock simulation techniques along with the ordinal optimization approach.*

## I. Introduction

Land mobile satellite systems and terrestrial cellular networks are rapidly evolving to meet the surge in demand for mobile services. At first, satellite systems and cellular networks were developed primarily as stand-alone systems. The concept of using satellite capacity to enhance cellular service by integrating the satellite and terrestrial systems has been introduced recently. The presence of shared communication capacity in the satellite layer of a hybrid system can be used not only to extend the geographical coverage but also to off-load localized congestion in the underlying cells.

In purely cellular networks, earlier studies have shown that efficient use of the system bandwidth can be achieved by reuse partitioning[1] and using hierarchical cell layout[2,3] with larger macrocells overlaying small microcells. Performance analysis of a hybrid satellite-cellular system with the satellite footprints forming the highest layer in the hierarchy was also studied[4]. However, the call assignment policy used had less degrees of freedom than those employed here. Moreover, the static channel split was assumed to be known.

This work builds upon earlier work[5] in which users' mobility, handoffs, and call assignment policy were not considered but, rather, only a static split of the total bandwidth into a terrestrial and a satellite component. In this paper, we use standard mobility models that permit us to evaluate the need (and probability) of hand-offs. We consider the problem of minimizing the probability of blocking call requests while at the same time we are interested in keeping the propagation delay small. Hence, an arriving call that is assigned to a satellite channel will incur longer propagation delay but may contribute to reduced overall blocking probability. More specifically, we introduce a multi-dimensional Markov chain-based model for a hybrid network consisting of 2 cells overlaid by 1 spot-beam which can be directly extended to any number of cells and spot-beams. Our main objective is to determine the optimal static channel split between the cellular and the satellite system, as well as deciding the call assignment policy in order to minimize a multi-dimensional cost function composed of the call blocking and dropping probabilities in addition to the satellite propagation delays.

In the literature, several different approaches have been considered for ordinal optimization[6]. In this paper, short simulation runs ($10^4$ arrival events) were used in conjunction with standard clock (SC) simulation techniques[7] to obtain an approximate ranking of policies, and it was observed that many of the high performance policies also perform well over long simulation runs ($10^6$ arrival events).

The paper is thus organized as follows: In section

II, system assumptions and the mathematical model are given. Candidate call assignment policies are introduced in section III. This is followed by the problem formulation and solution approaches in section IV. In section V, numerical and simulation results for various subproblems are given and discussed. Finally, the conclusions are drawn in section VI.

## II. System Description

### A. Assumptions and Definitions

In order to investigate the problem of optimizing the static channel split and the call assignment policy for a mobile hybrid network, we make the following assumptions and notational definitions:

1. New calls arrive at cell $C_i$ according to a Poisson arrival Process with rate $\lambda_i = \lambda,\ \forall$ i.

2. Call duration is exponentially distributed with mean $1/\mu$.

3. The studied network consists of:

- 2 cells, namely $C_1$ and $C_2$.
- 1 spot-beam 'S' covering the same area.

as shown in Figure 1.

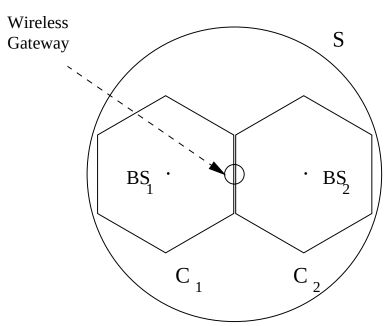



**Figure 1. A Hybrid Network of 2 Cells and 1 Spot-beam**

4. Total number of duplex channels available to the system is M, where

$$M = M_1 + M_2 + M_s$$

and,
$M_1$ = number of channels dedicated to $C_1$.
$M_2$ = number of channels dedicated to $C_2$.
$M_s$ = number of channels dedicated to S.

5. The two base stations, namely $BS_1$ and $BS_2$, communicate via either:
(a) Terrestrial wireline connection or,
(b) Gateway located on the border between the cells.

In this formulation, assumption (b) is considered for the model to be extendable to the case of mobile BSs in the future.

6. According to assumption 5.b, a mobile-mobile call originating in a cell and destined to the other cell needs 4 duplex channels if served by the cellular network.

