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WiMAX Location Update for Vehicle Applications

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Abstract In IEEE 802.16e mobile Worldwide Interoperability for Microwave Access (WiMAX), paging groups (PGs; groups of base stations) are used to identify the locations of mobile stations (MSs). An anchor paging controller (APC) is assigned to an MS to handle location tracking for the MS. During location update, the WiMAX network may or may not relocate the APC. This paper considers a linear WiMAX base station layout for vehicle applications, where a base station serves as a roadside unit, and a WiMAX MS installed in a vehicle serves as an onboard unit. In these vehicle applications, APC relocation may significantly affect the network traffic. This paper proposes an analytic model to study the performance of the location update with/without APC relocation. Our study provides guidelines to utilize the APC relocation for vehicles with various moving behaviors.

Keywords intelligent transportation systems · location update · mobility management · paging group

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1 Introduction

IEEE 802.16e mobile *Worldwide Interoperability for Microwave Access* (WiMAX) provides broadband wireless services with wide service coverage, high data throughput, and high mobility [9–11]. In Taiwan, an important WiMAX usage is to provide broadband access for vehicles. Figure 1 illustrates Taiwan WiMAX experience bus where people in the bus enjoy applications such as GPS/Navigation, portable digital TV, multimedia player, and so on.

Figure 2 shows a simplified WiMAX network architecture, which consists of the *connectivity service networks* (CSNs; see Fig. 2a) and the *access service networks* (ASNs; see Fig. 2b). An ASN provides radio access (such as radio resource management, paging and location management) to the WiMAX *mobile station* (MS; Fig. 2i). The ASN comprises *ASN gateways* (ASN-GWs; see Fig. 2c) and WiMAX *base stations* (BSs; see Fig. 2d). Every ASN-GW connects to several BSs. The ASN-GWs are also connected to each other to coordinate MS mobility. A CSN consists of network nodes such as the *mobile IP* (MIP) [4] *home agent* (HA; see Fig. 2f), the *authentication, authorization, and accounting* (AAA) server (see Fig. 2g) and the *dynamic host configuration protocol* (DHCP) server (see Fig. 2h). The CSN provides IP connectivity (such as Internet access and IP address allocation) to a WiMAX MS and interworks with the ASNs to support capabilities such as AAA and mobility management. Before an MS is allowed to access WiMAX services, it must be authenticated by the ASN-GW (which serves as the *authenticator*) and the AAA server in the CSN.

In Taiwan, a linear layout with 27 WiMAX BSs has been deployed from Taipei to Taoyuan International

Fig. 1 (*Left*) WiMAX experience bus; (*right*) broadband wireless access in the bus

Airport to cover highway and local road traffics (the distance is 30 km). The network is anticipated to extend to 679 BSs in north Taiwan for more general broadband wireless applications [5]. One of the applications aims for *intelligent transportation systems* (ITS) where the WiMAX BSs can be viewed as roadside units and the MSs are onboard units [2, 3, 6, 13]. In ITS applications, high mobility of vehicles may significantly affect network signalling overhead for location tracking, which is investigated in this paper.

We first introduce the WiMAX location tracking mechanism. In WiMAX, two *subscriber modes* characterize the activities of an MS attached to the network. In the *normal* mode, the MS sends or receives packets

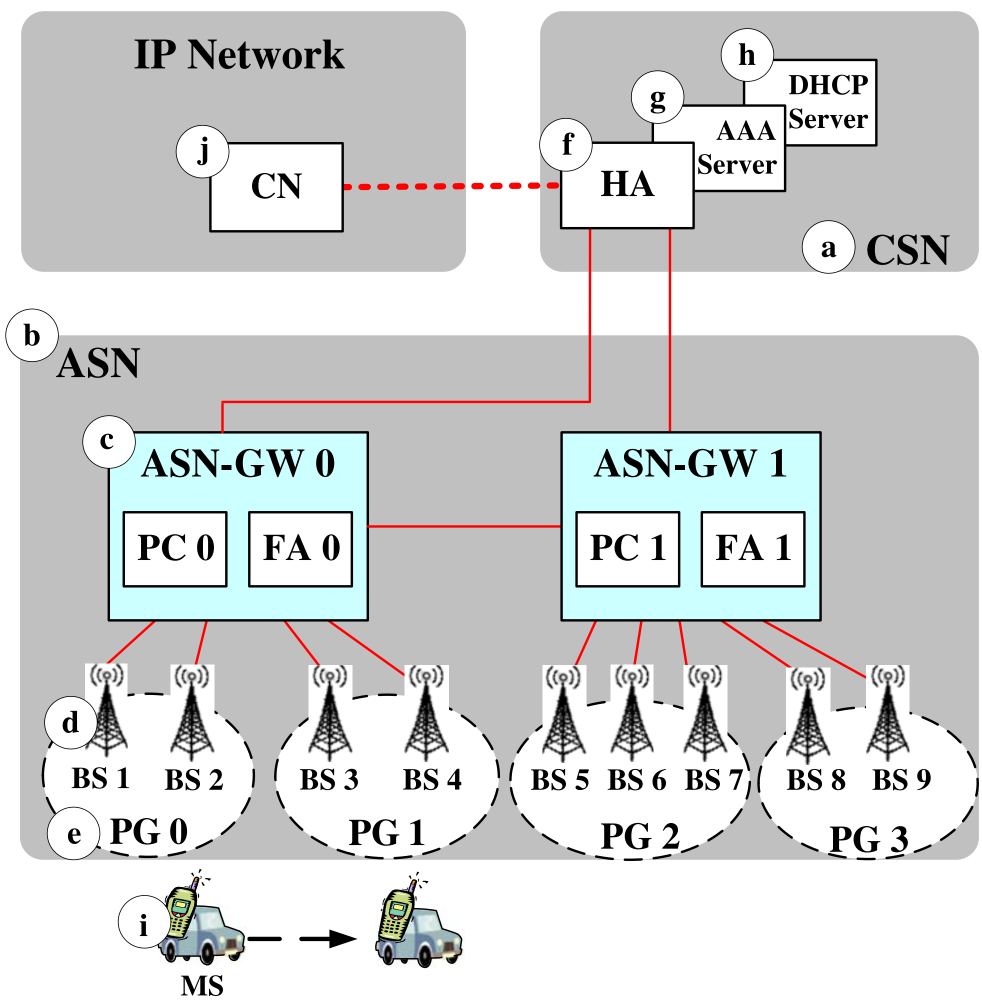


Fig. 2 A simplified WiMAX network architecture

to/from a BS. When there is no data transmission for a period, the MS switches from the normal mode to the *idle* mode to conserve resources.

