

Modeling of a Hybrid Ad Hoc Cellular Network System *

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This paper presents the modeling and performance analysis in the integrated ad hoc and cellular network systems. In the modeling of the other integrated systems [7, 10, 12, 14, 17], the handoff area was not considered. However, for mobile communications, handoff area is important, complicated and unstable area that is the boundary of cells. In our system, handoff area and queue are taken into consideration, and new and handoff calls are given priority, respectively. We derive and evaluate some characteristic values such as the mean waiting time. In numerical results, the analytical results in our system are compared with those in the other integrated system, and with the simulation results for the validation.

Keywords: ad hoc networks, cellular networks, relaying, integration, queueing system, modeling

1. INTRODUCTION

Mobile communications have achieved rapid growth in recent years and the further advancement is expected to realize the future ubiquitous society. However, since the bandwidth is limited, it is very important to consider how to use the limited resources efficiently.

With the purpose of reusing the limited radio resources and reducing power consumption, a cellular network was constructed [2]. Cellular networks require fixed base stations that are interconnected by a wired backbone, and base stations are very important for the networks [5]. However, the calls in cellular network systems are bound by the base station of the cell. This thing causes a trouble in a breakdown and disaster. That is, when the base station in a cell stops and do not fulfill the function, the user in the cell cannot communicate with the others. On the other hand, in ad hoc networks there is no fixed infrastructure [9, 11, 13, 18] and all links are formed by wireless links. Therefore, ad hoc networks can be deployed quickly [16]. Ad hoc networks have multi-hop communication function and if the distance between two mobile stations is large, they can communicate with each other via relay stations. Because ad hoc network systems are flexible and robust for a breakdown and disaster, they are suitable for the future ubiquitous society.

So far, various cellular network systems have been modeled and evaluated. As the general system, the study on the system with guard channels was represented by Guerin

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in [6]. In this system, some number of channels are used exclusively for handoff calls because blocking of a call in progress is less desirable than the blocking of a new call. However, the channels for handoff calls can be vacant in spite of the occurrence that the new calls are blocked when the generation rate of new calls is large and the generation rate of handoff calls is small. Moreover, the channel reservation scheme that priority is given to handoff calls reduces the total carried traffic [20, 21]. In [8], analysis of the system which some channels are reserved exclusively for handoff calls and there is the queues for the new and handoff calls was shown. The new calls can be blocked regardless of the situation that the channels for handoff calls are vacant when the generation rate of handoff calls is very small and the generation rate of new calls is very large. The system which handoff calls are given more priority than new calls is desirable for users, but we think that channels should be used efficiently toward ubiquitous society.

Ad hoc network systems are self-organized, self-managing and flexible [11], and the multi-hop communication in ad hoc networks leads to extending the coverage of existing wireless access technologies. Moreover, through the direct communication between neighboring terminals, it can be represented the improvement of reducing the cost of wireless access infrastructure, at the expense of some additional complexity [1, 16].

Integrated cellular and ad hoc systems were represented in [7, 10, 12, 14, 17]. However, these papers focus on the coverage of a relay station, and handoff area which is unstable, complicated and important is not taken into consideration. In [10], the blocking probability of new calls is focused on, and the analysis considering handoff calls is not be done in detail. In [12], handoff performance of the integrated cellular and ad hoc system is studied. However, handoff area and the waiting time for handoff calls are not considered. We think that modeling and analysis which deal with the important area for handoff calls should be done. Modeling of the system with handoff area represents the situation of a boundary in cells more clearly than that of the system without handoff area. Moreover, the handoff calls in the system with handoff area are not broken immediately in moving to the neighboring cell even if there are no available channels in the next cell.

Mobile-assisted connection-admission system in [3] and multihop cellular system in [4] were represented, respectively. However, in these systems, because mobile hosts carry out relaying, there is the difficulty and disadvantages in security and the mobility control of the mobile hosts [7]. In this paper, we consider the integrated ad hoc cellular network system where handoff area is taken into consideration and new and handoff calls are given priority, respectively. New calls are given the priority of relaying, and new calls in handoff area and handoff calls are given the priority of queueing. In the other researches [7, 14], only when a new call occurs, the communication via a relay station can be done. However, we also consider the communication by a relay station after moving to an adjacent cell. We derive and evaluate some characteristic values such as the mean waiting time of calls in handoff area. Especially, as regards the mean waiting time of calls in handoff area, we derive it in detail by considering the Laplace Stieltjes Transform for the probability distribution of the waiting time of calls. In the numerical results, we compare the analytical results in our system with the simulation ones in our system and with analytical ones in the other system [7, 14].

