Journal of the Korean Data & Information Science Society
2009, **20**(6), 1177–1190

한국데이터정보과학회지

Design and analytical evaluation of a fuzzy proxy caching for wireless internet

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Received 16 August 2009, revised 22 October 2009, accepted 30 October 2009

Abstract

In this paper, we propose a fuzzy proxy cache scheme for caching web documents in mobile base stations. In this scheme, a mobile cache model is used to facilitate data caching and data replication. Using the proposed cache scheme, the individual proxy in the base station makes cache decisions based solely on its local knowledge of the global cache state so that the entire wireless proxy cache system can be effectively managed without centralized control. To improve the performance of proxy caching, the proposed cache scheme predicts the direction of movement of mobile hosts, and uses various cache methods for neighboring proxy servers according to the fuzzy-logic-based control rules based on the membership degree of the mobile host. The performance of our cache scheme is evaluated analytically in terms of average response delay and average energy cost, and is compared with that of other mobile cache schemes.

Keywords: Base station, fuzzy logic, mobile caching, proxy cache, wireless internet.

1. Introduction

The popularity of wireless networks grows with the advances in wireless technologies and Internet applications. New generation wireless networks, such as G4 and WiMAX, have brought web applications into wireless. Figure 1.1 depicts a typical wireless Internet architecture. In this architecture, mobile hosts access the mobile network through base stations, which are interconnected by access routers to wireless LANs, and in turn are connected to the Internet through gateway routers (Wang *et al.*, 2007, Jiang *et al.*, 2000). Among numerous studies on enhancing the wireless Internet performance, the strategy of caching popular documents at locations close to the mobile hosts is an effective solution to improving the quality of wireless web applications. Especially, the development of a cooperative proxy cache system among distributed wireless base stations is required. Wireless providers often install cache appliances on the edge of a wireless network to act as the proxy to the Internet. With this approach, the wireless web performance is often compromised by the long latency between mobile clients, proxy caches, and the original web servers. A single proxy cache at the edge of a wireless network can also be overloaded and may become a bottleneck. To

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address these drawbacks, wireless base stations are often used as caching proxies for mobile hosts. Caching popular web documents in wireless base stations can alleviate the network traffic between base stations and web servers, and reduce user web request latencies. Providing caching mechanisms in wireless base stations can also reduce the connection time between the mobile host and the base station due to the reduced waiting time experienced in fetching remote web documents, thus saving the limited wireless bandwidth.

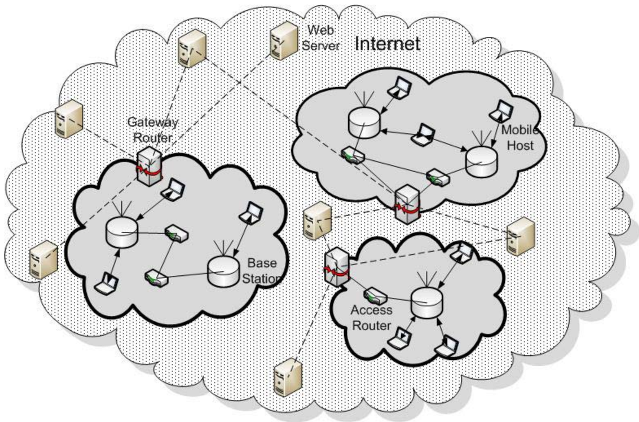

Figure 1.1 Wireless internet architecture

To address these challenges, we propose a fuzzy proxy cache scheme for distributed base stations. The proposed scheme predicts the mobility of mobile hosts and uses various cache methods for neighboring proxy servers inspired by fuzzy-logic-based control rules based on the membership function of the mobile host. The performance of our scheme is evaluated analytically in terms of average response delay and average energy cost, and is compared with that of other mobile cache schemes. Our analytical evaluation confirms that the performance of the proposed fuzzy proxy caching is superior to existing cache schemes.