7. A mobile user can access the satellite directly, not through its BS.

8. All call types have the same priority and all calls considered in the model are mobile-mobile calls.

9. Stationary BSs and spot-beam.

10. We define f as the fraction of calls that originated in a cell and destined to the other cell, where $0 \leq$ f $\leq 1$.

11. When mobiles served terrestrially reach the cell boundaries, the call could be handed-off either to the neighboring cell or to the overlaying spot-beam. In this formulation, call handoffs are assigned to either the neighboring cell or the overlaying spot-beam according to the same assignment strategy used for new calls.

12. The interhandoff time for a mobile in cell $C_i$ is exponentially distributed with rate $\lambda_{h_i}$, i=1,2.

13. Blocked calls are immediately lost.

### B. System Model

The state of the system can be defined by the vector $(n_{11}, n_{12}, n_{22}, n_s)$ where,
$n_{11}$ = number of calls of type '11'; calls served by $BS_1$ and both parties are in $C_1$.
$n_{12}$ = number of calls of type '12'; calls served by $BS_1$ and $BS_2$, where one of the parties is in $C_1$ and the other is in $C_2$.
$n_{22}$ = number of calls of type '22'; calls served by $BS_2$ and both parties are in $C_2$.
$n_s$ = number of calls of type 's'; calls served by S.

Accordingly, the system is modeled as a 4-dimensional Continuous-time Markov Chain. It should be noticed that calls of type '12' need 4 channels/call, while calls of types '11', '22', and 's' need only 2 channels/call. Therefore, the set of feasible states should satisfy the following constraints :

$$2n_{11} + 2n_{12} \leq M_1$$

$$2n_{22} + 2n_{12} \leq M_2$$

$$2n_s \leq M_s$$

The vector of steady-state probabilities $\underline{P}$ can now be determined by solving the global balance equations written in the following matrix form:

$$\underline{P}.Q = \underline{0} \quad (1)$$

$$\text{and} \quad \sum_{i=1}^{K} P_i = 1$$

Where Q is the state transition rate matrix and K is the number of states in the state space. The dimensions of the matrix Q as well as the state transition rates depend on the static channel allocation policy and the call assignment strategy.

## III. Call Assignment Policies

Two candidate call assignment policies have been examined to assess their performance in terms of minimizing the cost function formulated later.

In the interior of the state space, the first policy assigns a new incoming call or a handed-off one to either the terrestrial layer or the satellite layer randomly based on assignment probabilities for each call type. For the network shown in Figure 1, the call assignment probabilities are given by:

$P_{11}$ : probability of assigning a call with both parties in $C_1$ to cell $C_1$.
(1-$P_{11}$) : probability of assigning a call with both parties in $C_1$ to spot-beam S.
$P_{12}$ : probability of assigning a call with one of the parties in $C_1$ and the other in $C_2$ to cells $C_1$ and $C_2$.
(1-$P_{12}$) : probability of assigning a call with one of the parties in $C_1$ and the other in $C_2$ to spot-beam S.
$P_{22}$ : probability of assigning a call with both parties in $C_2$ to cell $C_2$.
(1-$P_{22}$) : probability of assigning a call with both parties in $C_2$ to spot-beam S.

When the system reaches the space boundaries due to a fully occupied cell $C_i$, i=1,2, while spot-beam S still has free channels, the assignment procedure switches from the *randomized* mode to a *deterministic* one where the incoming calls or the handed-off ones are assigned immediately to the satellite S. By the same argument, if the system reaches the space boundaries due to a fully occupied spot-beam, while the terrestrial layer still has free channels, call handoffs or new call arrivals are assigned immediately to the terrestrial network.

