April 2004

An Optimal Method for Using Multiple Gateways in Cellular IP Networks

Zheng da Wu
Bond University, Zheng_Da_Wu@bond.edu.au

An Optimal Method for Using Multiple Gateways in Cellular IP Networks

Z. D. Wu
School of Information Technology, Bond University
Gold Coast QLD 4226, Australia
Phone: +61 755 953311; Fax: +61 755 953320; E-mail: wz@bond.edu.au

Abstract

Cellular IP requires that a mobile host be using exactly one gateway to the Internet backbone with Mobile IP at a time. When multiply gateways are used in a cellular IP network, the optimal design for the multiple domains is needed. In this paper an analytical model is presented for the performance analysis of a cellular IPv6 network with multiple gateways. Based on this model, an optimal system design can be theoretically found in terms of the network size, traffic load, user population, user mobility and routing algorithm for IP packets in a domain. Consequently, an algorithm is proposed for breaking a large cellular IP domain into two small domains, which can be easily used for the system selection in practice. Finally, some numerical results are demonstrated for a number of typical cases presented in the algorithm.

1. Introduction

Mobile IP allows a mobile node to change its location without need to restart its applications or terminate any on going communication. It represents a simple and scalable global mobility solution but lacks the support for fast handoff control and paging found in cellular telephone networks. In contrast, 2G and 3G cellular systems offer seamless mobility management but built on complex and costly connection-oriented networking infrastructure. As a solution to these issues, the concept of cellular IP and later cellular IPv6 were proposed to provide seamless mobility support in a limited geographical area. The specification of Cellular IPv6 has been drafted by the IETF in [5][6], on which this paper is based.

Significant research in the field of cellular IP has been published over the last several years. The works mainly deal with the design, implementation and analysis of cellular IP protocols, including routing, handoff, and paging performance with a single gateway [1]-[4].

Cellular IP requires that a mobile host be using exactly one gateway to the Internet backbone with Mobile IP at a time [5]. It is recognised that if the size (or the number of nodes) of a domain network is large, its gateway potentially becomes a bottleneck of the system performance as all the IP packets from mobile hosts in the domain to the Internet, or vice versa, must go through the gateway. Thus, a cellular IP network may be equipped with multiple gateways to reduce the size of each domain. However, when the size of a domain network is small, the frequency of location update for the home registration with a mobile host will be increased, since the mobile host will have higher probability to move out of the small domain. As a result, it becomes a practical issue to find out the optimal size of the cellular IP domain, where the system, including the gateway, can achieve the best performance. In this paper an analytical model is presented for the performance analysis of a cellular IPv6 network with multiple gateways. Based on this model, an optimal system design can be theoretically found in terms of the network size, traffic load, user population, user mobility and routing algorithm for IP packets in a domain. Consequently, an algorithm is proposed for breaking a large cellular IP domain into two small domains, which can be easily used for the system selection in practice. Finally, some numerical results will be demonstrated for a number of typical cases presented in the algorithm.

2. System Descriptions

In this section cellular IPv6 with multiple gateways will be briefly described and the details of the protocol are specified in [5].

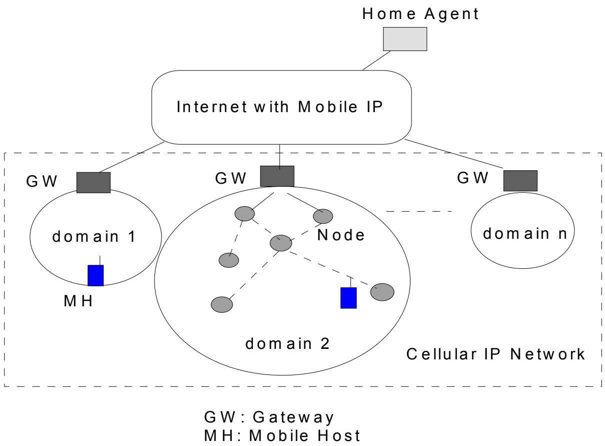


Figure1. Cellular IPv6 network with multiple gateways

As shown in Fig. 1, a cellular IPv6 network consists of several domains and each domain network attaches to the Internet through one gateway. The domain network is composed of interconnected cellular IP nodes (or base stations), which may represent real base stations in cellular telephone systems, Access-Points used in wireless LANs or wired LAN switches. A user of mobile hosts (MHs) travelling within the network can dynamically get a wireless connection to a node of the cellular network so as to send and receive IP packets.