The remainder of the paper is organized as follows. Section 2 offers a succinct review of mobile proxy caching. Section 3 proposes a fuzzy proxy cache scheme for wireless Internet. Section 4 contains our detailed analytical evaluation. Finally, concluding remarks are in Section 5.

2. Related works

A cooperative cache scheme specifies how multiple computing nodes share and manage the cached data in a collaborative manner. This paper focuses on caching of web documents. For on-demand data access applications, the traditional way of resolving a data request is to check the local cache first and send the request to the server after local cache misses. This scheme is referred to as SimpleCache (Yin and Cao, 2005), works well as long as the connection to the server is reliable and too expensive; otherwise, it results in failed data requests or request timeouts.

To increase data availability and to reduce the cost in terms of data access latency and energy consumption, hop-by-hop cache resolution allows a node on the forwarding path to serve as a proxy for resolving the request. If a forwarding node contains an un-expired copy of the requested data, it can send a reply to the requester and stop forwarding the data request (Du *et al.*, 2009).

A node's cooperation zone consists of the surrounding nodes within r-hop range of the node. The parameter r is called the radius of the cooperation zone. If a node does not have information about whether the requested data item is available in the zone, the node can reactively discover this by flooding the request within the zone. To restrict the flooding range, the TTL (time to live) value of the request is set to the zone radius r. The restricted flooding not only has the potential to discover the closest data location but also can serve as an announcement in the neighborhood and effectively segment the whole network into clusters, within which caching information is shared (Du *et al.*, 2009).

3. Fuzzy proxy caching

The proposed fuzzy cache scheme predicts the direction of movement of mobile hosts that hand-off to/from neighboring proxy servers through ARRSES (Adaptive-Response-Rate Single Exponential Smoothing) method (Makridalis *et al.*, 1998). Membership degrees are computed by the fuzzy membership function based on the direction of movement for a mobile host. Then the proposed scheme uses various cache methods: AMC (All Mobile Caching), PMC+AH (Popular Mobile Caching With All Headers), AHC (All Headers Caching), PHC (Popular Headers Caching) and NC (No Caching) for neighboring proxy servers according to the fuzzy-logic-based control rules based on the membership degree of the mobile host.

3.1. Mobility predicting

The mobility parameters of a mobile host are estimated by the history of recent hand-offs from any proxy server among six neighboring proxy servers to the current one. The predicted movement angle of the mobile host is computed by ARRSES. The method is described as being adaptive because the value of the parameter changes automatically when there is a change in the behaviour of the time series. The basic equation used by ARRSES for mobility prediction is:

$$F_{t+1} = \alpha_t Y_t + (1 - \alpha_t) F_t, \tag{3.1}$$

where $\alpha_{t+1} = |A_t/M_t|$, $A_t = \beta E_t + (1-\beta)A_{t-1}$, $M_t = \beta\,|E_t| + (1-\beta)M_{t-1}$, $E_t = Y_t - F_t$.

In (3.1), Y_t represents the actual movement angle under which the mobile host enters from the last proxy server to current proxy server. F_t represents the predicted movement angle of the mobile host at the last proxy server. α_t shows that the values of the smoothing constant at time $t+1$ (which is used to forecast for $k+2$) is calculated as the absolute value of the ratio of the smoothed error term to the smoothed absolute error term. A_t and M_t show how the smoothed error term and smoothed absolute error term are calculated by exponential smoothing. β is a parameter assuming values between 0.0 and 1.0. Finally, E_t defines error term as the difference between the actual and the forecast values. These are initialized as follows: $F_2 = Y_1$, $A_2 = A_3 = A_4 = \beta = 0.2$, $A_1 = M_1 = 0$.

