A DHT and MDP-based Mobility Management Scheme for Large-Scale Mobile Internet

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Abstract—**Scalable mobility support is an important task in large-scale mobile Internet. A considerable amount of research on distributed hash table (DHT) based mobility support schemes, which are highly user scalable and load balanced, has been done. However these schemes have shortcomings in query and update performances and network scalability. It is because although routing of overlay itself is effective, there is inconsistency between logical and physical topologies, so the actual physical network performances are not necessarily efficient. In this article, while modeling the overlay mapping query to a Markov decision process (MDP), we define the reward function combining physical layer information with application layer information. Then we present a Markov decision routing (MDR) algorithm, which improves backward induction to get the global optimal strategy, and can balance the complexity of the time and space. We propose a DHT and MDR-based mobility management (DMDRMM) scheme. The numerical results show that the scheme inherits the advantages of the DHT-based management structure, and optimizes the update and query performances of dDHT especially for large-scale network.**

I. INTRODUCTION

In typical mobile Internet architectures, a few types of mobility agents are used to maintain the mobility of a mobile node (MN): a home agent (HA) in Mobile IPv6 (MIPv6) [1], a mobility anchor point (MAP) in Hierarchical Mobile IPv6 (HMIPv6) [2], and a local mobility anchor (LMA) in Proxy Mobile IPv6 (PMIPv6) [3]. If a high burden of tasks is concentrated on a single mobility agent, the mobility agent may become a bottleneck node. So, how to provide a scalable service by distributing the network load among multiple mobility agents is an important issue.

To address the scalability problem, a number of Peer-to-Peer (P2P) based mobility supports were proposed [4]–[13]. In [14], by analyzing the similarities and differences of P2P network and mobility management, we showed that the DHT-based information spreading way has the reference value for mobility management. By comparing these schemes with MIPv6 and HMIPv6, we showed that the DHT-based mobility support schemes are highly user scalable and load balanced, but these schemes have shortcomings in query and update performances especially for a large-scale network. It is because although routing of overlay itself is effective, there is inconsistency between logical and physical topologies, so the actual physical network performances are not necessarily efficient.

In this paper, we design mobility support based on the DHT-based management structure to reduce the effects of inconsistency on mobility management. We model the mapping query via overlay network to a finite-horizon MDP, and define the reward function combining physical layer information with application layer information. Then we present a Markov decision routing algorithm called MDR. The algorithm improves backward induction to get the global optimal strategy, and has the characteristics of distributed computing. Moreover, we propose a DHT and MDR-based mobility management scheme called DMDRMM. The scheme inherits the advantages on load balance and user scalability of the DHT-based management structure, and optimizes the update and query performances of dDHT especially when the network scale is larger. So the scheme is suitable for large-scale mobility management.

The rest of this paper is organized as follows. Section II describes the performance problem of DHT-based mobility supports, and summarizes the related works on processing the consistency problem. The MDP model formulation is given in Section III. The MDR algorithm is presented in Section IV. Section V elaborates the update and query operations of DMDRMM. The performance analysis and simulation results are presented in Section VI. Conclusion is given in Section VII.

II. PROBLEM STATEMENT

A. DHT based Management Structure

In [14], the P2P-based mobility supports are classified into the subnet-level DHT-based (sDHT) scheme and the domain-level DHT-based (dDHT) scheme according to the ways of overlay network construction. Fig. 1 shows the management structure of dDHT. In dDHT, the network is divided into multiple management domains, and each domain includes multiple subnets and is equipped with a mobility agent (MA). The MAs form a DHT-based overlay network. Here, the overlay is based on the simple and efficient Chord [15] topology.

There are three identifiers for each MN. Home Address (HoA) is a stable IP address to identify the MN. Care-of-Address (CoA) is a temporary IP address acquired in a foreign network when moving, and indicates MN's current location. Object Identifier (oID) is obtained by hashing the HoA, and is used in overlay network. Moreover, each MA in the overlay network has a Node Identifier (nID), which is obtained

by hashing MA's IP address. The MAs keep the mappings between the oIDs and the CoAs. Here, the consistency Hash function is used to ensure uniformly distributed mappings.

B. Performance Problem

In [14], we presented a performance analysis model for DHT-based mobility management schemes, and compared such schemes with MIPv6 and HMIPv6.

The results show that DHT-based mobility management schemes enable improvement in terms of load balance and user scalability compared with the traditional mechanisms. And the load balance of sDHT and dDHT is not effected by user distribution and movement model, and keeps good in various scenes. So it is very necessary to introduce the distributed information spreading way into mobility management.

But there exist deficiencies in query and update performances and network scalability. As shown in Fig. 2, although the performances of dDHT are better than sDHT, the delay performances of DHT-based schemes are worse than MIP schemes, especially for a large-scale network. It is because that the inconsistency of logical and physical topologies limits the effective routing of overlay itself. Therefore, we should design efficient mobility support directly against these deficiencies, based on the domain-level management structure, to reduce the effects of topology inconsistency on mobility management.

C. Related Works

In P2P networks, there are three traditional methods to process the consistency problem [16]. 1) Proximity identifier selection, also called geographical layout, is based on underlayer hash function, using space encoding technology. 2) Proximity route selection chooses the next hop combining the physical layer information with the application layer information. 3) Proximity neighbor selection does directly on the application layer, and maintains a certain amount of physical adjacent neighbors when building and updating routing table.

In the related works of DHT-based mobility management, PNR [6] borrows the first method, and presents the geographical longest prefix matching scheme which builds the topologically-aware overlay network. This method can fundamentally eliminate topology inconsistency, but lose the load balance, stability and scalability of the network constructed by consistency hash function. It doesn't accord with the performance requirements of efficient mobility support for large-scale network. Moreover, the third method introduces a large number of maintenance costs.