In the next section, system model is shown and the performance analysis is represented. Section 3 gives the numerical results and we conclude in section 4.

2. SYSTEM MODEL

There are two cells, cellA and cellB, in this system and M channels are assigned to cellA and cellB, respectively.

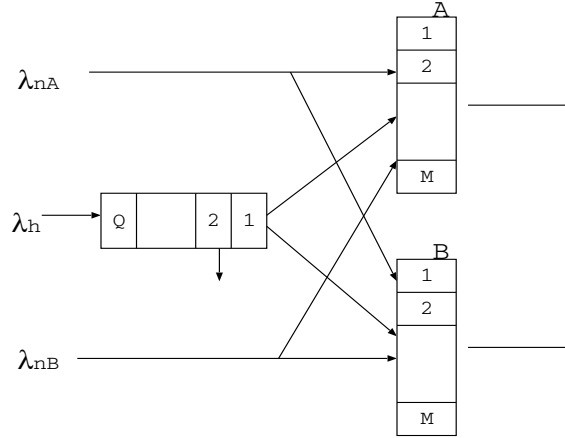


Fig. 1. System model.

System model is shown in Fig. 1. Handoff area is defined as the overlap region of cells and handoff calls are defined as the calls that move to the neighboring cell, and then handoff process is done within the handoff area. In this system, new calls are given the priority of relaying. New calls in handoff area and handoff calls are given the priority of queueing. We assume that a relay station is set in handoff area and the coverage, that is, the area covered by the relay station is represented as ratio l , which is the ratio to the area of a cell. If there are no channels available in cellA (cellB) on arrival, the new calls which are in the area covered by a relay station can be relayed to the other cell. New calls in handoff area and handoff calls use the channel in the cell which has more free channels in the two cells. This thing makes the bias of the traffic between the two cells small. Here, after leaving handoff area and moving to an adjacent cell completely, the handoff calls using a channel in the previous cell are assumed to use the channel while the handoff calls are in the area covered by a relay station. We assume that the area covered by a relay station is larger than handoff area. When the handoff calls with the channel of the previous cell leave the area covered by a relay station, the handoff calls release the channel and arise as new calls in the current cell. Therefore, the possibility that handoff calls possess more channels prior to new calls comes to be small.

We assume that the arrival processes of new calls in cellA, cellB, handoff area, and handoff calls are all Poisson with their rates λ_{nA} , λ_{nB} , λ_{vh} , and λ_{hh} . The call holding times of new and handoff calls, the dwell times of cells and handoff area are also assumed to be exponentially distributed with their rates μ , μ_d and μ_w . λ_h is the rate which represents the arrivals of new calls in handoff area and handoff calls, where $\lambda_h = \lambda_{vh} + \lambda_{hh}$. μ_{td} and μ_{tw} are the rate of releasing a channel and the rate of leaving a queue halfway, respectively, where $\mu_{td} = \mu + \mu_d$ and $\mu_{tw} = \mu + \mu_w$.

If the number of the channels being used in cell A is the same as that in cell B , we assume that new calls in handoff area and handoff calls use a channel for cell A or cell B with the probability of 0.5. New calls in handoff area and handoff calls can wait in a queue with capacity Q while they are in handoff area if there are no channels available in the both cells. New calls in cell A (cell B) are blocked if there are no channels available in cell A (cell B) and they cannot use the channels in the other cell. New calls in handoff area and handoff calls are blocked if the queue is full. If the calls in the queue cannot get a new channel while they are in handoff area, they leave the queue halfway.

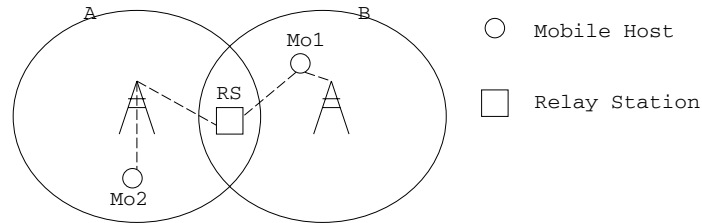


Fig. 2. Relaying.