3.2. Mobile cache structure

Designing a cache model has to be based on the characteristics of the cached data and the specific caching environment. In wireless proxy caching environments, the cached documents may be migrated to the current base station proxy server from other base stations instead of being directly fetched from the original web servers. To cope with the characteristics of cached documents and wireless environments, a mobile cache structure featured in Figure 3.1 is designed. The mobile cache structure consists of two portions. The cache structure body is the cached document. The header includes *ID, Tag, State bytes, Link fields, Client list, Origin* and *Requests* . The *ID* field contains a *UUID* (universal unique ID) which the *URL* of the cached document is hashed. *Tag* is the name of the cached document. *State bytes* a reused to store caching state information about the cached document. Because the cached document might be migrated from other base station proxy servers, *link fields* are needed to provide links to proxy servers that previously owned or searched for this document, so that subsequent web requests in nearby base stations can easily find this cached documents. *Link field* is organized as a pair of integer <*NID, Dist*>. *NID* is used to look up the neighbor table for a neighbor base station's IP address. *Dist* is round-trip network distance to reach the cached document through the base station specified by *NID*. *ClientList* contains the IDs of the mobile hosts that are currently accessing the cached document. *Origin* indicates whether this current web replica is fetched from the original web server or is migrated from another proxy server in the cooperative proxy cache system. *Requests* represent the number of requests for the cached document during the time that the mobile host resides in the region of the proxy server.

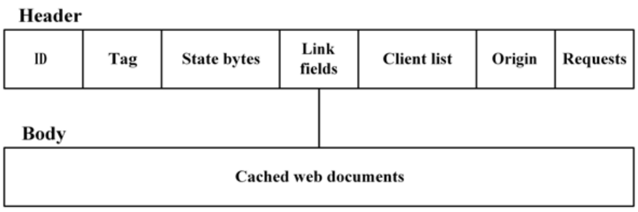

Figure 3.1 Mobile cache structure.

3.3. Cache methods

When a new document request reaches a certain proxy server from a mobile host, the proxy server takes actions based the following different situations as follows:

1. All mobile caching (AMC): If the entire mobile cache structure is cached, the web request is satisfied.

2. Popular mobile caching with all headers (PMC+AH): The proxy server has cached only the bodies of popular documents that are based on the request rate per time unit. The request rate is computed by dividing the average residential time of the mobile host into the value of *Requests* within the header of mobile cache structure. Accordingly,

the request of popular document is resolved by this proxy server. Otherwise, the search process becomes the same as below AHC.

3. All headers caching (AHC): If only the header of the mobile cache structure is cached in this proxy server, the current proxy will check the header of the mobile cache structure for the shortest distance to the cached web replicas. If the distance to the nearest web replica is larger than its expected response time by directly requesting from the original web server, a query is sent to the original web server. Otherwise, a query message will be created, and propagated, along the links in the headers of mobile cache lines, to the proxy server that holds the nearest web replica.

4. Popular headers caching (PHC): The headers of popular document is cached only in this proxy server. Accordingly, the request of popular document is resolved as above AHC. Otherwise, the search process becomes the same as below NC.

5. No caching (NC): If nothing is cached at this proxy server, the proxy server first sends a query message to all its neighbor proxies and waits for the responses from them. The query message will be disseminated to other peer proxies through peer relay until the message lifetime is expired or a matching mobile cache line (maybe header only) is reached. The proxy that has the matching mobile cache line responds the query. The responding message is routed back to the requesting proxy along the query path. The proxies on the routing path create or update the appropriate mobile cache structure headers based on the responding message to provide links to the cached web replica. Once the responding messages reach the requesting proxy and related mobile cache structure header is created on that proxy, the rest of the search process would be same as AHC.

3.4. Fuzzy control rules

In fuzzy proxy caching, the normal distribution derived from Eq. (3.1) is standardized. The random variable X is normally distributed as $N(\mu, \sigma^2)$, where μ and σ represent the expected mobility direction and its variance, respectively. If X is normally distributed as $N(\mu, \sigma^2)$, the standardized variable follows normal distribution. The variable X for average adjacent angle of each neighboring proxy server is transformed to the standardized variable z by (3.2).

$$z = \frac{x - \mu}{\sigma} \tag{3.2}$$

where μ is the predicted movement angle F_{t+1} using (3.1), and σ is the error E_t=$Y_t - F_t$. The standardized value z has the membership degree of [0.0, 1.0] by the fuzzy membership function of (3.3). Figure 3.2 shows the graph that represents the membership degree of neighboring proxy server according to μ and σ.