Several procedures defined in WiMAX are exercised when the MS is in the idle mode. For example, the *location update* (LU) procedure is exercised for location tracking of an MS [1]. When there are incoming packets for the idle MS, the *paging* procedure is exercised to alert the MS. Then the MS performs the *idle mode exit* procedure to return to the normal mode and starts data transmission. In the control plane, the *paging controller* (PC) in an ASN-GW (see Fig. 2c) handles the location tracking and the paging operations for the idle MSs. All BSs connected to a PC are partitioned into several *paging groups* (PGs; see Fig. 2e). The PGs are used for MS tracking. For each MS in the idle mode, the network assigns a PC called the *anchor PC* (or APC) to the MS. Every APC is associated with a database called *location register* (LR) that contains the MS tracking and paging information of the idle mode MSs. The information includes the current PG where the MS resides, the paging parameters, the QoS profiles, etc. Suppose that an MS in the normal mode enters the idle mode through PG 0 in Fig. 2, and PC 0 serves as the APC of the MS. When this idle MS moves from PG 1 to PG 2, it performs LU procedure to inform its APC (i.e., PC 0) of the new location through PC 1. After location update, PC 1 serves as the *relay PC* for the MS and all PC-related control messages are delivered between PC 0 (the APC) and the MS indirectly through PC 1.

When the MS enters the normal mode, data transmission with handover is supported by the MIP. In Fig. 2, assume that an MS first enters the WiMAX network (in the normal mode) and obtains an IP address through ASN-GW 0. The MS then registers to the HA (see Fig. 2f) in the CSN to indicate that the *foreign agent* (FA) is FA 0 associated with ASN-GW 0 (see Fig. 2c). At this point, the MS can start data transmission with a *corresponding node* (CN; see Fig. 2j). When the MS moves from BS 4 to BS 5, the local ASN-GW is changed from ASN-GW 0 to ASN-GW 1. The data between FA 0 and the MS is then delivered through ASN-GW 0, ASN-GW 1 and BS 5.

In WiMAX, the APC is only defined in the idle mode and does not play any role in the normal mode. When an MS switches from the idle mode to the normal mode, the APC is no longer associated with the MS; i.e., the MS information is removed from the LR of the APC (through the idle mode exit procedure). When the MS enters the idle mode again, a new APC is assigned to the MS by exercising the *idle mode entry* procedure. In the idle mode, WiMAX provides two alternatives to reassign the APC during the MS movement: *static* or *dynamic*. When the MS moves from an old PG to a new PG, the APC can be dynamically reassigned during the LU procedure. If the APC reassignment occurs frequently, these APC/LR relocations result in extra network signalling overhead. On the other hand, if the APC reassignment occurs infrequently, the APC may be far away from the MS after several movements. In this case, long delays for message exchange will be expected in the LU procedures. This paper analyzes the cost for the APC/LR reassignment under Taiwan's linear WiMAX BS layout for ITS.

This paper is organized as follows. In Section 2, we describe the LU procedure. Section 3 illustrates two scenarios to study the cost for the APC/LR relocation due to MS (vehicle) mobility. Section 4 numerically compares these two scenarios.

2 The location update procedure

This section describes the location update (LU) procedure exercised in the idle mode [10, 11]. Figure 3a illustrates how the LU procedure is performed when an idle MS moves from a BS in PG 1 to another BS in PG 2. Without loss of generality, we assume that PC 0 is the MS's APC, and both the APC (PC 0) and the FA (FA 0) are collocated in ASN-GW 0. We also assume that a specific ASN-GW serves as the idle MS's authenticator. When the idle MS moves to ASN-GW 1, the relay PC (e.g., PC 1 in Fig. 3a) may become the APC. For the description purpose, let S_R be the LU scenario with APC relocation and S_W be the LU scenario without APC relocation. The LU procedure with APC relocation scheme S_R is described as follows (see S_R in Fig. 3a):