The second assignment rule enables switching from the *randomized* mode to a *deterministic* one upon reaching certain thresholds, namely $\gamma_{11}/2$, $\gamma_{12}/2$, and $\gamma_{22}/2$ on the number of calls of types '11', '12', and '22' respectively as given below,

$$P_{11} = 0 \ \text{ if } \ 2n_{11} = \gamma_{11}$$
$$P_{12} = 0 \ \text{ if } \ 2n_{12} = \gamma_{12}$$
$$P_{22} = 0 \ \text{ if } \ 2n_{22} = \gamma_{22}$$

Where,

$$\gamma_{11} + \gamma_{12} = M_1$$
$$\gamma_{22} + \gamma_{12} = M_2$$

## IV. Problem Definition

The optimal call assignment strategy (of the first type introduced in section III) and channel allocation policy are obtained by solving the following minimization problem:

$$\min_{P_{11},P_{12},P_{22},M_1,M_2,M_s} (P_b + \alpha_1.P_d + \alpha_2.\Psi) \quad (2)$$

s.t.

$$\text{M} = M_1 + M_2 + M_s$$
$$0 \leq P_{11} \leq 1$$
$$0 \leq P_{12} \leq 1$$
$$0 \leq P_{22} \leq 1$$

Where,
$P_b$ = average new call blocking probability.
$P_d$ = average call dropping probability.
$\Psi$ = average percentage of satellite calls in the system, which represents the contribution of the satellite propagation delay in the cost function.
$\alpha_1$ and $\alpha_2$ are weighting factors.

The difficulty in the above formulation is the choice of the design parameters $\alpha_1$ and $\alpha_2$, since there is no well defined procedure for choosing them. The following formulation is an equivalent and much easier one,

$$\min_{P_{11},P_{12},P_{22},M_1,M_2,M_s} P_b \quad (3)$$

s.t.

$$P_d \leq \beta_1$$
$$\Psi \leq \beta_2$$
$$\text{M} = M_1 + M_2 + M_s$$
$$0 \leq P_{11} \leq 1$$
$$0 \leq P_{12} \leq 1$$
$$0 \leq P_{22} \leq 1$$

Where $\beta_1$ and $\beta_2$ are equivalent design parameters such that for every chosen $\beta_1$ and $\beta_2$ there are corresponding values of $\alpha_1$ and $\alpha_2$ respectively, and $0 \leq \beta_1, \beta_2 \leq 1$.

In the following subsections, we consider solving subproblems which lead to the solution of the target problem formulated in (3).

### A. The Optimum Static Channel Split for a Given Assignment Rule

Given $P_{11}, P_{12}$, and $P_{22}$ and employing the first call assignment rule in section III, the objective is to solve the following minimization problem subject to the same constraints in (3):

$$\min_{M_1, M_2, M_s} P_b \qquad (4)$$

We consider solving this subproblem numerically and through simulation. For all possible channel allocation policies, the 4-dimensional Markov chain did not satisfy the detailed balance equations and hence is irreversible[10], due to changing the call assignment rule at the space boundaries. Consequently, the product-form solution was not applicable here, and we had to solve the global balance equations for small state spaces. On the other hand, for large state spaces simulation was the only feasible way to measure the system performance under various channel allocation policies. Standard clock simulation techniques were employed to evaluate the performance of the channel allocation policies and compare the simulation results with the numerical ones for small state spaces. Moreover, the *ordinal optimization* approach was used with standard clock simulation to speed up the simulations. This was done through performing *short simulation runs* which gave rankings of policies that have good agreement with those achieved via longer runs.

### B. The Optimum Call Assignment for a Given Channel Allocation

According to section III, two call assignment policies are to be investigated, namely switching from a randomized assignment rule to a deterministic one at the space boundaries, and switching at the boundaries of a hypercubic subspace within the original state space.

#### *1. Switching at the Space Boundaries*

Given $M_1$, and $M_2$, the objective is to solve the following minimization problem subject to the constraints in (3):

$$\min_{P_{11}, P_{12}, P_{22}} P_b \qquad (5)$$

This subproblem has been solved via SC simulation in conjunction with ordinal optimization.

#### *2. Switching at the Boundaries of a Hypercubic Subspace*

Given $M_1$, $M_2$, $P_{11}$, $P_{12}$, and $P_{22}$, the objective then is to solve the following minimization problem:

$$\min_{\gamma_{11}, \gamma_{12}, \gamma_{22}} P_b \qquad (6)$$

s.t.

$$\gamma_{11} + \gamma_{12} = M_1$$
$$\gamma_{22} + \gamma_{12} = M_2$$

In addition to the constraints in (3).