$$\mu_{NPD}(z) = e^{-\frac{z^2}{2}} \tag{3.3}$$

The standardized value for the average adjacent angle of each neighboring proxy server is normalized by the fuzzy set that has value between 0.0 and 1.0. The normalized values are

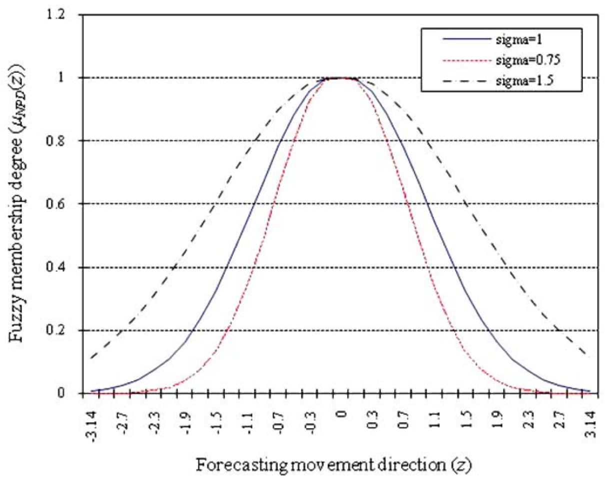

Figure 3.2 Membership degree for predicting direction of movement.

divided into five regions. These regions can be denoted by five basic fuzzy sets: VL (Very Low), L (Low), M (Medium), H (High) and VH (Very High). The normalization of the fuzzy set for neighboring proxy servers is shown in Table 3.1.

Table 3.1 The normalization of the fuzzy set for neighboring proxy servers.

Membership function	Normalized full set	Normalized regions	Basic fuzzy sets
$\mu_{NPD}(z)$	[0.00 ~ 1.00]	[0.00 ~ 0.24]	VL
		[0.25 ~ 0.39]	L
		[0.40 ~ 0.59]	M
		[0.60 ~ 0.79]	H
		[0.80 ~ 1.00]	VL

The current proxy server uses five different cache methods for neighboring proxy servers according to the fuzzy set of neighboring proxy direction and the fuzzy set of neighboring proxy capacity. Table 3.2 shows the control rules for the proposed fuzzy proxy caching. If the possibility that moves a mobile host to a neighboring proxy server is VH and the capacity of the neighboring proxy server is L, the current proxy server uses AMC method for the neighboring proxy server. Also, if the possibility that moves a mobile host to a neighboring proxy server is VL and the capacity of the neighboring proxy server is S, the current proxy server uses NC method for the neighboring proxy server.

Figure 3.3 shows the example of the proposed fuzzy proxy caching, where the different shades of black of proxy server zones represent the different cache methods from AMC to NC those apply in neighboring proxy servers, respectively. The current proxy server selects a cache method for a neighboring proxy server in consideration of the average adjacent angle of the neighboring proxy server for the predicted direction of movement. For example, the current proxy server uses AHC as cache method for the proxy servers of the neighboring server regions (A, B) those NPD is VH, while the current proxy server uses NC as cache

Table 3.2 Table 3.2 Control rules for fuzzy proxy caching.

		NPC L	NPC M	NPC S
NPD	VH	AMC	AMC	PMC+AH
	H	AMC	PMC+AH	AHC
	M	PMC+AH	AHC	PHC
	L	AHC	PHC	NC
	VL	PHC	NC	NC

(input variables) NPD (neighboring proxy direction): VH, H, M, L, VL
NPC (neighboring proxy capacity): L (large), M (medium), S (small)
(output variables) Cache method: AMC, PMC+AH, AHC, PHC, NC

method for the proxy server of the neighboring server region (E) that NPD is VL.