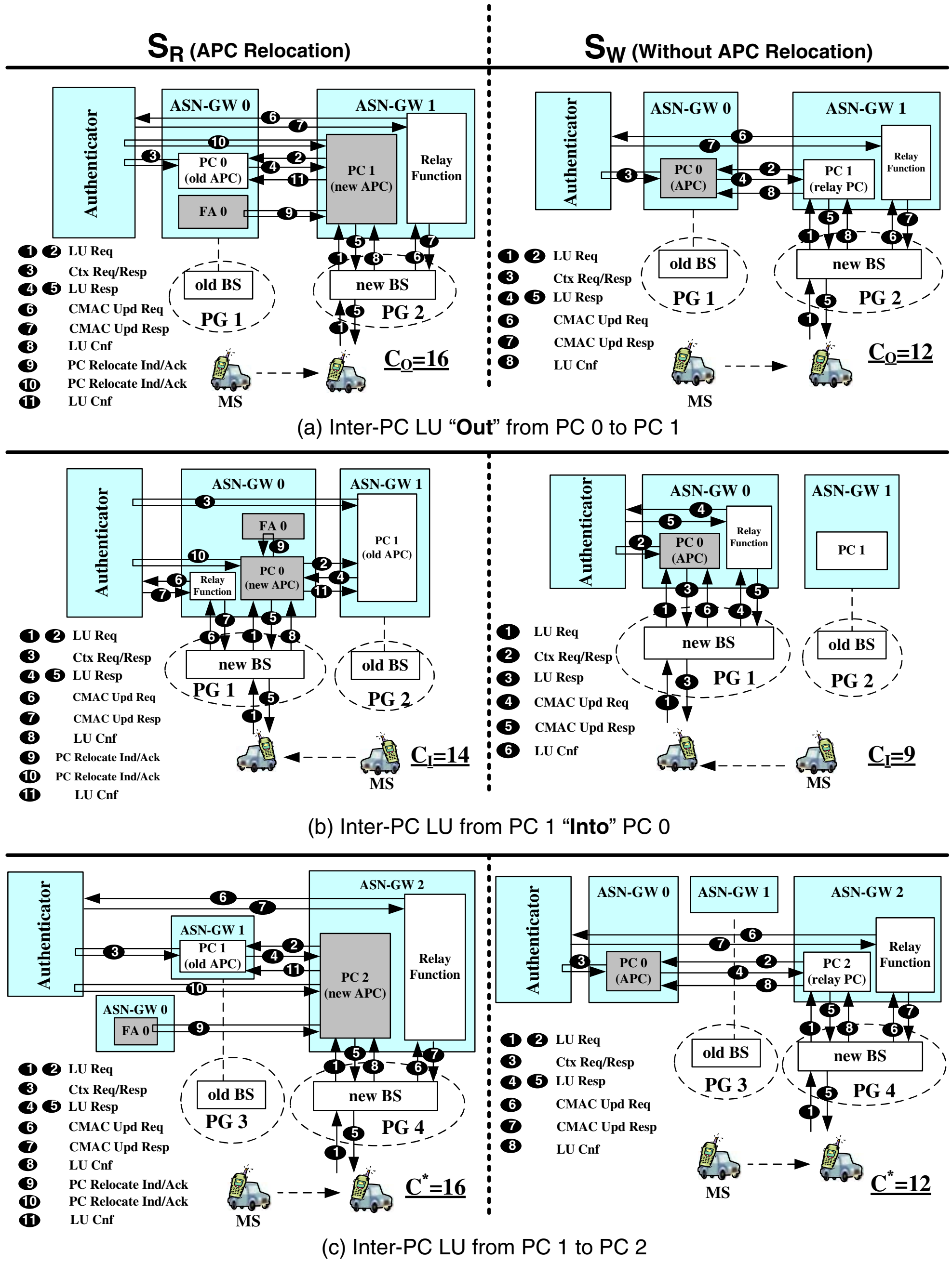
Step 1 The MS moves from PC 0 to PC 1. Through the new BS, the MS sends an **LU Request** message to PC 1.

Step 2 PC 1 decides to relocate the APC and selects itself as the APC. The **LU Request** message is forwarded to PC 0 with a relocation indicator.

Step 3 PC 0 retrieves the *Authorization Key* (AK) context from the authenticator through the **Context Request/ Response** message exchange.

Steps 4 and 5 The LU result (with the AK context and the MS's record data) is delivered to PC 1 by the **LU Response** message. PC 1 stores the received information (including the MS's new location) in its LR. The **LU Response** message

Fig. 3 Flows of Inter-PC LUs with signalling costs (**a**–**c**)



then carries the AK context (to be retrieved by the new BS) and the LU result (for the MS).

Steps 6 and 7 To prevent the replay attack, the new BS updates *Cipher-based Message Authentication Code* (CMAC) *Key Count* (the latest counter value for the MS's request message) with the authenticator through the **CMAC Update Request/Response** message exchange.

Step 8 The new BS notifies PC 1 of the completion of the LU procedure by an **LU Confirm** message.

Steps 9 and 10 PC 1 informs both the MS's FA (i.e., FA 0) and authenticator about the APC relocation through the **PC Relocation Indication/Acknowledge** message exchange.

Step 11 PC 1 informs PC 0 that the LU procedure is completed by the **LU Confirm**

message. After receiving the message, PC 0 removes the MS's record from its LR.

The LU procedure without APC relocation (see S_W in Fig. 3a) is similar to that with APC relocation, except that Steps 9 and 10 are eliminated. For S_W in Fig. 3a, PC 1 serves as the relay PC, and no relocation indicator is added in the **LU Request** message in Step 2. Therefore, the network needs not to transfer the MS data to the new APC/LR in Step 4.

3 Analytic analysis

This section studies the expected location update cost during the idle period. When the MS enters the idle mode, we assume that PC 0 is assigned as its APC and is collocated with its FA (FA 0). A location update can be an inter-PC LU (e.g., from BS 4 to BS 5 in Fig. 2) or an intra-PC LU (e.g., from BS 2 to BS 3 in Fig. 2), and the associated costs are elaborated below. In our study, the network signalling cost is measured through the messages exchanged between the network nodes.

- C_O: the cost of an inter-PC LU "Out" from PC 0 (to any neighboring PC; see Fig. 3a). For S_R, $C_O = 16$. For S_W, $C_O = 12$.
- C_I: the cost of an inter-PC LU from the neighboring PCs "Into" PC 0 (see Fig. 3b). For S_R, $C_I = 14$. For S_W, $C_I = 9$.
- C^*: the cost of an inter-PC LU without involving PC 0 (see Fig. 3c). For S_R, $C^* = 16$. For S_W, $C^* = 12$.
- c: the cost of an intra-PC LU within PC 0 (see Fig. 4a). For both S_R and S_W, $c = 9$.
- c^*: the cost of an intra-PC LU in any PC other than PC 0 (see Fig. 4b). For S_R, $c^* = 9$. For S_W, $c^* = 12$.
- C: the expected cost of an LU in the idle mode.

We propose an analytic model to study the expected LU cost C for both S_R and S_W. Figure 5 shows the MS movement state-transition diagram with the linear configuration of PGs and PCs. Figure 5a illustrates the state-transition diagram for the MS movement among PGs. We use a one-dimensional linear layout of PGs to represent an extension of Taiwan's WiMAX-based ITS deployment described in Section 1, where state i represents that the MS visits PG i ($-\infty < i < \infty$). The MS moves from state i to states $i+1$ and $i-1$ with probabilities p and $1-p$, respectively. Let P_j^k be the probability that from PG 0, the MS visits PG j after k PG movements, where $k \geq 0$. From the state-transition diagram in Fig. 5a, P_j^k is derived as follows. For $j \geq 0$

$$P_j^k = \begin{cases} \binom{k}{\frac{k-j}{2}} p^j \left[p(1-p)\right]^{\frac{k-j}{2}}, & k \geq j \geq 0 \text{ and } k-j \text{ is even} \\ 0, & \text{otherwise} \end{cases}. \tag{1}$$