For this subproblem the global balance equations had to be solved numerically, since the product-form solution is not applicable here due to the irreversibility of the Markov chain, while for larger state spaces we will have to resort to simulation.

## V. Results

The network shown in Figure 1 was analyzed assuming the numerical parameters given in Table 1. It should be pointed out here that the following results were obtained with no constraints enforced on $P_d$ or $\Psi$ while minimizing $P_b$ unless otherwise stated, i.e. $\beta_1$ and $\beta_2$ were assumed to be 1 in (3).

Table 1. System Parameters

| | |
|---|---|
| Total System Bandwidth (M) | 8 |
| Call Arrival Rate per Cell ($\lambda$) | 0.333 |
| Call Service Rate ($\mu$) | 0.333 |
| Call Handoff Rate from $C_1$ ($\lambda_{h_1}$) | 0.5 |
| Call Handoff Rate from $C_2$ ($\lambda_{h_2}$) | 0.5 |
| Fraction of Calls originated in a cell and destined to the other cell (f) | 0.5 |

Considering the first subproblem, the optimum static channel split for a given call assignment policy was determined for the following call assignment probabilities:

$$P_{11} = P_{12} = P_{22} = 0.5$$

Recall that each mobile-mobile call needs 2-duplex channels per cell or spot-beam. Hence, the set of channel allocation policies to be examined can be restricted to 15 policy having even values for $M_1$, $M_2$, and $M_s$. Furthermore, the channel allocation policies investigated were restricted to only 9 policies, given in Table 2, due to the symmetry of the parameters associated with cells $C_1$ and $C_2$. Therefore, the two policies $M_1 = m_1, M_2 = m_2, M_s = m_s$, and $M_1 = m_2, M_2 = m_1, M_s = m_s$ had exactly the same performance.

Table 2. Channel Allocation Policies

| Policy | $M_1$ | $M_2$ | $M_s$ |
|---|---|---|---|
| Policy #1 | 0 | 0 | 8 |
| Policy #2 | 2 | 0 | 6 |
| Policy #3 | 2 | 2 | 4 |
| Policy #4 | 2 | 4 | 2 |
| Policy #5 | 4 | 0 | 4 |
| Policy #6 | 4 | 4 | 0 |
| Policy #7 | 2 | 6 | 0 |
| Policy #8 | 6 | 0 | 2 |
| Policy #9 | 8 | 0 | 0 |

As indicated earlier, this subproblem was solved through:

1. Numerical Techniques: the global balance equations were solved (using *Mathematica 3.0*) for the system steady-state probabilities under each channel split policy, from which the call blocking and dropping probabilities can be determined and compared.

2. Simulation: a SC simulation model was developed using C++ and run on a SUN-ULTRA workstation.

In Figure 2, the call blocking and dropping probabilities obtained numerically and via SC simulation were noticed to have good agreement for all channel allocation policies. Moreover, the optimum channel allocation policy turned out to be the *"All-Channels-to-Satellite"* policy ($M_1 = 0$, $M_2 = 0$, $M_s = 8$) since no constraints were enforced on the dropping probabilities or the propagation delays. If the satellite propagation delay is included in the cost function, the *"All-Channels-to-Satellite"* policy is expected to have higher cost depending on the weight associated with the propagation delay relative to the call blocking probability. Later in this section, we investigate that the optimum channel allocation policy might differ from the above mentioned one if a constraint was imposed on the satellite propagation delay. In Figures 3 and 4 ordinal rankings based on call blocking and dropping probabilities were plotted for simulation runs of various lengths versus the exact ranking obtained numerically. It was noticed that short simulation runs while giving inaccurate call blocking and dropping probabilities still maintain the ordinal ranking of the best policies.