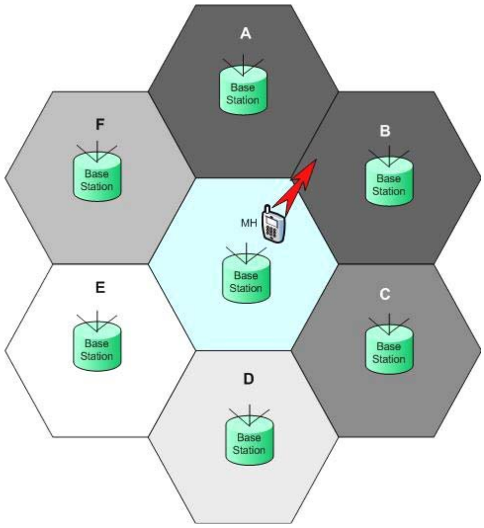

Figure 3.3 Application example of various cache methods within fuzzy proxy caching

3.5. Cache resolution

The proposed fuzzy proxy caching uses a composite approach to cache resolution whose details are illustrated in Figure 3.4. The fuzzy proxy caching forwards the web request to the proxy server after the local cache misses. If the requested document is in the proxy server, the document is returned. Otherwise, the fuzzy proxy caching uses profile-based resolution. Profile-based resolution maintains a historical profile of previously received document requests. The proxy server checks the headers of its mobile cache structure for finding the shortest hops to the cached replica of the document. If the number of hops to the proxy server that has the nearest web replica is greater than r-hops, the request is forwarded to original web server. Otherwise, the requested document is sent along the forwarding link within the header of its mobile cache structure to the node that holds the closest document replica. If a forwarding node has the requested document, the web request gets resolved before reaching the nearest proxy server. Otherwise, the request is sent to the original web server.

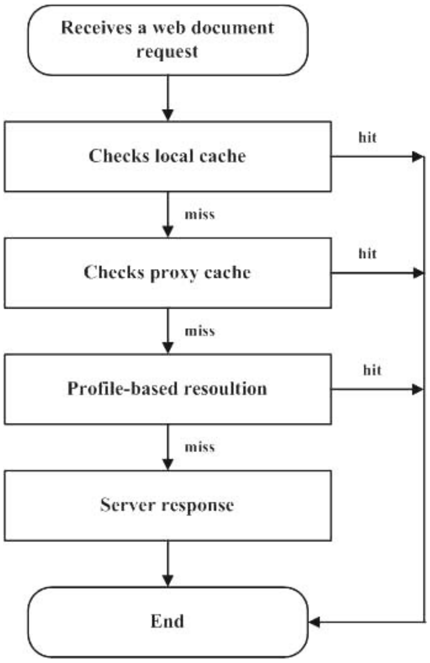

Figure 3.4 Resolution process of fuzzy proxy caching.

4. Analytical evaluation

The following assumptions are made for the analytical evaluation for fuzzy proxy caching (Feeney and Nilsson, 2001):

- The response delay and energy cost is 0 if the local cache contains the requested document. This is a reasonable assumption because the local cache access cost can be ignored when compared to inter-node communication.
- If a document request cannot be satisfied from the local cache, we assume that the response delay is proportional to the travel distance in hops of the document request, that is, $Response\_delay=\alpha\times Travel\_distance$ and α is a constant. In this analysis, we normalize α to 1 since this does not change the analysis and comparison results.
- If a document request cannot be satisfied from the local cache, we assume that the energy cost is proportional to the number of messages triggered by the document request, that is, $Energy\_cost=\beta\times Number\_of\_messages$. Similarity, we normalize β to 1 since this does not change the results.

Table 4.1 Notations for an analytical evaluation.

Notation	Description
P_d	The probability that a mobile host has a copy of document d.
P_d^z	The probability that a node in the zone of the requesting mobile host has a copy of document d.
P_d^{ps}	The probability that the proxy server of the requesting mobile host has a copy of document d.
P_d^{pf}	The probability that the profile node in requesting node's proxy server has a copy of document d.
L	The distance in hops between the requesting mobile host and the original web server.
r	The radius of the cooperation zone of the requesting mobile host.
ρ	The average node density.
D_0	Average response delay of the SimpleCache approach.
D_1	Average response delay of the hop-by-hop approach.
D_2	Average response delay of the zone-based approach.
D_3	Average response delay of the fuzzy proxy cache approach.
E_0	Average energy cost of the SimpleCache approach.
E_1	Average energy cost of the hop-by-hop approach.
E_2	Average energy cost of the zone-based approach.
E_3	Average energy cost of the fuzzy proxy cache approach.