Note that Eq. 1 is partially validated for $j = 0$ and $p = 1-p = 0.5$ [7]. Due to the symmetric PG layout, from Eq. 1, P_j^k for $j < 0$ can be expressed as

$$P_j^k = \begin{cases} \binom{k}{\frac{k+j}{2}} (1-p)^{-j} \left[p(1-p)\right]^{\frac{k+j}{2}}, & k \geq -j > 0 \text{ and } k+j \text{ is even} \\ 0, & \text{otherwise} \end{cases}. \tag{2}$$

Let $P_{i,j}^k$ be the probability that starting from PG i, the MS visits PG j after k PG movements. From Eqs. 1 and 2, the probability $P_{i,j}^k$ can be generalized as

$$P_{i,j}^k = \begin{cases} \binom{k}{\frac{k-(j-i)}{2}} p^{j-i} \left[p(1-p)\right]^{\frac{k-(j-i)}{2}}, & j \geq i, k \geq |j-i| \geq 0 \text{ and } k-|j-i| \text{ is even} \\ \binom{k}{\frac{k+(j-i)}{2}} (1-p)^{-(j-i)} \left[p(1-p)\right]^{\frac{k+(j-i)}{2}}, & j < i, k \geq |j-i| > 0 \text{ and } k-|j-i| \text{ is even} \\ 0, & \text{otherwise} \end{cases}. \tag{3}$$

Based on the above model, we define five parameters to compute C as follows:

- $\Pi_O(k)$: the expected number of the inter-PC movements "Out" from PC 0 (to PC -1 or PC 1) during k PG movements of the MS.
- $\Pi_I(k)$: the expected number of the inter-PC movements from PC -1 or PC 1 "Into" PC 0 during k PG movements of the MS.
- $\Pi^*(k)$: the expected number of the inter-PC movements without visiting PC 0 during k PG movements of the MS.

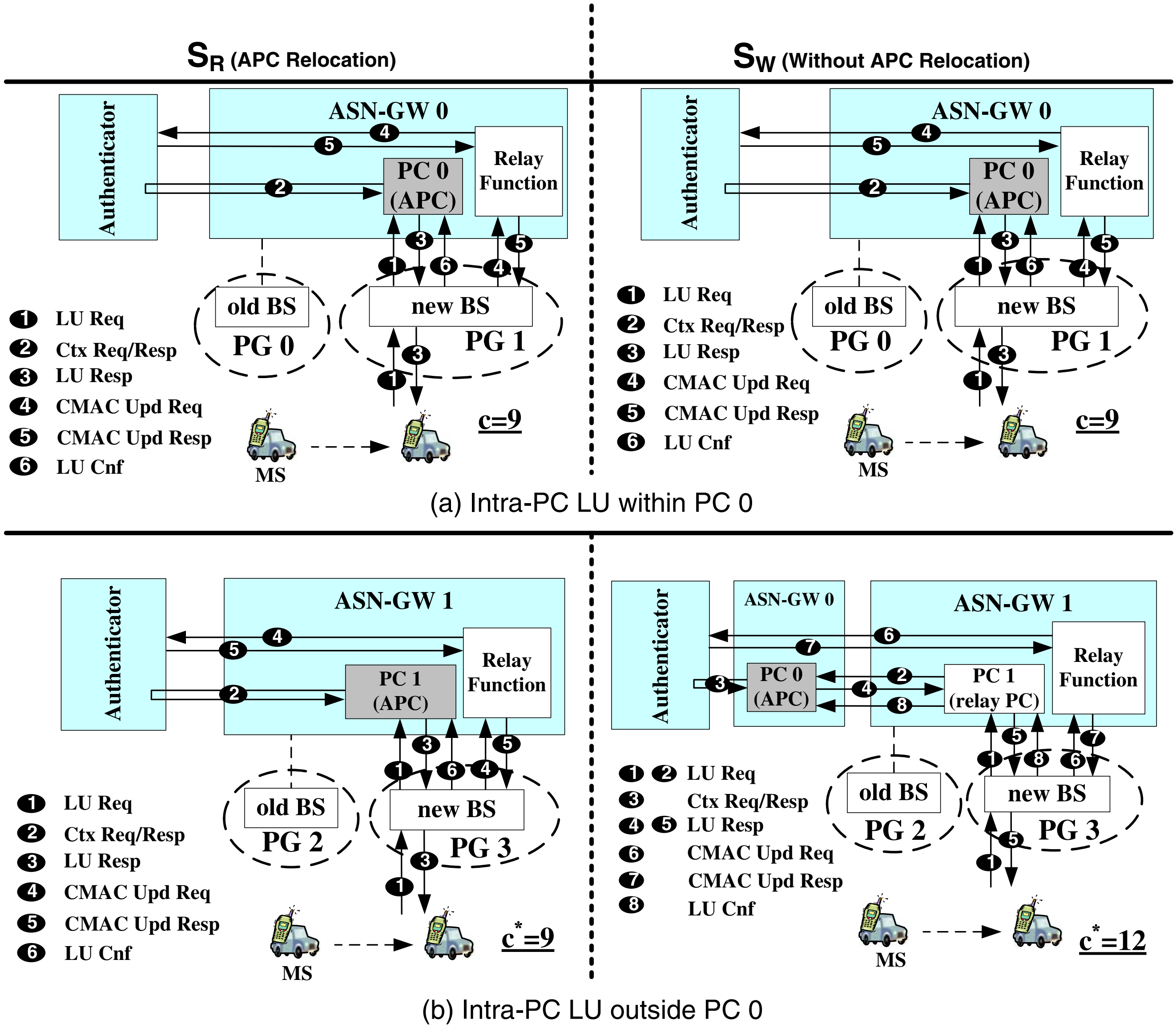


Fig. 4 Flows of intra-PC LUs with signalling costs (**a**, **b**)