Different from the Internet cellular IP uses *route-cache* and *paging-cache*, equipped in the cellular IP nodes, for routing packets to/from MHs. In order for each node to select its uplink neighbour, the Uplink Neighbour Selection algorithm is proposed in [5].

Similar to Mobile IPv6, when an MH enters a new cellular IP domain, it must register with its home agent (HA). The registered care-of-address (CoA) is the address of the new gateway. Besides, the MH must maintain route paths for itself. The MH periodically sends route-update or paging update packets to the gateway. The intermediate nodes that receive the packets update their caches and forward the packets to the gateway. The gateway thus uses the reverse path caches to forward IP packets to the MH from the Internet.

Cellular IP allows MHs to enter either *active* state or *idl*e state. If an MH is transmitting or receiving IP packets it is in active state. If the MN does not send or receive any packet in a pre-defined time interval, it enters an idle state, in which it only maintains its paging-caches for passive connection. By using idle states of MHs their power consumption can be reduced. Idle MHs crossing cell boundaries (or cellular node boundaries) within a *Paging Area* (PA), which consists of a group of cells, do not need to transmit control packets to update their location with the HA. However, active MHs must send location-update packets whenever they move out of a cell rather than a PA.

When an IP packet arrives at a gateway from a corresponding node (CN), the gateway searches for its destined MH in the paging-cache. If it is found in the cache, the packet (or paging packet) is sent to one of the down-link neighbours specified in the paging-cache. Otherwise, the gateway broadcasts the paging packet to overall down-link neighbours. After receiving the paging packet, the MH immediately sends a route-update packet to the gateway for creating its down-link path and enters active state. As a result, cellular IP nodes are able to route packets to the correct location of the MH.

Traffic between MHs with a wireless access IP network is important consideration for the application at cellular IP protocol. In order to optimize the network performance, a *route optimization* option is proposed for both cellular IP and cellular IPv6 in [6]. By using this mechanism, two MHs located in the same domain network can exchange IP packets directly without contacting the gateway and their home agents.

3. Model and Optimization

3.1. Modelling

Assume a cellular IPv6 network consists of N nodes and G domains, where each domain has K modes.

Thus, $G = \lceil N/K \rceil$ also represents the number of gateways equipped in the network. Suppose that mobile hosts may travel between *N* nodes randomly. It means that each MH may visit a node more than once and also may move back and forth between two modes. Since active MHs and idle MHs have different rules and mechanisms for their location tracking as discussed in the last section, their location tracking are modelled separately.

Assume a *movement* occurs whenever an active MH moves out of a node. Therefore, the movements of the MH can be modelled as a discrete system [8]. At moment *1*, the MH may reside in cell *1, 2, ..., N*, where a *cell* represents the coverage of a cellular IP node in which it can communicates with MHs. At moment *2*, the MH may move to any of the other *N-1* cells. Assuming that the MN will move out to the other *N-1* cells with probability *1/(N-1)*. Thus, the probability of an active MH moving out of one domain with size *k* at moment *m* is

$$P_a^m = \frac{N-k}{N-1}\left(\frac{k-1}{N-1}\right)^{m-2},$$

$$\text{where } 2 \le m < \infty \qquad (1)$$

It notes that P_a^m also represents the probability of the MN performing a home registration at moment *m*, where *m* is a random variable. Thus, the expectation of M can be expressed as

$$E_a[M] = \sum_{m=2}^{\infty} m P_a^m = \frac{N-1}{N-k} + 1 \qquad (2)$$

The average location update cost consists of two parts, the route update cost within the domain and the home registration cost when the MH moves out the domain. Assume the average time an MH stays in a cell of each domain before making a movement is τ. Thus, the average location update cost can be obtained by

$$C_{LU-a} = \frac{C_{H-a}}{E_a[M]\tau} + \frac{C_a}{\tau} \qquad (3)$$

where C_a and C_{H-a} are the route update cost and the home registration cost for the active MH respectively. The details of evaluating C_a and C_{H-a} will be given in the next subsection.