Using Fig. 2, we state how a call is relayed to the other cell. In Fig. 2, new call Mo1 uses the channel if there are vacant channels in cell B . If there are no available channels in cell B and Mo1 is within the area which is covered by a relay station (RS), Mo1 can use a channel in cell A via RS. Here, RS has two air interfaces, one is the cellular interface which communicates with a base station, and the other is the relaying interface which communicates with a mobile host [7]. Mo1 is blocked when all channels in the both cells are busy or when the channels in cell B are all busy and Mo1 is not covered by RS.

When Mo1 which is using the channel in cell B and is covered by RS moves to cell A , Mo1 is assigned a channel in the cell which has more free channels in the two cells. If Mo1 is assigned a channel in cell A , general handoff is processed. If Mo1 uses a channel in cell B , Mo1 uses the channel while it is in the area covered by RS, and when Mo1 leaves the area, Mo1 arises as new calls in cell A . This thing makes the possibility that handoff calls possess more channels prior to new calls small.

From the system cost's point of view, comparing with non-relaying systems, there is the extra signaling overhead in channel using. Naturally, more signaling packets are sent and received than in non-relaying, and so the signaling traffic in the integrated system increase [7]. However, as seen in [7], it is not significant under a normal traffic intensity.

2.1 Performance Analysis

We define the state of the system as (i, j, s) , where i denotes the number of being used channels of cell A , j does the number of being used channels of cell B , and s does the number of calls in the queue.

The state transition diagram is shown in Fig. 3. The steady state probability is represented as $p_{i,j,s}$. We present the following flow balance equations to derive the steady state probabilities. In the following equations, we define the unit step function as

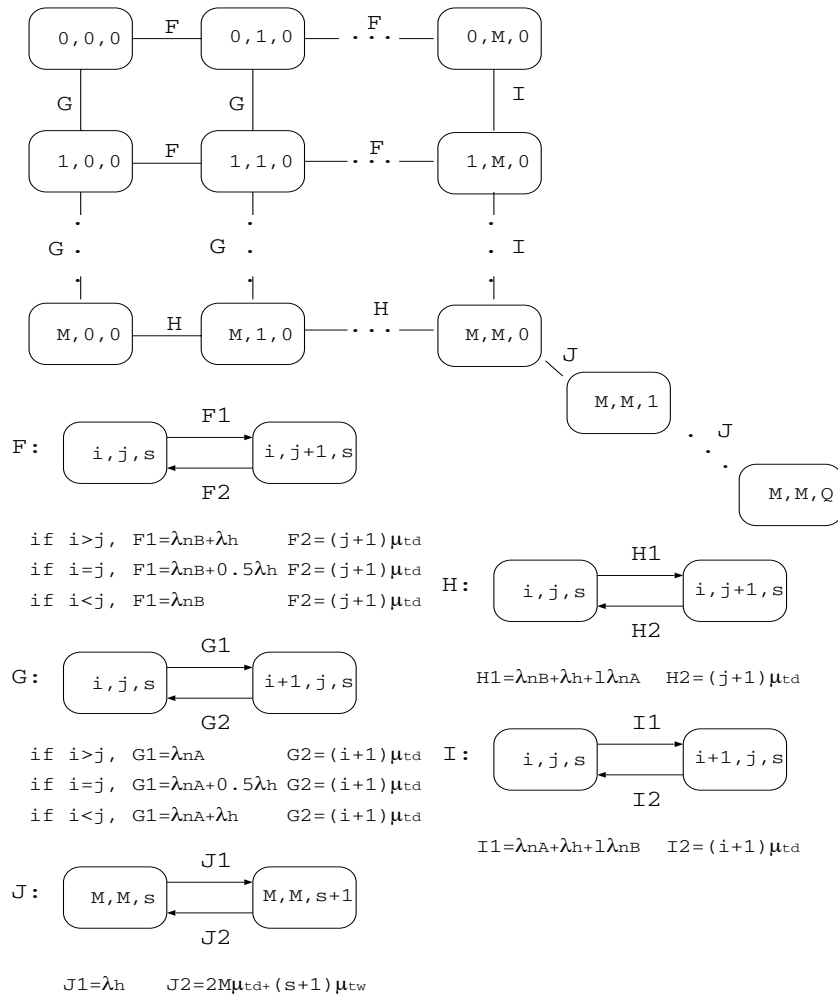


Fig. 3. State transition diagram.

$$u(n) = \begin{cases} 1 & n \geq 0 \\ 0 & n < 0. \end{cases} \quad (1)$$

Flow balance equations are as follows.