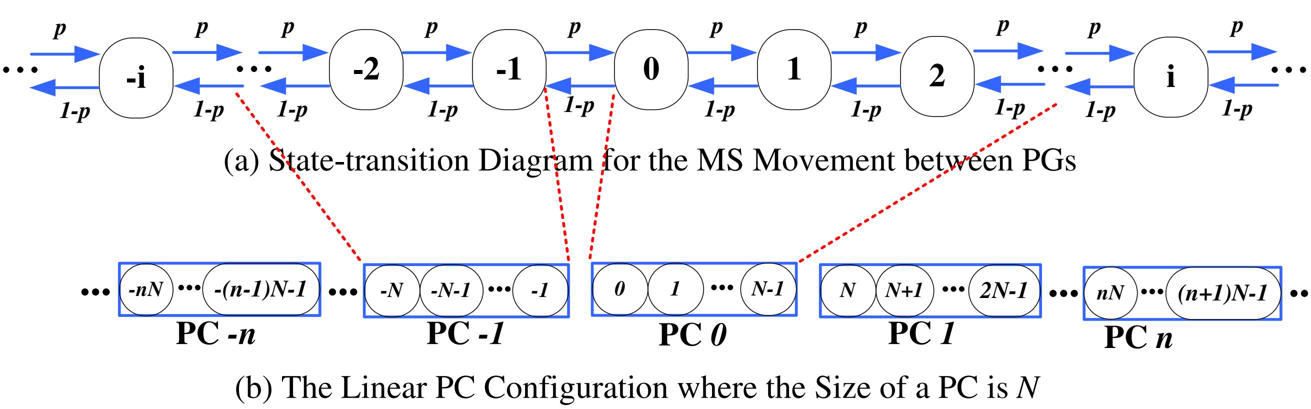


Fig. 5 The MS movement state-transition diagram with linear configuration of PGs and PCs (**a**, **b**)

- $\pi(k)$: the expected number of the intra-PC movements within PC 0 during k PG movements of the MS.
- $\pi^*(k)$: the expected number of the intra-PC movements in any PC other than PC 0 during k PG movements of the MS.

Figure 5b illustrates a PC configuration with linear PG layout to derive the above five parameters. In this figure, every PC consists of N PGs ($N \geq 1$). For example, PC n covers the PGs from nN to $(n+1)N-1$, and PC $-n$ covers the PGs from $-nN$ to $-(n-1)N-1$.

$\Pi_O(k)$ is derived as follows. Starting from PG i, the probability that the MS moves out from PC 0 (i.e., from PG 0 to PG -1 or from PG $N-1$ to PG N) at the m-th PG movement is $(1-p)P_{i,0}^{m-1} + pP_{i,N-1}^{m-1}$. Therefore, during k PG movements, the expected number of inter-PC movements out from PC 0 can be expressed as $\sum_{m=1}^{k}\left[(1-p)P_{i,0}^{m-1} + pP_{i,N-1}^{m-1}\right]$. For simplicity, assume that the MS initially resides in any of the N PGs in PC 0 with the same probability $1/N$. Then

$$\Pi_O(k) = \left(\frac{1}{N}\right)\left\{\sum_{i=0}^{N-1}\sum_{m=1}^{k}\left[(1-p)P_{i,0}^{m-1} + pP_{i,N-1}^{m-1}\right]\right\}. \quad (4)$$

Similar to the derivation of Eq. 4, we have

$$\Pi_I(k) = \left(\frac{1}{N}\right)\left\{\sum_{i=0}^{N-1}\sum_{m=1}^{k}\left[pP_{i,-1}^{m-1} + (1-p)P_{i,N}^{m-1}\right]\right\}. \quad (5)$$

$\Pi^*(k)$ is derived as follows. Starting from PG i ($0 \leq i < N$), after k PG movements, PCs $\pm\left\lceil\frac{k}{N}\right\rceil$ are the farthest PCs that can be visited by the MS, and the probability to make an inter-PC movement between PCs $-l, -l+1$ or between PCs $l, l-1$ at the m-th movement is $\left[pP_{i,-(l-1)N-1}^{m-1} + (1-p)P_{i,-(l-1)N}^{m-1}\right] + \left[pP_{i,lN-1}^{m-1} + (1-p)P_{i,lN}^{m-1}\right]$, where $2 \leq l \leq \left\lceil\frac{k}{N}\right\rceil$. In this case, the probability that at the m-th movement, the MS makes an inter-PC LU without involving PC 0 can be expressed as

$$\sum_{l=2}^{\left\lceil\frac{k}{N}\right\rceil}\left\{\left[pP_{i,-(l-1)N-1}^{m-1} + (1-p)P_{i,-(l-1)N}^{m-1}\right] + \left[pP_{i,lN-1}^{m-1} + (1-p)P_{i,lN}^{m-1}\right]\right\}. \quad (6)$$

From the definition for $\Pi^*(k)$ and Eq. 6, we have

$$\Pi^*(k) = \left(\frac{1}{N}\right)\left\{\sum_{i=0}^{N-1}\sum_{m=1}^{k}\sum_{l=2}^{\left\lceil\frac{k}{N}\right\rceil}\left\{p\left[P_{i,-(l-1)N-1}^{m-1} + P_{i,lN-1}^{m-1}\right] + (1-p)\left[P_{i,-(l-1)N}^{m-1} + P_{i,lN}^{m-1}\right]\right\}\right\}. \quad (7)$$

Note that for $\left\lceil\frac{k}{N}\right\rceil \leq 1$, $\Pi^*(k) = 0$.

To compute $\pi(k)$, we classify the intra-PC movements inside PC 0 into two types.

- First-type: the MS moves to the boundary PGs of PC 0 (i.e., the MS moves from PG $N-2$ to PG $N-1$ or from PG 1 to PG 0 in Fig. 5b).
- Second-type: the MS moves to the non-boundary PGs (e.g., the MS moves from PG $N-1$ to PG $N-2$ or from PG 0 to PG 1 in Fig. 5b with $N \geq 3$).