Cellular IP allows idle MHs to roam large geographic area without the need to transmit location update packets at cell borders, instead, at the border of PAs. Assume each PA has *J* nodes. Similar to deriving Equation (1), the probability of an idle MH moving out of a PA within a domain with size k at moment *x* is

$$P_i^x = \frac{k-J}{k-1}\left(\frac{J-1}{k-1}\right)^{x-2},$$

$$\text{where } 2 \le x < \infty \qquad (4)$$

Thus, P_i^x also represents the probability of an idle MH performing a paging-update at moment *x*. Further, it can be shown that the expectation of random variable *X* is

$$E_i[x] = \sum_{x=2}^{\infty} x P_i^x = \frac{k-1}{k-J} + 1 \qquad (5)$$

As a result, the average location update cost for an idle MH is expressed as

$$C_{LU-i} = \frac{C_i}{E_i[X]\tau} + \frac{C_{H-i}}{E_a[M]\tau} \qquad (6)$$

where C_i is the paging-update cost for the idle MH in the domain and C_{H-i} is its home registration cost. The calculation of these two costs will be also discussed in the next subsection.

3.2 Signalling Cost Function

The signalling cost in a cellular IP network deals with the cost of *location update* and *packet delivery*. The performance metric of the network is evaluated based on the total signalling cot in this paper.

3.2.1 Location Update Cost

For an active MH its location cost consists of two parts, C_a and C_{H-a}, as mentioned before. The cost of route-update for the active MH, C_a, is due to its location change from one cell to another within a domain. C_a includes the transmission cost for route-update packet delivery and the processing cost for route update at the nodes it travelled through. Thus, C_a may be evaluated as below:

$$C_a = \varphi_{bs} + \varphi_{ho} + (\mu l_{bg} + \omega)\delta_{ua} \quad (7)$$

where φ_{bs} is the processing cost at a *base station* (or a cellular IP node) through which the active MH is permitted to access the cellular network; φ_{ho} is the processing cost of handoff when the active MH moves from one node to another node. Let l_{bg} be the average distance between the base station the active MH currently attached and the gateway, through which the MH delivers IP packets to the Internet. The distance is measured in terms of the number of hops between them. Assume that the transmission cost is proportional to the distance between the source and the destination and the proportionality constant is δ_{ua}. Since the transmission cost of the wireless link is higher than that of the wired link, it is assumed that the transmission cost over the wireless link is ω times higher than the unit distance wire-line transmission cost. Therefore, the transmission cost between the MH and the gateway is expressed as $(\mu l_{bg} + \omega)\delta_{ua}$ in Equation (7), where $\mu \geq 1$ is used for adjusting the cost of wired or wireless links on the path between the base station and the gateway.

When an active MH moves out of a domain, it performs location update via its home agent and this cost is represented by C_{H-a}, which is calculated as below.

$$C_{H-a} = C_a + \varphi_m + \varphi_g + \varphi_h + 2l_{gh}\delta_{hu} \quad (8)$$

where φ_m is the processing cost at the MH for getting a new care-of address; φ_g and φ_h are the processing cost of location update for the home registration at the gateway and at the home agent respectively. Similarly, l_{gh} represents the distance between the gateway and the home agent and δ_{hu} is the proportionality constant for the transmission cost between the gateway and the home agent.

The cost of paging-update for an idle MH within a domain, C_i, is due to its location change from one paging area to another. Using the similar method above, C_i can be expressed as

$$C_i = \varphi_{bs} + (\mu l_{bg} + \omega)\delta_{ui} \quad (9)$$

It notes that there is no cost for handoff with idle MH. Similar to δ_{ua}, δ_{ui} is the proportionality constant for the transmission cost between the idle MH and the gateway. When the idle MH moves out of a domain, it also performs location update via its home agent and this cost is denoted as C_{H-i}, which can be further computed by

$$C_{H-i} = C_i + C_{H-a} - C_a \quad (10)$$

Suppose an MH enters active state or idle state at a time with probabilities p_a and p_i respectively, where $p_a + p_i = 1$. Base on Equations (1) – (10), the average location update cost for the MH, C_{LU}, can be obtained by

$$C_{LU} = p_a C_{LU-a} + p_i C_{LU-i} \quad (11)$$

where C_{LU-a} and C_{LU-i} were introduced in the last subsection.