In Figure 5, the same channel allocation policies investigated before were compared for their average blocking probability, average dropping probability and average percentage of satellite calls (representing the contribution of satellite propagation delays). Thus, the multi-dimensional cost function was optimized by enforcing upper bounds on two optimization criteria and then minimizing the third subject to these constraints. For instance, if we impose

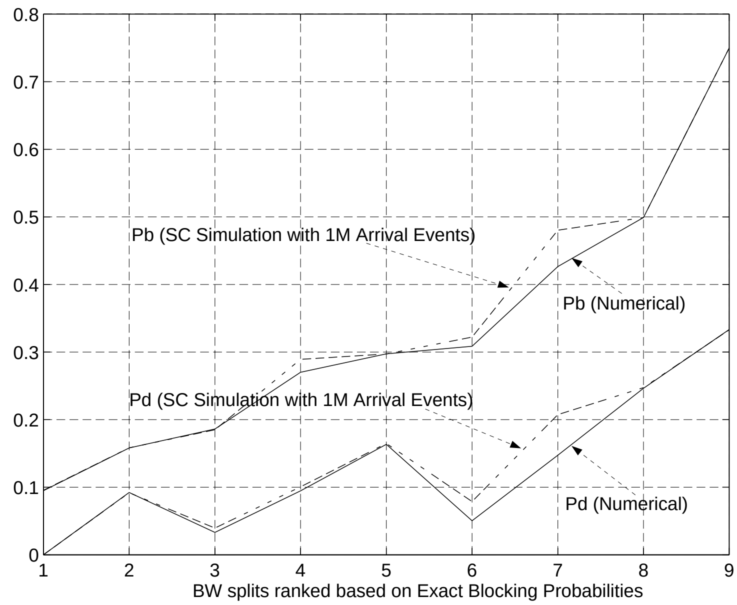
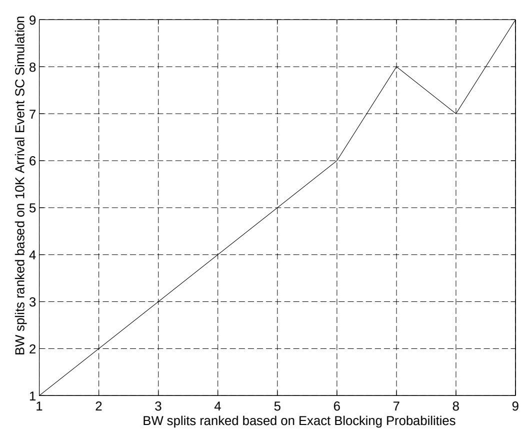
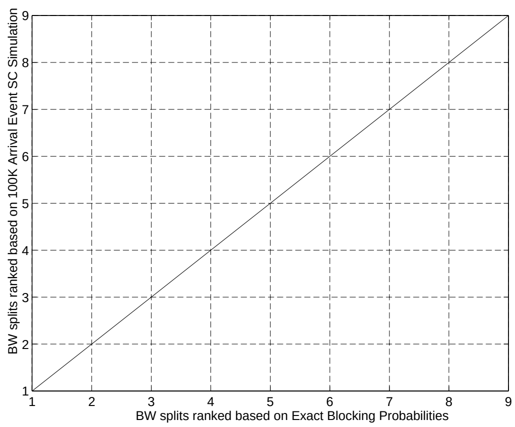