For $N = 1$, there are no intra-PC movements and $\pi(k) = 0$. For $N = 2$, all PGs are boundary PGs, and no second-type movements are made. For $N \geq 2$, starting from PG i, the expected number of the first-type movements during k PG movements is $\sum_{m=1}^{k}\left[(1-p)P_{i,1}^{m-1} + pP_{i,N-2}^{m-1}\right]$. For $N \geq 3$, the expected number of the second-type movements during k PG movements is $\sum_{m=1}^{k}\sum_{j=1}^{N-2}P_{i,j}^{m}$. Therefore, $\pi(k)$ can be expressed as

$$\pi(k) = \begin{cases} 0, & N=1 \\ \left(\frac{1}{N}\right)\left\{\sum_{i=0}^{N-1}\sum_{m=1}^{k}\left[(1-p)P_{i,1}^{m-1} + pP_{i,N-2}^{m-1}\right]\right\}, & N=2 \\ \left(\frac{1}{N}\right)\left\{\sum_{i=0}^{N-1}\sum_{m=1}^{k}\left[(1-p)P_{i,1}^{m-1} + pP_{i,N-2}^{m-1} + \sum_{j=1}^{N-2}P_{i,j}^{m}\right]\right\}, & N \geq 3 \end{cases}. \quad (8)$$

From Eqs. 4, 5, 7 and 8, we have

$$\pi^*(k) = k - \Pi_O(k) - \Pi_I(k) - \Pi^*(k) - \pi(k). \quad (9)$$

Equations 4, 5, 7 and 8 are validated against the simulation experiments (see Table 1) [12], where the differences are within 2%. Note that due to the symmetric PG

Table 1 Comparison between analytic and simulation results ($k = 39$)

p	0.5	0.6	0.7	0.8	0.9	1.0
$N = 1$						
$\Pi_O(k)$ (analytic)	5.0148	3.9794	2.4783	1.6666	1.25	1
$\Pi_O(k)$ (simulation)	4.9899	3.9488	2.473	1.6729	1.2513	1
Error(%)	0.50	0.77	0.21	0.38	0.54	0
$\Pi_I(k)$ (analytic)	4.0148	2.9794	1.4783	0.6666	0.25	0
$\Pi_I(k)$ (simulation)	3.9899	2.9488	1.473	0.6729	0.2513	0
Error(%)	0.62	1.03	0.36	0.54	0.54	0
$\Pi^*(k)$ (analytic)	29.9703	32.0412	35.0434	36.6668	37.50	38
$\Pi^*(k)$ (simulation)	30.0203	32.1024	35.054	36.6541	37.4973	38
Error(%)	0.16	0.19	0.03	0.03	0.01	0
$N = 2$						
$\Pi_O(k)$ (analytic)	4.5148	3.6036	2.2599	1.5416	1.1944	1
$\Pi_O(k)$ (simulation)	4.4939	3.5678	2.2529	1.5452	1.1961	1
Error(%)	0.46	0.99	0.31	0.23	0.14	0
$\Pi_I(k)$ (analytic)	3.6402	2.6613	1.2645	0.5416	0.1944	0
$\Pi_I(k)$ (simulation)	3.6179	2.6246	1.258	0.5452	0.1961	0
Error(%)	0.61	1.38	0.51	0.66	0.87	0
$\Pi^*(k)$ (analytic)	11.345	13.2352	15.9756	17.4168	18.1111	18.50
$\Pi^*(k)$ (simulation)	11.3908	13.3037	15.988	17.4095	18.1086	18.50
Error(%)	0.40	0.52	0.08	0.04	0.01	0
$\pi(k)$ (analytic)	4.5148	3.4794	1.9783	1.1666	0.75	0.50
$\pi(k)$ (simulation)	4.4921	3.4449	1.9755	1.1714	0.7517	0.50
Error(%)	0.05	0.99	0.14	0.41	0.22	0
$N = 9$						
$\Pi_O(k)$ (analytic)	2.312	2.1995	1.7973	1.3815	1.1406	1
$\Pi_O(k)$ (simulation)	2.3131	2.1983	1.7931	1.3810	1.1406	1
Error(%)	0.05	0.06	0.23	0.03	0.01	0
$\Pi_I(k)$ (analytic)	1.7991	1.4715	0.8366	0.3822	0.1406	0
$\Pi_I(k)$ (simulation)	1.7974	1.4678	0.8339	0.382	0.1406	0
Error(%)	0.09	0.25	0.32	0.04	0.04	0
$\Pi^*(k)$ (analytic)	0.2222	0.6623	1.6995	2.5697	3.0521	3.3333
$\Pi^*(k)$ (simulation)	0.2219	0.6675	1.7063	2.5698	3.052	3.3333
Error(%)	0.17	0.79	0.40	0	0	0
$\pi(k)$ (analytic)	23.0427	18.8287	11.7555	7.4215	5.2461	4
$\pi(k)$ (simulation)	22.9828	18.7273	11.7141	7.4246	5.2476	4
Error(%)	0.26	0.54	0.35	0.04	0.03	0

structure in each PC, the effect for p is identical to that for $1 - p$. Therefore, it suffices to consider $0.5 \leq p \leq 1$ in our study. Our simulation program is written in C++, which works as follows:

Step 1. Decide the PC size N, the right move probability p and the number k of PG movements. (e.g., $k = 39$ for Table 1).

Step 2. An MS is initially assigned to the PGs in PC 0 with the same probability.

Step 3. According to the right move probability p, we randomly generate a series of PG movements for the MS.

Step 4. Log the numbers of each type of the LUs during the k PG movements.

Step 5. Repeat Steps 2–4 for one million times.

Step 6. Use the numbers of LU types obtained from Step 4 to calculate $\Pi_I(k)$, $\Pi_O(k)$, $\Pi^*(k)$, $\pi(k)$ and $\pi^*(k)$.

Let $\Pr[K = k]$ be the probability that during the idle period t, the MS makes k PG movements. Let t have the Gamma distribution [8, 12] with density function $f(.)$, mean $1/\mu$, variance V and Laplace transform

$$f^*(s) = \left(\frac{1}{Vs\mu + 1}\right)^{\frac{1}{V\mu^2}}. \quad (10)$$

Suppose that the residence time of the MS at a PG is exponentially distributed with the mean $1/\lambda$. Then, $\Pr[K = k]$ can be expressed as

$$\begin{aligned}\Pr[K = k] &= \int_{t=0}^{\infty} \Pr[k \text{ LUs in } t]\, f(t)\, dt \\ &= \int_{t=0}^{\infty} \left[\frac{(\lambda t)^k}{k!}\right] e^{-\lambda t} f(t)\, dt \\ &= \left(\frac{\lambda^k}{k!}\right) \int_{t=0}^{\infty} e^{-\lambda t} t^k f(t)\, dt \\ &= \left[\frac{(-\lambda)^k}{k!}\right] \left[\frac{d^k f^*(s)}{ds^k}\right]\Bigg|_{s=\lambda}. \end{aligned} \tag{11}$$