In the case of $i = 0, j = 0, s = 0$,

$$(\lambda_{nA} + \lambda_{nB} + \lambda_h)p_{i,j,s} = \mu_{td}p_{i+1,j,s} + \mu_{td}p_{i,j+1,s}.$$

In the case of $i = j, i \neq M, j \neq M, i \neq 0, j \neq 0, s = 0$,

$$\begin{aligned} & (\lambda_{nA} + \lambda_{nB} + \lambda_h + i\mu_{td} + j\mu_{td})p_{i,j,s} \\ & = (\lambda_{nA} + \lambda_h)p_{i-1,j,s} + (j+1)\mu_{td}p_{i,j+1,s} + (i+1)\mu_{td}p_{i+1,j,s} + (\lambda_{nB} + \lambda_h)p_{i,j-1,s}. \end{aligned}$$

In the case of $i < M, j < M, i < j, s = 0$,

$$\begin{aligned} & (u(i-1)\mu_{td} + \lambda_{nA} + \lambda_{nB} + \lambda_h + j\mu_{td})p_{i,j,s} \\ &= u(i-1)(\lambda_{nA} + \lambda_h)p_{i-1,j,s} + (j+1)\mu_{td}p_{i,j+1,s} + (i+1)\mu_{td}p_{i+1,j,s} \\ & \quad + (\lambda_{nB} + u(i-j+1) \times 0.5\lambda_h)p_{i,j-1,s}. \end{aligned}$$

In the case of $i < M, j < M, i > j, s = 0$,

$$\begin{aligned} & (i\mu_{td} + \lambda_{nA} + \lambda_{nB} + \lambda_h + j\mu_{td})p_{i,j,s} \\ &= (\lambda_{nA} + u(j-i+1) \times 0.5\lambda_h)p_{i-1,j,s} + (j+1)\mu_{td}p_{i,j+1,s} + (i+1)\mu_{td}p_{i+1,j,s} \\ & \quad + u(j-1)(\lambda_{nB} + \lambda_h)p_{i,j-1,s}. \end{aligned}$$

In the case of $i = M, j \neq M, s = 0$,

$$\begin{aligned} & (M\mu_{td} + \lambda_{nB} + \lambda_h + l\lambda_{nA} + j\mu_{td})p_{i,j,s} \\ &= (\lambda_{nA} + u(j-i+1) \times 0.5\lambda_h)p_{i-1,j,s} + (j+1)\mu_{td}p_{i,j+1,s} + u(j-1)(\lambda_{nB} + \lambda_h + l\lambda_{nA})p_{i,j-1,s}. \end{aligned}$$

In the case of $j = M, 0 \leq i \leq M, s = 0$,

$$\begin{aligned} & (i\mu_{td} + \lambda_h + u(j-i-1)(\lambda_{nA} + l\lambda_{nB}) + j\mu_{td})p_{i,j,s} \\ &= u(i-1)(\lambda_{nA} + \lambda_h + l\lambda_{nB})p_{i-1,j,s} + u(j-i-1)(i+1)\mu_{td}p_{i+1,j,s} \\ & \quad + u(i-j)(\mu_{rw} + 2M\mu_{td})p_{i,j,s+1} + u(j-i-2)\lambda_{nB} + u(i-j+1)(\lambda_{nB} + u(i-j)(\lambda_h + l\lambda_{nA})) \\ & \quad + u(j-i-1) \times 0.5\lambda_h)p_{i,j-1,s}. \end{aligned}$$

In the case of $s \geq 1$,

$$(u(Q-s-1)\lambda_h + s\mu_{rw} + 2M\mu_{td})p_{i,j,s} = \lambda_h p_{i,j,s-1} + u(Q-s-1)((s+1)\mu_{rw} + 2M\mu_{td})p_{i,j,s+1}.$$

From the conservation law of the state probabilities, we have

$$\sum_{i=0}^M \sum_{j=0}^M p_{i,j,0} + \sum_{s=1}^Q p_{M,M,s} = 1. \quad (2)$$

By these equations, we can get steady state probabilities and find the following characteristic values.