P_d is the probability that a mobile host has a copy of document d. It can be estimated by the percentage of caching mobile hosts in the network from history profiles. P_d can be different for different document items, but we suppose for the same document item every mobile host has the same P_d. The average density ρ is used to estimate the total number of mobile hosts in a two-dimensional space. Accordingly, the number of mobile hosts within r-hop range of the requesting mobile host is estimated by $\rho\pi r^2$.

4.1. SimpleCache approach

For the SimpleCache approach, a document request is forwarded to the server after local cache misses. In this case, the average response delay is

$$D_0 = 0 \times P_d + L(1 - P_d). \tag{4.1}$$

While the average energy cost is

$$E_0 = 0 \times P_d + L(1 - P_d). \tag{4.2}$$

The functions show that the response delay and energy cost increases as the server distance L increases and decreases as P_d increases.

4.2. Hop-by-Hop approach

For the hop-by-hop cache resolution scheme, each forwarding node checks the forwarded request and resolves the request if the document is in the local cache. For this approach, the average response delay is

$$
\begin{aligned}
D_1 =& 0 \times P_d + 1 \times (1-P_d)P_d + 2 \times (1-P_d)^2 P_d + \cdots \\
&+ (L-1) \times (1-P_d)^{L-1} P_d + L \times (1-P_d)^L \\
=& \sum_{i=0}^{L-1} i P_d (1-P_d)^i + L(1-P_d)^L.
\end{aligned}
$$

The first term of above equation D_1, power series is solved as follows.

$$
\begin{aligned}
D_{11} &= \sum_{i=0}^{L-1} i P_d (1-P_d)^i \\
&= P_d(1-P_d) + 2P_d(1-P_d)^2 + \cdots + (L-1)P_d(1-P_d)^{L-1}
\end{aligned}
\tag{4.3}
$$

Multiply both sides by $(1-P_d)$,

$$
\begin{aligned}
(1-P_d)D_{11} =& P_d(1-P_d)^2 + 2P_d(1-P_d)^3 + \cdots \\
&+ (L-2)P_d(1-P_d)^{L-1} + (L-1)P_d(1-P_d)^L.
\end{aligned}
\tag{4.4}
$$

Subtract (4.4) from (4.3).

$$
\begin{aligned}
D_{11} - (1-P_d)D_{11} &= P_d(1-P_d) + P_d(1-P_d)^2 + \cdots \\
&\quad + P_d(1-P_d)^{L-1} - (L-1)P_d(1-P_d)^L \\
P_d D_{11} &= P_d(1-P_d) \cdot \frac{1-(1-P_d)^{L-1}}{1-(1-P_d)} - (L-1)P_d(1-P_d)^L \\
D_{11} &= \frac{(1-P_d)-(1-P_d)^L}{P_d} - (L-1)(1-P_d)^L
\end{aligned}
$$

Accordingly, D_1 is as follows:

$$
\begin{aligned}
D_1 &= \frac{(1-P_d)-(1-P_d)^L}{P_d} - (L-1)(1-P_d)^L + L(1-P_d)^L \\
&= \frac{1-P_d}{P_d}\left[1-(1-P_d)^L\right]
\end{aligned}
\tag{4.5}
$$

While the energy cost is

$$
E = \frac{1-P_d}{P_d}\left[1-(1-P_d)^L\right]. \tag{4.6}
$$

The average travel distance of hop-by-hop approach is actually bounded by (1-P_d)/P_d no matter how large L becomes. As L and hence the number of forwarding nodes increases, the probability of resolving a document request on the forwarding path increases.