3.2.2 Packet Delivery Cost

The cost function for packet delivery from a CN to an MH in cellular IP network can be derived based on two cases, as shown as Figure 2.

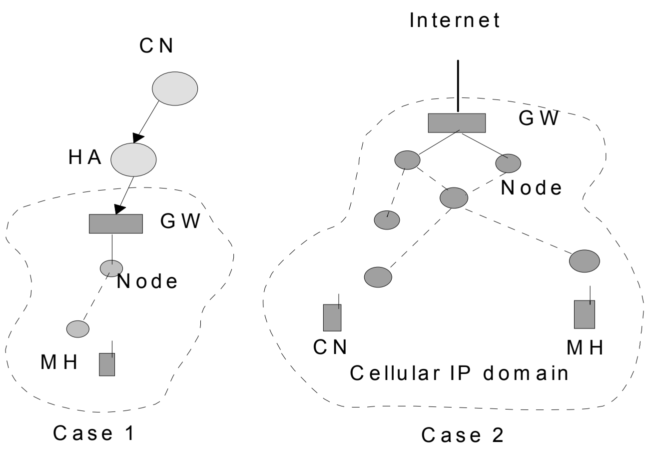


Figure 2: Two cases for IP packets delivery from CN to MH

In Case 1 every IP packet destined for an MH is first intercepted by the home agent and then tunnelled to the gateway, through which it is forwarded to the MH. The packet delivery cost includes both transmission and processing. The transmission cost in Case 1 is expressed as

$$T_1 = (l_{ch} + l_{hg} + \mu l_{gb} + \omega)\delta_d \quad (12)$$

where l_{ch} is the distance between the CN and the HA; l_{hg} is the distance between the HA and the gateway; l_{gb} is the distance between the gateway and the base-station currently serving the MN; δ_d represents the proportionality constant for the transmission cost in this case.

In Case 1 the processing cost deals with processing IP packets at the gateway and the HA. The processing cost at the gateway includes decapsulation of the tunnelled IP packets from the HA, looking up route and paging-caches and checking if there is an entry for the destined MH in the caches. The load of the gateway for processing and routing packets also depends on the number of nodes, *k*, in the domain. If *k* is large, the complexity of route and paging caches look up in the gateway is high and thus, the system performance is degraded. Since the total bandwidth of a domain is limited, if the traffic to the gateway is heavy, the transmission delay and the number of retransmission cannot be bounded. Suppose the average number of MHs in a cell is *S*. The average number of MHs in a domain becomes *kS*. Further, the complexity of the gateway caches lookup is proportional to *kS*. Since the route and paging caches lookup is similar to a route table lookup, the complexity of MH entry lookup is proportional to the logarithm of the length of the caches [9]. Therefore, the processing cost at gateway is expressed as

$$G_{PD} = \lambda \xi k(\alpha S p_a + \beta S p_i) \quad (13)$$

where λ is the packet arrival rate for each MH; α and β are weighting factors of route-update cache with active MHs and paging-update cache with idle MH respectively; ξ is a constant which characterizes the bandwidth allocation cost at the gateway. The larger the ξ is, the more negative effects an MH experiences due to not enough network bandwidth available. The processing cost function at the HA may be simply defined as

$$H_{PD} = \lambda \vartheta \quad (14)$$

where ϑ is a packet delivery processing cost constant at the HA. As a result, the packet delivery cost in Case 1 is given by

$$W_{PD-out} = T_1 + G_{PD} + H_{PD} \quad (15)$$

Suppose the route optimization option is employed in Case 2, where the CN can send IP packets to the MN directly without the assistance of the HA since both the CN and MH are located in the same domain. Consider the topology of a cellular IP domain network as a tree approximately, where the gateway plays a role of the root. The largest path from an MH to the gateway is $\log_b k$, where b is the average number of the network interfaces equipped in each base station, through which it communicates with its neighbours. Thus, the processing cost in Case 2 may be obtained by

$$W_{PD-in} = 2\delta_d \log_b k + \varphi_c \qquad (16)$$

where φ_c denotes the processing cost at crossover node; $2\log_b k$ represents the distance between the CN and the MH via a crossover node and δ_d is the proportionality constant for transmission cost between them. The total packet delivery cost per unit time for an MH, C_{PD}, is summed up as below.