The blocking probability of new calls in cellA is obtained as follows.

$$P_{nA} = \sum_{s=0}^Q p_{M,M,s} + \sum_{j=0}^{M-1} p_{M,j,0}(1-l). \quad (3)$$

The blocking probability of new calls in cellB is represented as

$$P_{nB} = \sum_{s=0}^Q p_{M,M,s} + \sum_{i=0}^{M-1} p_{i,M,0}(1-l). \quad (4)$$

The blocking probability of new calls in handoff area and handoff calls is expressed as

$$P_h = p_{M,M,Q}. \quad (5)$$

The total carried traffic T_{ch} in cellA and cellB is defined as the average number of occupied channels in cellA and cellB.

$$T_{ch} = \sum_{i=0}^M \sum_{j=0}^M (i+j)p_{i,j,0} + \sum_{s=1}^Q 2Mp_{M,M,s}. \quad (6)$$

If the calls in the queue cannot get a new channel while they are in handoff area, they leave the queue halfway. We define the probability that a call in the queue leaves the queue without getting a new channel as P_w . Here, as P_w , we don't consider the case that a handoff call leaves the queue without getting a new channel due to it's completion.

$$\begin{aligned} P_w &= \sum_{s=0}^{Q-1} \sum_{f=1}^{s+1} p_{M,M,s} \left(\prod_{k=s-f+3}^{s+1} P[X > Y_k] \right) \times \frac{\mu_w}{\mu_{tw} + \nu_s - f + 2} \\ &= \sum_{s=0}^{Q-1} \sum_{f=1}^{s+1} p_{M,M,s} \left(\prod_{k=s-f+3}^{s+1} \frac{\nu_k}{\mu_{tw} + \nu_k} \right) \times \frac{\mu_w}{\mu_{tw} + \nu_s - f + 2}, \end{aligned} \quad (7)$$

where k denotes the order in the queue of the tagged call, X is the random variable that represents the interval between an arbitrary time and the time that the tagged call in the queue leaves the queue without getting a new channel or completes the communication, and Y_k is the random variable that represents the interval between an arbitrary time and the time that the calls except the tagged call move to an adjacent cell, complete the communication or leave the queue without getting a new channel. X and Y_k are exponentially distributed with their rates μ_{tw} and ν_k , respectively, where ν_k is $\nu_k = 2M\mu_{td} + (k-1)\mu_{tw}$. f denotes the sum of the numbers of the forward steps and the one time of the event that the tagged call leaves the queue without getting a new channel.

Finally, we derive the mean waiting time $E[T]$ of a call in handoff area. $E[T]$ is expressed as

$$E[T] = - \left. \frac{dT^*(s)}{ds} \right|_{s=0} = - \sum_{k=1}^Q p_{M,M,k} \left. \frac{dT_k^*(s)}{ds} \right|_{s=0}, \quad (8)$$

where $T_k^*(s)$ is defined as the Laplace Stieltjes Transform for the probability distribution of the waiting time of the call that enters the queue when M channels in cellA and cellB are busy, respectively, and $k-1$ calls are in the queue. Then we have

$$T_k^*(s) = C_k^*(s) + D_k^*(s)T_{k-1}^*(s). \quad (9)$$

If $k=1$, then

$$T_1^*(s) = C_1^*(s) + D_1^*(s). \quad (10)$$

Here, $C_k^*(s)$ and $D_k^*(s)$ is defined as follows. $C_k^*(s)$ is defined as the Laplace Stieltjes Transform for the distribution that represents the interval from an arbitrary point to the point that the tagged call in the queue is completed or leaves the queue due to moving out of the handoff area.

$$c_k(t)dt = \Pr[t < X < t + dt, Y_k > t] = \mu_{tw} e^{-(\mu_{tw} + \nu_k)t} dt. \quad (11)$$

Therefore,

$$C_k^*(s) = \int_0^\infty e^{-st} dC_k(t) = \frac{\mu_{tw}}{s + \mu_{tw} + \nu_k}. \quad (12)$$

Next, we define the $D_k^*(s)$ as the Laplace Stieltjes Transform for the distribution that represents the interval from an arbitrary point to the point that calls except the tagged calls in the queue are completed, move to the neighboring cell or leave the queue without getting a new channel.