4.3. Zone-based approach

The zone-based approach floods the cooperation zone requesting for the document after local cache misses. The probability of success of the zone-based approach depends on the existence of a document in the cooperation zone. Let r be the radius of the cooperation zone, and P_d^z the probability of a node in the zone caches d locally. The probability of getting the requested document d from within the cooperation zone is as follows.

$$P(r) = 1 - (1 - P_d^z)^{\rho\pi r^2 - 1}$$

The average response delay is calculated based on three possible situations: a request can be satisfied from the local cache, from the broadcast within the cooperation zone, or from the web server. The probabilities of these three scenarios are P_d, (1-P_d)P (r) and (1-P_d)(1-P (r)), respectively. Correspondingly, the response delay for these situations is 0, r, and r +L, respectively. Therefore, the average response delay is

$$\begin{aligned} D_2 &= 0 \times P_d + (1 - P_d)\left[rP(r) + L(1 - P(r))\right] \\ &= (1 - P_d)\left[rP(r) + L(1 - P(r))\right]. \end{aligned} \tag{4.7}$$

Upon a local cache miss and if the document is found within the zone, the energy cost is taken to be $\rho\pi r^2$. Therefore, the average response delay is

$$\begin{aligned} E_2 &= 0 \times P_d + (1 - P_d)\left[\rho\pi r^2 + L(1 - P(r))\right] \\ &= (1 - P_d)\left[\rho\pi r^2 + L(1 - P(r))\right]. \end{aligned} \tag{4.8}$$

4.4. Fuzzy proxy cache approach

The average response delay of fuzzy proxy caching is calculated based on four possible situations: a request can be satisfied from the local cache, from the proxy server of requesting mobile host, from the profile node in the proxy server, or from the web server. The probabilities of these four scenarios are P_d, $(1 - P_d)P_d^{ps}$, $(1 - P_d)(1 - P_d^{ps})P_d^{pf}$ and $(1 - P_d)(1 - P_d^{ps})(1 - P_d^{pf})$, respectively. Correspondingly, the response delay for these situations is 0, 1, (r +1)/2 and L , respectively. Therefore, the average response delay is

$$\begin{aligned} D_3 &= 0 \times P_d + (1 - P_d)\left[1 \times P_d^{ps} + (1 - P_d^{ps})\left\{\frac{r+1}{2} \times P_d^{ps} + L(1 - P_d^{pf})\right\}\right] \\ &= (1 - P_d)\left[P_d^{ps} + (1 - P_d^{ps})\left(L + \frac{r+1-2L}{2}P_d^{pf}\right)\right]. \end{aligned} \tag{4.9}$$

While the average energy cost is

$$E_3 = (1 - P_d)\left[P_d^{ps} + (1 - P_d^{ps})\left(L + \frac{r+1-2L}{2}P_d^{pf}\right)\right]. \tag{4.10}$$

The parameters and values of the performance evaluation for fuzzy proxy caching are shown in Table 4.2. First, we assume that the neighboring proxy server capacity is medium.

From the normal distribution and hexagonal cell structures, we know that current proxy server has two neighboring proxy servers those NPD is VH, one neighboring proxy server that NPD is H, one neighboring proxy server that NPD is M, one neighboring proxy server that NPD is L and one neighboring proxy server is VL. The cumulative distribution of requests to popular documents is studied in (Breshu *et al* ., 1999). The top of 25 ~ 40% of all documents accounts for 70% of the requests, and the top of 70% and 80% of documents accounts for 90% of requests. We set that the values of P_d^{ps} and P_d^{pf} are 0.75 and 0.85 with consideration of above conditions, respectively.

Table 4.2 Parameters and values for performance evaluation.