From Eq. 10, for $k \geq 1$, we have

$$\frac{d^k f^*(s)}{ds^k} = (-1)^k V^k \mu^k \left(\frac{1}{V\mu s + 1}\right)^{\frac{1}{V\mu^2}+k} \times \prod_{l=1}^{k} \left(\frac{1}{V\mu^2} + l - 1\right). \tag{12}$$

Substituting Eq. 12 into Eq. 11, $\Pr[K = k]$ is expressed as

$$\begin{aligned}\Pr[K = k] &= \begin{cases} \left(\frac{1}{V\mu\lambda+1}\right)^{\frac{1}{V\mu^2}}, & \text{for } k = 0 \\ \left(\frac{\lambda^k}{k!}\right) V^k \mu^k \left(\frac{1}{V\mu\lambda+1}\right)^{\frac{1}{V\mu^2}+k} \prod_{l=1}^{k} \left(\frac{1}{V\mu^2} + l - 1\right), & \text{for } k \geq 1 \end{cases} \\ &= \begin{cases} \left(\frac{1}{V\mu\lambda+1}\right)^{\frac{1}{V\mu^2}}, & \text{for } k = 0 \\ \binom{\frac{1}{V\mu^2}+k-1}{k} (V\mu\lambda)^k \left(\frac{1}{V\mu\lambda+1}\right)^{\frac{1}{V\mu^2}+k}, & \text{for } k \geq 1 \end{cases}. \end{aligned} \tag{13}$$

From Eqs. 4, 5, 7–9 and 13, the normalized expected cost C of an LU can be expressed as

$$C = \sum_{k=1}^{\infty} \left(\frac{1}{k}\right) \{C_O\, \Pi_O(k) + C_I\, \Pi_I(k) + C^*\, \Pi^*(k) + c\,\pi(k) + c^*\,\pi^*(k)]\} \Pr[K = k]. \tag{14}$$

We note that Eq. 14 is affected by λ/μ (the update rate or the speed to move out of a PG) and p (the moving direction of a vehicle). An MS with large λ/μ and p represents a vehicle moving in highway. An MS with small λ/μ and p represents a vehicle moving in local roads.

4 Performance evaluation

This section studies the performance for both S_R and S_W. We investigate the effects of parameters N (the PC size), p (the right move probability), λ/μ (the update rate or the speed of the vehicle) and V (the variance of idle period) on the expected signalling cost of a location update (LU) operation. Let C_R and C_W be the LU costs (the expected number of messages sent in an LU) for S_R and S_W, respectively. We note that the costs of the paging and idle mode exit procedures for both S_R and S_W are the same and are not considered in this paper.

Figure 6 plots C_R and C_W as functions of N, p and λ/μ, where the idle period is exponentially distributed ($V = 1/\mu^2$).

In this figure, $\lambda/\mu = 1.85$, 24, 240, $p = 0.5$, 0.8, and N ranges from 1 to 20. We first point out several facts. From Fig. 6, we have

Fact 1. As N increases, more intra-PC LUs (with lower costs) and less inter-PC LUs (with higher costs) are exercised.

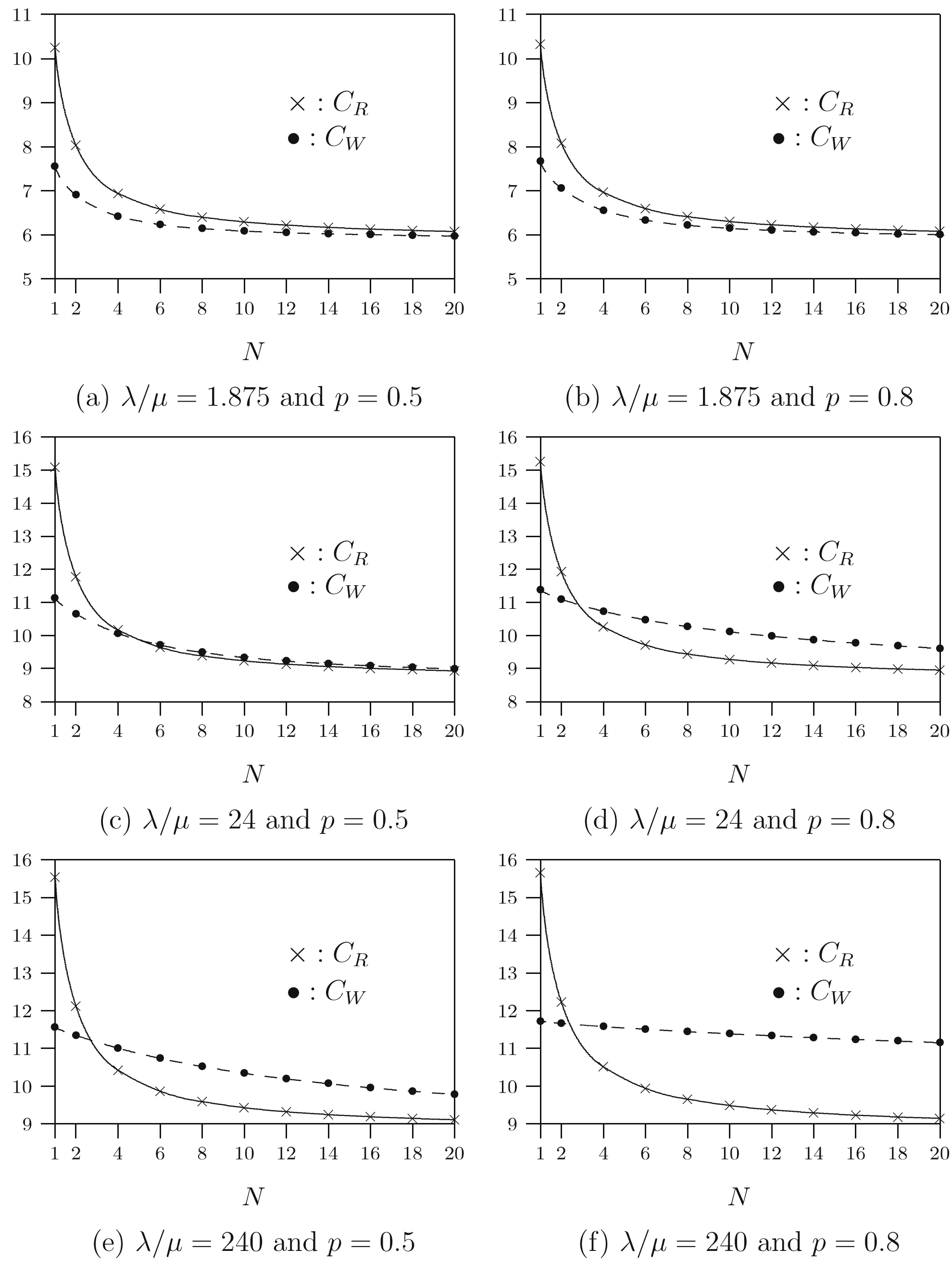
Fact 2. When λ/μ is very small, few LUs occur in an idle period, and it is more likely that the MS only makes intra-PC LUs within PC 0. When λ/μ is large, more LUs outside PC 0 occur.