$$C_{PD} = p_{in} W_{PD-in} + (1 - p_{in}) W_{PD-out} \qquad (17)$$

where p_{in} represents the probability of both the CN and MH reside in the same domain when they communicate with each other. Based on the above analysis, the average signalling cost per time unit for an MH, *C*, can be finally evaluated by

$$C = C_{LU} + C_{PD} \qquad (18)$$

where C_{LU} was given in Section 3.1.

3.3 Optimization

In order to achieve the optimal system design for a cellular IPv6 network with multiple gateways, an optimization method is introduced in this section.

The optimal number of cellular IP nodes in a domain is defined as the value of *k* that minimizes the cost function as given in Equation (18). Similar to the algorithms introduced in [10] the cost difference function between the system with *k* and the system with *k-1* ($k \geq 2$) is derived as

$$\Delta C(k, \lambda, \tau) = C(k, \lambda, \tau) - C(k-1, \lambda, \tau) \quad (19)$$

where λ and τ are the average packet arrival rate and the average residence time in a cell for all MH respectively. Since *k* is an integer and the cost function is not a continuous function of *k*, it is not appropriate to take derivative with respect to *k* of the cost function to get the minimum. However, given ΔC, the solutions to solving the local minimum can be obtained based on an iterative algorithm as below:

$$k_{opt}(\lambda, \tau) = \begin{cases} 1, & if \quad \Delta C(k=2, \lambda, \tau) > 0 \\ \max\{k : \Delta C(k, \lambda, \tau)\}, & otherwise \end{cases}$$

Once k_{opt} is found out, the optimal number of gateways can be determined by $G_{opt} \approx N / k_{opt}$, where *N* is the total number of nodes in the cellular IP network.

4. Algorithm

To find k_{opt} in various situations depends on the specification of many parameters as defined in the last section. Since the computation for k_{opt} is a tedious work, an alternative algorithm for the optimal system design is proposed in this section, which can be easily used in practice.

In order to find the optimal number of gateways for a cellular IPv6 network, one practical problem is that when the size (or traffic load) of a domain becomes large, the system designer must decide if the "large" domain is broken into two "small" domains. In other words, it is necessary to find a way to make decision between the two schemes, using one large domain or two small domains, so as to achieve the best system performance. This is can be achieved by a decision algorithm which is proposed as the followings.

Suppose that vector $\vec{V}$ contains the value of all of the system parameters, such as *N, k, J,* λ, τ, l_{bg}, φ_{bs} and the others, which are defined for calculating the cost functions in Equations (1)-(18). Similar to the analysis in PCS networks, the *call-to-mobility ratio*

(CMR) is defined as the ratio of the packet arrival rate to the mobility rate, i.e., $CMR = \lambda\tau$. The cost function (18) may be rewritten as

$$C = f(CMR, \vec{V}).$$

Thus, the average signalling cost per time unit for each MH, *C*, is a function of variable *CMR* given the value of $\vec{V}$. Further, denote $C_{large}(CMR)$ and $C_{small}(CMR)$ as the cost functions of the large domain and the two small domains respectively.

Decision Algorithm:

- Specify the values of $\vec{V}$
- For each $CMR = r_i$, $i = 1,2,...,I$, and $r_i < r_{i+1}$, calculate $\vec{C}_L(r_i) = \{C_{large}(r_i) \mid i = 1,2,...,I.\}$ and $\vec{C}_S(r_i) = \{C_{small}(r_i) \mid i = 1,2,...I.\}$
- Compare $\vec{C}_L(r_i)$ with $\vec{C}_S(r_i)$

  Case 1: If $\vec{C}_L(r_i) > \vec{C}_S(r_i)$ for all r_i
  Choose the design with two small domains.

  Case 2: If $\vec{C}_L(r_i) \le \vec{C}_S(r_i)$
  Choose the design with a large domain.