$$d_k(t)dt = \Pr[t < Y_k < t + dt, X > t] = \nu_k e^{-(\mu_{tw} + \nu_k)t} dt. \quad (13)$$

Therefore,

$$D_k^*(s) = \int_0^\infty e^{-st} dD_k(t) = \frac{2M \mu_{td} + (k-1) \mu_{tw}}{s + \mu_{tw} + \nu_k}. \quad (14)$$

3. NUMERICAL RESULTS

In this section, we show the numerical results with respect to the blocking probabilities of the new calls in cell A and cell B , the total carried traffic, the blocking probability of the calls in handoff area, the probability that a call leaves the queue halfway, and the mean waiting time of calls in the queue. The parameters are set according to the following case. People with the speed of $50m$ per minute pass cells of diameter $500m$, that there is handoff areas of $50m$, and that the mean holding times of a call is 2 minutes. The generation rate of handoff calls is according to the other parameter and the state of the system. $\mu = 0.00833$, $M = 20$, $Q = 5$, $l = 0.2$. When the traffic load ρ ($\rho = \lambda/\mu$) increases, we see how the characteristics values change.

The values in our considered system are compared with those in the other integrated system [7, 14], and we compare the analytical results in our system with the simulation results for the validation. The situation of the simulation is the same way with the one that was set in the analytic. We finished the simulation when a million unit was done, and the simulation is based on Queueing Simulation Program in [15] and Simulation model of a cell in [19].

Figs. 4 to 9 show the blocking probabilities of new calls in cell A and cell B , the total carried traffic, the blocking probability of calls in handoff area, the probability that a call leaves the queue halfway, and the mean waiting time of calls in the queue versus ρ . As regards the blocking probability of calls in handoff area, the probability that a call leaves the queue halfway, and the mean waiting time of calls in the queue, only the analytical

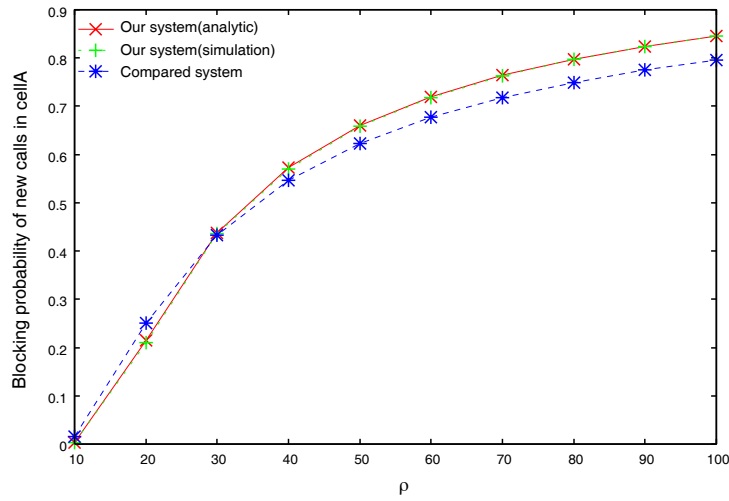


Fig. 4. Comparison of blocking probability of new calls in cellA versus ρ .

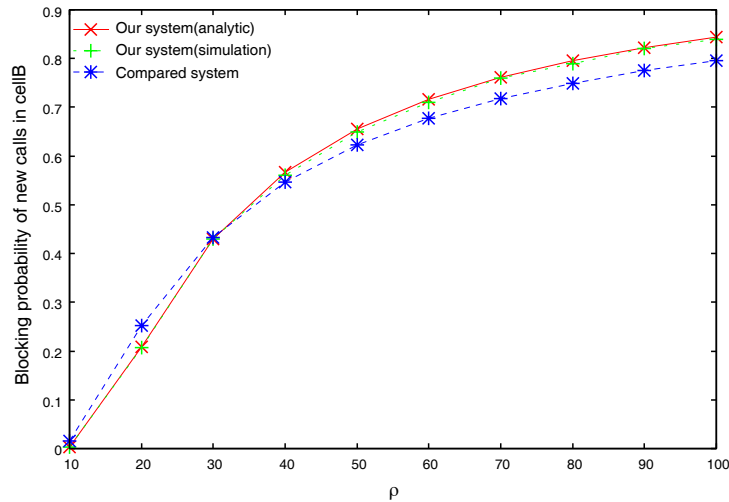


Fig. 5. Comparison of blocking probability of new calls in cellB versus ρ .

and simulation results in our system are represented because a queue and handoff area are not taken into consideration in the compared system [7, 14].