**Figure 2. Blocking and Dropping Probabilities for Channel Allocation Policies (Numerical and Simulation Results)**




**(a)**

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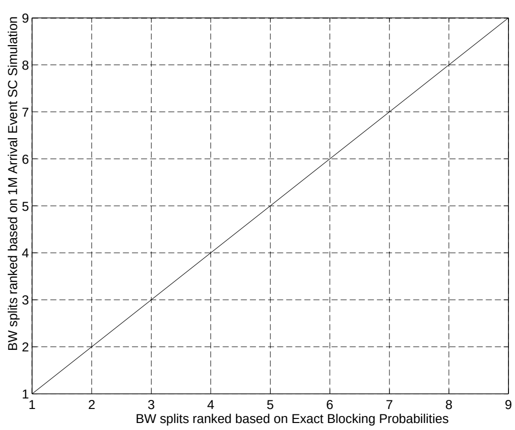
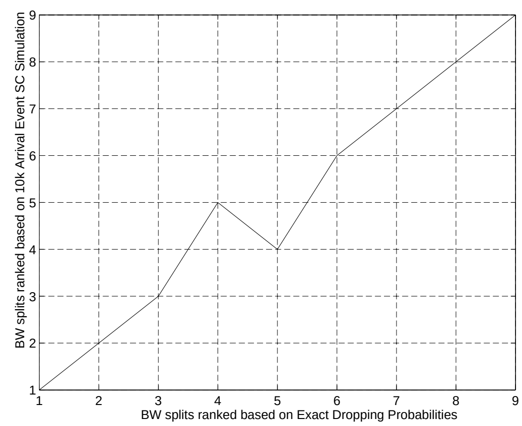
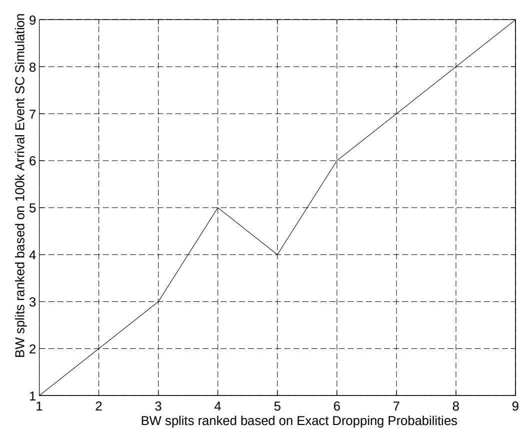



**(c)**

**Figure 3. Ordinal Rankings based on Blocking Probabilities for Channel Allocation Policies: (a) 10K Arrival Event, (b) 100K Arrival Event, (c) 1M Arrival Event**




**(a)**

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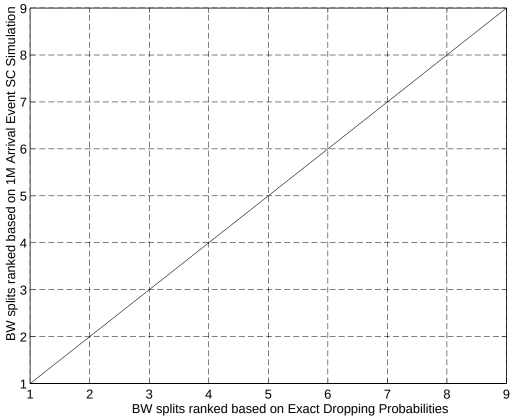


**(c)**

**Figure 4. Ordinal Rankings based on Dropping Probabilities for Channel Allocation Policies : (a) 10K Arrival Event, (b) 100K Arrival Event, (c) 1M Arrival Event**

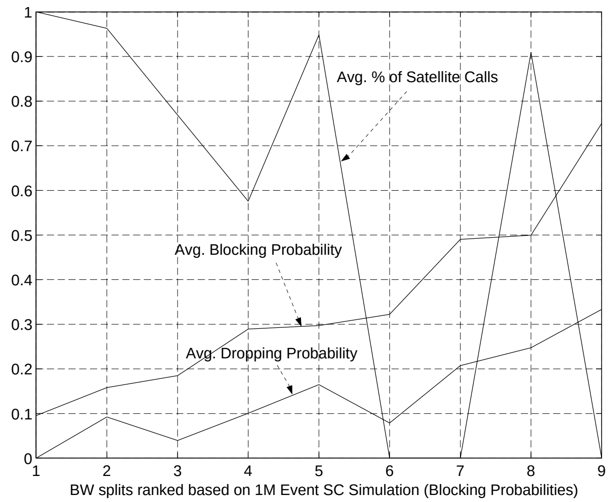


**Figure 5. Simulation based Call Blocking, Dropping, and Propagation Delay Performance for the Channel Allocation Policies**

the following constraints on $P_d$ and $\Psi$:

$$P_d \leq 1$$
$$\Psi \leq 0.6$$

It can be obtained from Figure 5 that the minimum $P_b$ is 0.29 and achieved by policy #4 ($M_1 = 2, M_2 = 4, M_s = 2$). Accordingly, it can be concluded that splitting the available bandwidth into terrestrial and satellite components minimizes the multi-dimensional cost function formulated earlier as compared to the two extremes, namely *pure cellular network* and *pure satellite network*.