  Case 3: If $\vec{C}_L(r_i) > \vec{C}_S(r_i)$ for r_i, $i = 1,2,...,R$ and $\vec{C}_L(r_i) \le \vec{C}_S(r_i)$ for r_i, $i = R+1, R+2,...,I$
  The decision is subject to the requirement of the *CMR*. If the *CMR* requirement is lower, or $CMR \le r_R$, choose the design with two small domains, otherwise, choose a single large domain design, where r_R is a critical value of *CMR*.

  Case 4: It is an opposite situation of Case 3. The same principle of the decision as in Case 3 can be applied.

Comparing with calculating the optimal size of a domain, k_{opt}, as shown in the last section, this algorithm is considerably simple in use without losing the original goal. Thus, it is more practical.

5. Numerical Results

As discussed in the last section, the design algorithm is based on the computation of the cost function for a cellular IPv6 network domain. In this section, a number of typical cases addressed in the algorithm are demonstrated numerically. Suppose that the system specification vector, $\vec{V}$, is initialized based on the values given in table 1, for examples, *J=4*, . φ_h=25 and α=0.3.

Table 1: A set of initialized values for the system specification vector, $\vec{V}$.

J	φ_{bs}	φ_{ho}	μ	l_{bg}	ω	δ_{ua}	φ_m	φ_g
4	10	10	0.5	4	10	0.8	15	20
φ_h	l_{gh}	δ_{hu}	δ_{ui}	p_a	p_i	l_{ch}	δ_d	ξ
25	10	0.1	0.6	0.2	0.8	10	0.3	0.1
α	β	S	ϑ	b	φ_c	p_{in}	p_{out}	N
0.3	0.7	100	5	4	10	0.8	0.2	30

The performance comparison of the average costs between a large domain and the two small domains is given in Figure 1, where the large domain has $N = 30$ nodes and each of the small domains has 15 nodes. The specifications of all the other parameters are the same for the both schemes as shown in Table 1. The result shows the cost of the large domain is lower under all the conditions of *CBR*. This corresponds to Case 2 in the algorithm. Thus, the large domain will be selected.

Figure 1: Result for Case 2 in the decision algorithm

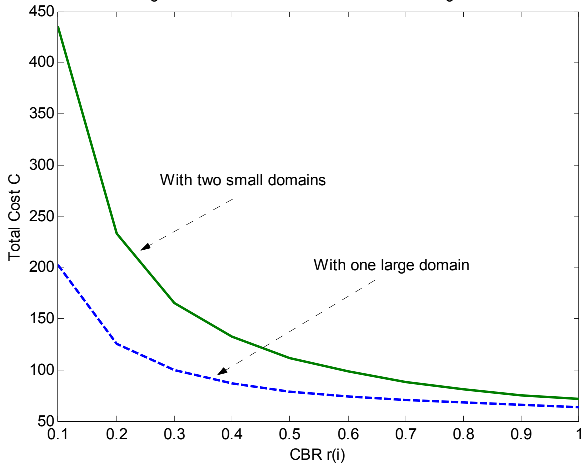
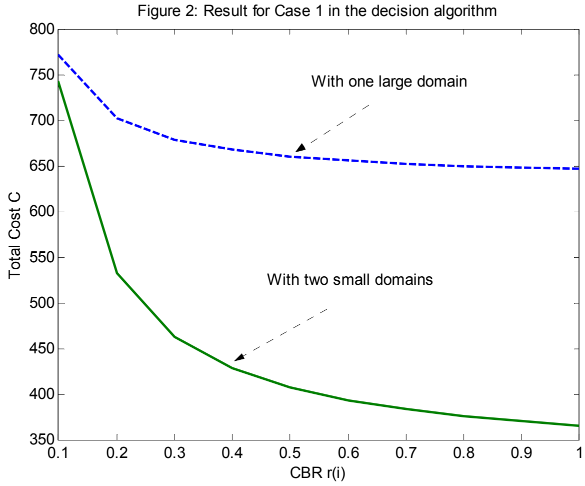