Parameter	Value
P_d	0.2 ~ 0.5
P_d^z	0.1
P_d^{ps}	0.75
P_d^{pf}	0.85
L	20
r	3 ~ 5
ρ	1

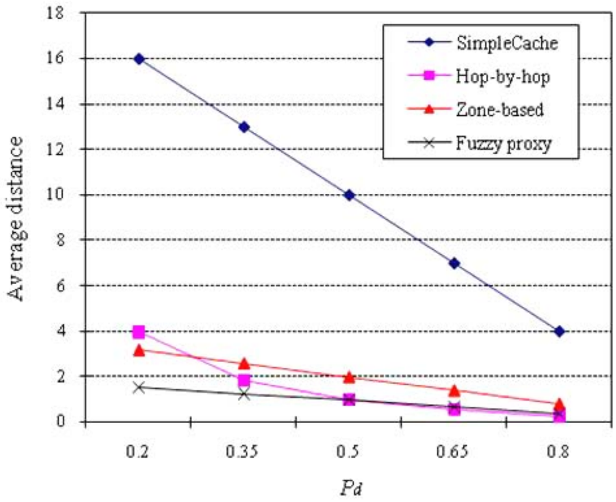

Figure 4.1 Expected travel distance with different P_d.

Figure 4.1 shows the expected travel distance according to local cache hit ratio (P_d) in the case that L is 20. From this figure, we know the following facts: the expected travel distance of fuzzy proxy caching is shorter than those of SimpleCache and zone-based approaches regardless of P_d, the expected travel distance of fuzzy proxy caching is shorter than that of hop-by-hop approach in the case that the local cache hit ratio is less than 0.5, but the expected travel distance of fuzzy proxy caching is very little longer than that of hop-by-hop approach in case that the local cache hit ratio is greater than 0.5. In mobile environments, the local cache hit ratio of mobile hosts is lower than that of fixed host because mobile hosts have restricted power and memory space. Accordingly, the proposed fuzzy proxy caching is more applicable cache approach to the mobile hosts in wireless Internet.

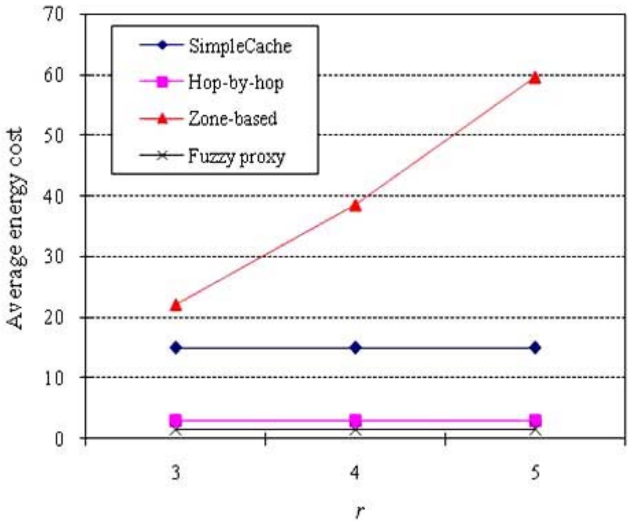

Figure 4.2 Expected energy cost with different r.

Figure 4.2 shows the expected energy cost according to the radius of cooperation zone (r) in case that local cache hit ratio is 0.25. From this figure, we know that the expected energy cost of zone-based approach increases linearly as r increases and the expected energy cost of fuzzy proxy caching is smaller than those of other cache approaches regardless of r. Therefore, we identify again that the proposed fuzzy proxy caching is most applicable cache approach to the mobile hosts in wireless Internet.

5. Concluding remarks

In this paper, we proposed a fuzzy proxy cache scheme for wireless Internet. The proposed cache scheme predicts the direction of movement of mobile hosts, and uses various cache methods for neighboring proxy servers according to the fuzzy-logic-based control rules based on the membership degree of the mobile host.Our scheme was evaluated analytically in terms of average response delay and average energy cost. Our evaluation revealed that the expected travel distance of the proposed approach is shorter than those of other approaches and its expected energy cost is smaller. Therefore, we believe that the proposed fuzzy proxy caching is very promising for wireless Internet.

Future work includes a detailed performance analysis of our scheme through simulations and studying of fuzzy proxy caching approaches for MANETs (Mobile Ad Hoc Networks) and VANETs (Vehicular Ad Hoc Networks).

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