For the second subproblem formulated in section IV, two assignment policies have been studied for a given channel allocation policy. First, the problem formulated in (5) was solved for the optimum call assignment probabilities given the following static channel split:

$$M_1 = 2,\ M_2 = 2,\ M_s = 4$$

The call assignment probabilities can take any value in the range [0,1], leading to an infinite pool of call assignment policies. We have chosen a finite subset of policies that cover the whole range. Initially, a large subset (1331 policy) was chosen. The solution via SC simulation with $10^6$ arrival events within this subset was infeasible due to the very long simulation time incurred. Therefore, the set was reduced to a smaller one (64 policy) covering the [0,1] range, which gave reasonable simulation time. The ranking of policies based on blocking and dropping probabilities generated by various simulation lengths are shown in Figures 6 and 7 respectively. It can be noticed from Figure 6 that the blocking trajectory for 10K arrival events has a wider performance range between best and worst policies than that associated with 1M arrival events. Furthermore, by increasing the simulation length, this range monotonically decreases. Therefore, given the small performance range between extreme policies, the following simple call assignment policies worth to be examined:

1. Cellular First (CF) Assignment Policy ($P_{11} = P_{12} = P_{22} = 1$): this policy had a blocking probability based ranking of 29 out of the 64 policies investigated, and a dropping probability based ranking of 17.
2. Satellite First (SF) Assignment Policy ($P_{11} = P_{12} = P_{22} = 0$): it had a blocking probability based ranking of 44 out of 64, and a dropping probability based ranking of 63.

From the above results, two observations can be pointed out. First, the CF policy outperforms the SF policy (with respect to $P_b$ and $P_d$) which can be explained by recalling that the satellite capacity in a beam is shared by all the cells overlaid by that beam. So, when congestion occurs in a particular cell, i.e. its cellular channels fill up, then under the CF policy some satellite channels may still be free to off-load the congestion, while under the SF policy, no free channels are available, as they are being used also by calls from cells with no congestion. Second, the CF policy gave blocking and dropping rates ($P_b = 0.1854$ , $P_d = 0.0366$) that are not much inferior to those achieved by the optimum policy ($P_b = 0.1841$, $P_d = 0.0359$). Hence, with the advantage of CF being easy to implement, it can be considered a sub-optimal call assignment policy for this hybrid system.

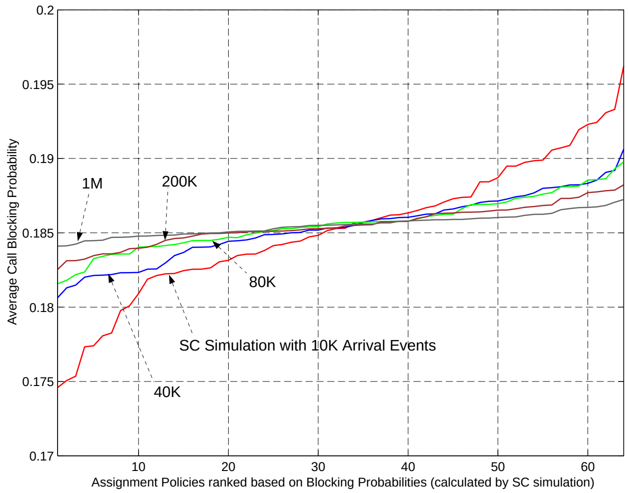


**Figure 6. Call Blocking Probabilities for Call Assignment Policies Ranked on SC Simulations of different lengths**

On the other hand, the problem formulated in (6) has been solved for the optimum switch thresholds given that the total system bandwidth M = 20 channels along with the following static channel split and call assignment probabilities:

$$M_1 = 8,\ M_2 = 8,\ M_s = 4$$
$$P_{11} = P_{12} = P_{22} = 0.5$$

From the constraints of subproblem (6), the set of threshold policies are restricted to those having even values for $\gamma_{11}$, $\gamma_{12}$, and $\gamma_{22}$. Consequently, the threshold policies examined are given below,

$$\gamma_{11} = 8,\ \gamma_{12} = 0,\ \gamma_{22} = 8$$
$$\gamma_{11} = 6,\ \gamma_{12} = 2,\ \gamma_{22} = 6$$
$$\gamma_{11} = 4,\ \gamma_{12} = 4,\ \gamma_{22} = 4$$
$$\gamma_{11} = 2,\ \gamma_{12} = 6,\ \gamma_{22} = 2$$
$$\gamma_{11} = 0,\ \gamma_{12} = 8,\ \gamma_{22} = 0$$

These policies are compared with the case of switching at the original state space boundaries in Table 3.