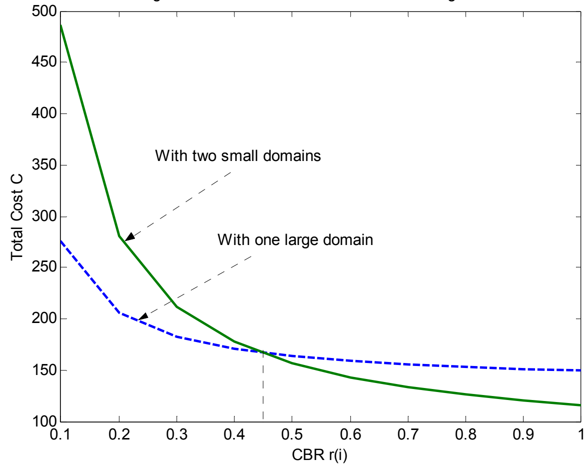
Figure 2: Result for Case 1 in the decision algorithm



If we change the size of the large domain to $N = 500$ (or each of small domains has 250 nodes) and retain the rest of specifications, the result of the performance comparison between the two schemes is shown in Figure 2, which is opposite to Figure 1. In this situation, the two small domains should be employed. It illustrates Case 1 analysed in the algorithm.

If the size of the large domain changes to $N = 100$, the result of Case 3 discussed in the algorithm takes place, which is demonstrated in Figure 3. In such situation, the large domain is selected if the *CBM* requirement is lower than $R = 0.45$, where $R = 0.45$ is the critical point for making decision. Otherwise, the scheme with the two small domain should be adopted.

Figure 3: Result for Case 3 in the decision algorithm



Conclusions

It is a practical issue to find the optimal design for a Cellular IP network with multiple gateways, as it depends on many factors, such as the network size, traffic load, user population, user mobility and routing algorithm. This paper presented an analytical model for Cellular IP networks with multiple gateways. Based on this model, a theoretical optimization can be obtained. In order to use this model easily in practice, a decision algorithm was developed and its numerical examples were demonstrated.

References

[1] A. T. Campbell, Gomez, J., Kim, S., Turnyi, Z., Wan, C-Y, and A, Valko, "Design, Implementation and Evaluation of Cellular IP", IEEE Personal Communications, June/July 2000.

[2] Andrew T. Campbell, Jaview Gomez, Sanghyo Kim, and Chieh-Yih Wan, "Comparison of IP Micro-mobility Protocols", IEEE Wireless Communications, February 2002.

[3] A. Valko, "Cellular IP – new approach of Internet host mobility", ACM Computer Communication Reviews, January, 1999.

[4] A. T. Campbell, J., Kim, S., Turnyi, Z., Wan, C-Y, and A, Valko, “Internet Micromobility”, Journal of High Speed Networks, Special Issue on Multimedia in Wired and Wireless Environment, Vol. 11, No. 3-4, pp.177-198, September 2002.

[5] Zach D. Shelby, Dionisios Gatzounas, Andrew Campbell, and Chieh-Yih Wan, “Cellular IPv6”, <draft-sheby-cellularipv6-01.txt>, Internet Draft, July 2001.

[6] Zach D. Shelby, Petri Mahonen, Dionisios Gatzounas, Alessandro Inzerilli, and Ville Typpo, “Cellular IP route Optimization”, <draft-shelby-cip-routeoptimizationn-00.txt”.

[7] D. Johnson and C. Perkins, “Mobility Support in IPv6”, <draft-ietf-mobileip-ipv6-24.txt>, June 2003.

[8] J. Xie and I.F Akyildiz, “A Novel Distributed Dynamic Location Management Scheme for Minimizing Signalling Coast in Mobile IP”, IEEE Transactions on Mobile Computing, July-September 2002.

[9] H.-Y. Tzeng and T. Przygienda, “On Fast Address-Look Algorithms”, IEEE J. Selected Area in Comm. (JSAC), vol. no. 6, pp.1067-1082, June 1999.

[10] H. Xie, S. Tabbane, D. J. Goodman, “Dynamic Location Area Management and Performance Analysis”, Proc. 43rd IEEE Vehicular Technology Conf., pp. 536-539, 1993.

[11] Z.D. Wu, “An Approach for Optimizing Binding Lifetime with Mobile IPv6”, Proc. of 28th IEEE Conference on Local Computer Networks”, pp.82-88, 2003.