Fact 3. If an MS makes more inter-PC LUs (with costs C_I, C_O or C^*; see Fig. 3), then $C_R > C_W$.

Fact 4. If an MS makes more intra-PC LUs outside PC 0 (with cost $c*$; see Fig. 4), then $C_R < C_W$.

Effects of p In practice, a small p (e.g., $p = 0.5$ in Figs. 6a, c and e) represents the movement of a pedestrian or a vehicle in local roads, and a large p (e.g., $p = 0.8$ in Figs. 6b, d and f) represents the movement of a vehicle in highways. When p increases, the MS tends to move to one direction, and more LUs without involving PC 0 are exercised. That is, Fact 4 becomes more significant as p increases, and C_W increases faster than C_R does.

Fig. 6 C_R and C_W for $V = 1/\mu^2$ (**a–f**)

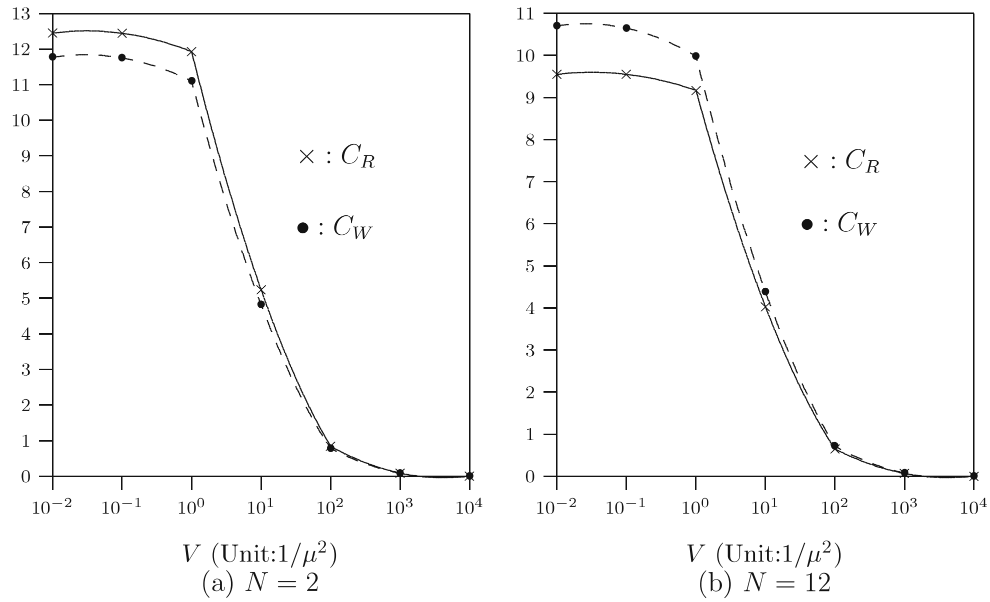


Effects of N and λ/μ Figure 6 shows an intuitive result that C_R and C_W decrease as N increases (Fact 1). This figure also shows that C_R and C_W increase as λ/μ increases. When λ/μ is very small (see Fig. 6a and b), the expected LU cost is small (Fact 2). The increase of λ/μ results in more LUs with higher costs.

Figure 6 indicates that S_W outperforms S_R when N or λ/μ are small. Conversely, S_R is better than S_W when both N and λ/μ are large. When N is small, $C_R > C_W$ (Facts 1 and 3). When λ/μ is small, more LUs around PC 0 are exercised (Fact 3), and $C_R > C_W$. When both λ/μ and N are large, more intra-PC LUs outside PC 0 are exercised, and $C_R < C_W$ (Facts 1, 2 and 4). Therefore, for highway traffic (i.e., λ/μ and p are large) and when the PC size is sufficiently large (e.g., $N > 3$ in our examples), S_R is better than S_W. For local road traffic (i.e., λ/μ and p are small), S_W outperforms S_R.

Effects of V Figure 7 shows that C_R and C_W are decreasing functions of the variance V of idle periods. When V is small, less long and short idle periods are observed, and C_R/C_W are mainly affected by the parameters N, p and λ/μ as previously described. When

Fig. 7 C_R and C_W for $p = 0.8$ and $\lambda/\mu = 24$ (**a**, **b**)



V is large, many short idle periods with few LUs are observed (i.e., Pr[$K = 0$] is large in Eq. 14), and C_R/C_W significantly decrease as V increases. In this case, $C_R \approx C_W$.

5 Conclusions

This paper studied the WiMAX-based ITS systems where the base stations serve as roadside units and the mobile stations installed in vehicles serve as the onboard units. We investigated the impact of vehicle mobility on location update of two APC relocation scenarios for WiMAX-based ITS: with APC relocation (S_R) and without APC relocation (S_W). An analytic model was proposed to model the expected location update cost C for the one-dimensional WiMAX paging group configuration. The analytic results were validated against the simulation experiments. Our study indicates the following results:

- For a vehicle or a pedestrian in local roads, S_W outperforms S_R.
- For a vehicle in highway, S_R outperforms S_W when the PC size is sufficiently large.

These results provide guidelines to activate the APC mechanism for vehicles with various moving behaviors.

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