In Figs. 4 and 5, the blocking probabilities of new calls in cellA and cellB versus ρ are represented, respectively. In the both figures, when ρ is small, the blocking probabilities of new calls of cellA and cellB in our system are smaller than those in the compared system. However, as ρ gets larger, the values in our considered system come to be larger than those in the compared system. This is why the calls that can wait in the queue use more channels than new calls when the traffic load is large. The analytical results are almost coincident with the simulation results.

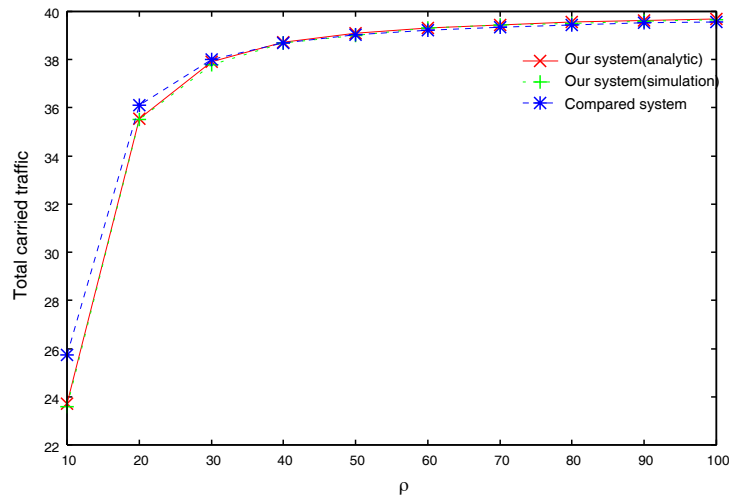


Fig. 6. Comparison of total carried traffic versus ρ .

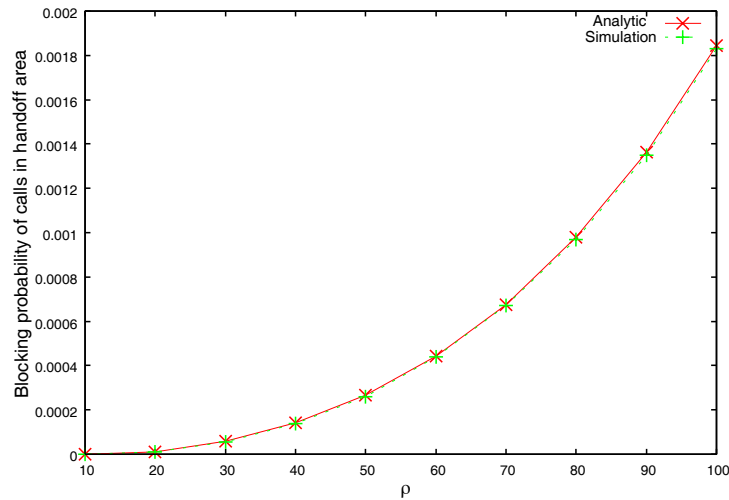


Fig. 7. Comparison of blocking probability of calls in handoff area versus ρ .

In Fig. 6, the total carried traffic in cellA and cellB versus ρ is represented. When ρ is small, the total carried traffic in our system is smaller than that in the compared system. From around $\rho=40$, the values in our system come to be larger than that in the compared system. At $\rho=100$, the total carried traffic in our system and in the compared system are 39.67507 and 39.57630, respectively. That the carried traffic is large is desirable if only the other performance is within the admitted QoS. The analytical and simulation results almost agree.