Table 3. Switching Policies

| **Switching Policy** | $P_b$ | $P_d$ |
|---|---|---|
| Switch at the original state space boundaries | 0.0076 | 0.0025 |
| $\gamma_{11} = 8,\ \gamma_{12} = 0,\ \gamma_{22} = 8$ | 0.1887 | 0.0003 |
| $\gamma_{11} = 6,\ \gamma_{12} = 2,\ \gamma_{22} = 6$ | 0.072 | 0.0009 |
| $\gamma_{11} = 4,\ \gamma_{12} = 4,\ \gamma_{22} = 4$ | 0.0268 | 0.0015 |
| $\gamma_{11} = 2,\ \gamma_{12} = 6,\ \gamma_{22} = 2$ | 0.0448 | 0.0012 |
| $\gamma_{11} = 0,\ \gamma_{12} = 8,\ \gamma_{22} = 0$ | 0.174 | 0.0001 |

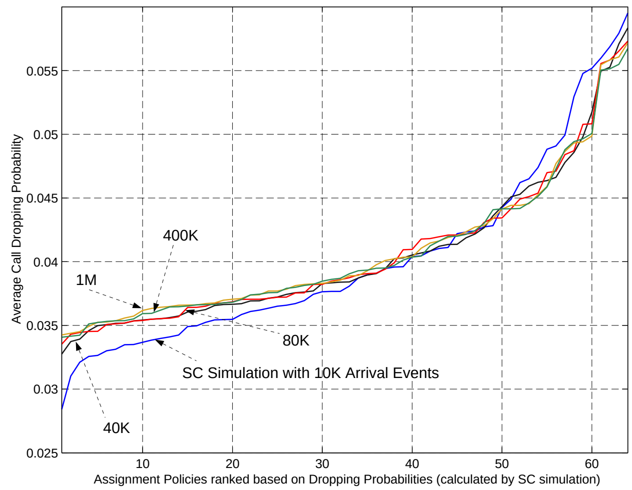


**Figure 7. Call Dropping Probabilities for Call Assignment Policies Ranked on SC Simulations of different lengths**

From Table 3, it can be noticed that for the given static channel split, call assignment probabilities and system numerical parameters, enforcing the switch from randomized to deterministic assignment at hypercubic thresholds improves the call dropping probability as compared to the original state space. This is achieved at the expense of increasing the new call blocking probability. Therefore, with the assumption that dropping an on-going call is less required than blocking a new one, the second assignment strategy suggests an approach for reducing the dropping rate with a tolerable degradation in the blocking rate.

## VI. Conclusions

In this paper we determined the optimal static channel split and call assignment policy for a hybrid network. The objective was to minimize a multi-dimensional cost function composed of the call blocking and dropping probabilities in addition to the satellite propagation delays. For the subproblem of optimizing the static channel split given a call assignment policy, we observed that short simulation runs maintain the ordinal ranking of the best policies. Furthermore, the optimal static channel split turned out to be the *"All-Channels- to-Satellite"* policy if the blocking probability was the only optimization criterion. On the other hand, if the contribution of satellite propagation delays was included in the cost function, the hybrid system was found to be the optimum as compared to the *pure cellular network* and *pure satellite network* extremes. Next, the subproblem of optimizing the call assignment policy given a static channel split was solved. For the *"Switching at the Space boundaries"* assignment strategy, it was noticed that the performance range between extreme policies was small. Accordingly, the simple *Cellular First* assignment policy is recommended to be a suboptimal solution for the hybrid system. On the other hand, the second call assignment policy which allows switching from a randomized to a deterministic mode at the boundaries of a hypercubic subspace was examined. It was noticed that this policy reduces the call dropping rate at the expense of a tolerable degradation in the blocking rate. Therefore, this assignment strategy suggests an approach for the designer to control the blocking and dropping rates in order to satisfy the constraints given in the system specifications.

## VII. Acknowledgment

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