From Fig. 7, the analytical and simulation results in our system are shown. Figs. 7 and 8 show the blocking probability of calls in handoff area and the probability that a call

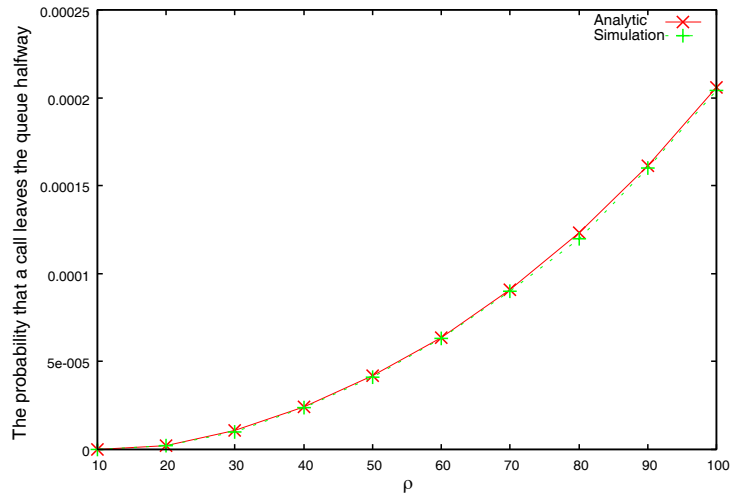


Fig. 8. Comparison of the probability that a call leaves the queue halfway versus ρ .

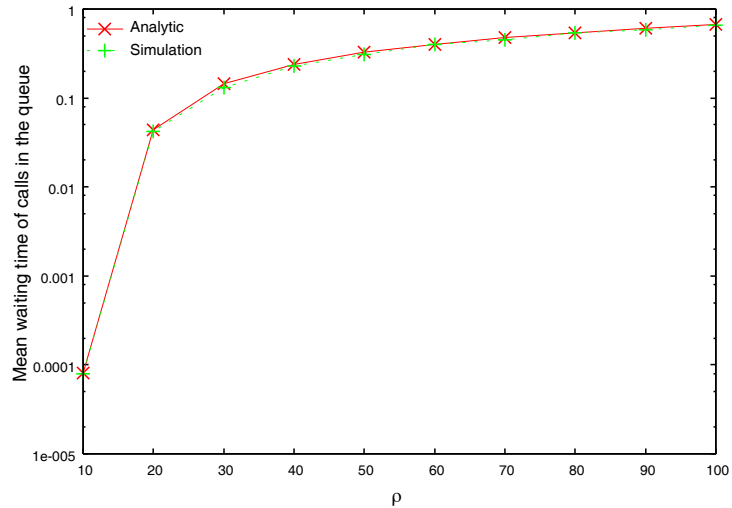


Fig. 9. Comparison of mean waiting time of calls in the queue versus ρ .

leaves the queue halfway versus ρ , respectively. In the both figures, the values are small even if the traffic load is large. Considering that handoff calls are more important than new calls for users, this results by queueing are desirable. The analytical results are almost coincident with the simulation results.

Fig. 9 shows the mean waiting time of calls in the queue versus ρ . When the traffic load ρ is small, the mean waiting time of calls in the queue increases sharply. As the traffic load increases, the rate of the increase comes to be small. When the traffic load is very large, the mean waiting time of calls in the queue become stable because the queue is finite. The analytical and simulation results agree well.

As seen in all figures, on the whole, the analytical and simulation results agree well. Therefore, the analysis was validated and it leads to an indicator in a design and control. As regards the total carried traffic, the values in our system were larger than those in the compared system when the traffic load is large. The blocking probabilities of new calls in cellA and cellB for our system were larger than those for the compared system. However, if only we set the parameters well while considering the admitted QoS, we can get the desirable performance results.

4. CONCLUSION

We presented the modeling and performance evaluation in the integrated ad hoc and cellular network systems, where handoff area is taken into consideration and new and handoff calls are given priority. We derived the blocking probability of new calls in cellA, cellB, the blocking probability of calls in handoff area, the probability that a call leaves the queue halfway, the total carried traffic, and the mean waiting time of calls in the queue. In numerical results, the characteristic values in our system were compared with those in the other system. Moreover, we compared the analytical results with the simulation results, and the two values agreed well.

In this paper, the integrated system with the handoff area which is unstable, complicated and very important was modeled and analyzed in detail. From the numerical results, we found that the total carried traffic in our system gets larger than that in the compared system when the traffic load is large. As the blocking probabilities of new calls in cellA and cellB, the values in our system were larger than those in the compared system as the traffic load is large. However, if only the performance is within the admitted QoS, it is no problem. Therefore, setting parameters cleverly while considering QoS leads to high traffic and we can construct an effective channel using and desirable system. As future work, modeling and analysis of the further complicated channel using system toward the future ubiquitous society is needed.

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