Therefore, we use the solution of the second method in this paper. In the mapping query process, the choice of next hop node is not only based on the logical distance to the destination, but also according to the delay information of neighbor nodes. And considering the mapping query process is a sequential decision making process, and has memoryless property, we use Markov decision process theory to model it.

III. System Model

In this section, we describe how the mapping query problem can be formulated as a Markov decision process (MDP).
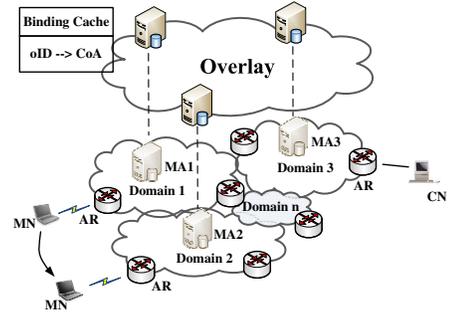

Fig. 1. The DHT based mobility management structure.

A MDP model, can be characterized by five elements [17]: decision epochs (or stages), states, actions, transition probabilities and rewards, defined by $\{K, S, A(s), p(.|s,a), r(s,a)\}$. At each decision epoch, the process is in some state $s \in S$, and the decision maker may choose any action $a \in A(s)$. With this state and action, the process then evolves to a new state s' according to a transition probability function $p(.|s,a)$. The new state lasts for a period of time, and then the decision maker chooses a new action again. For any action that the decision maker chooses at each state, there is a corresponding reward $r(s,a)$. The goal of each decision is to maximize the expected total reward it can obtain during the query process.

A. Stages, States, Actions and Transition Probabilities

The whole query process can be naturally divided into several stages, and each stage corresponds to one hop in the query process. Because the actual hop count in any query is finite, the query process belongs to a finite-horizon problem. $K = \{0, 1, 2, ..., N_\pi(s)\}$, where $N_\pi(s)$ is a random variable, which is the terminal time for some given initial state s.

The state contains the information of the current MA that is queried, and the physical delays between optional next-hop MAs and current MA. The state space can be expressed as:

$$S = M \times D^1 \times D^2 \times ... \times D^{|M|}, \qquad (1)$$

where $\times$ denotes the Cartesian product, M presents the set of optional MAs' $nIDs$, $D^m (m \in |M|)$ denotes the set of transmission delays to available MAs, $|M|$ is the cardinality of the set M. Let vector $s = (i, d_{i_1}, d_{i_2}, ..., d_{i_{|M|}})$ denote the current state, where i is the nID of current MA, i_m is the nID of the available m-th MA in the routing table of MA i, d_{i_m} is the transmission delay from MA i to MA i_m.

At each stage, based on the current state s, the current MA makes a decision $a \in A(s) = \{i_1, i_2, ..., i_{|M|}\}$, and chooses the next hop node. The state transfers from s to $s' = (j, d_{j_1}, d_{j_2}, ..., d_{j_{|M|}})$, and the transition probability is:

$$p(s'|s,a) = \begin{cases} 1, & j = a \\ 0, & j \neq a. \end{cases} \qquad (2)$$

B. Reward Functions

When an MA chooses an action a in state s, it receives an immediate reward $r(s,a)$, which depends on the distance benefit function $f_o(s,a)$ and the delay benefit function $f_d(s,a)$.

(a) Effects of network scale on average update delay

(b) Effects of network scale on average query delay

(c) Effects of domain scale on average update delay

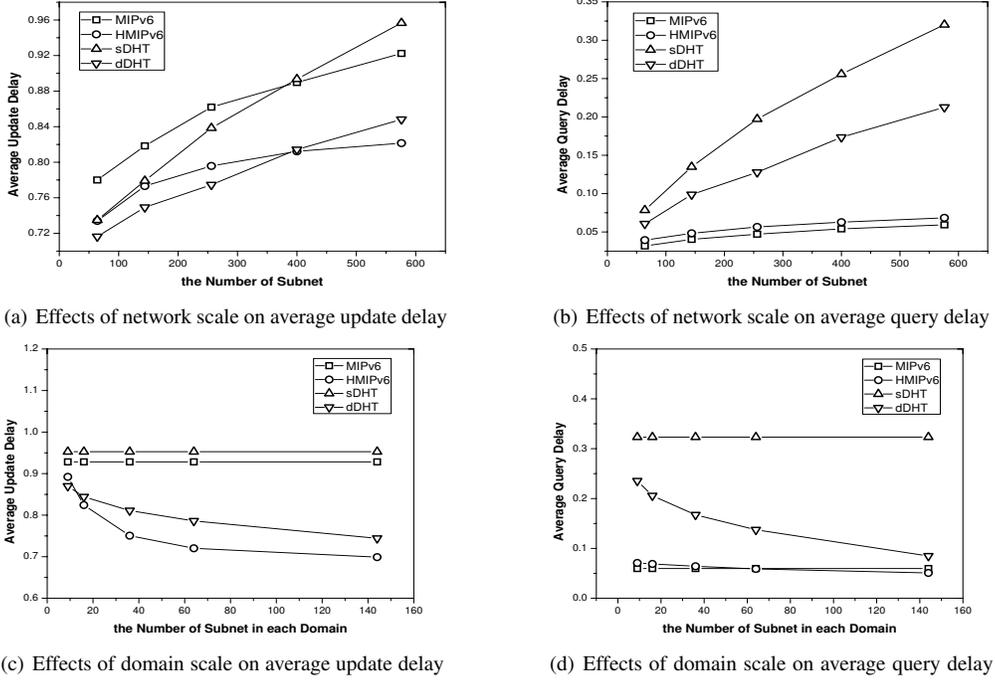(d) Effects of domain scale on average query delay

Fig. 2. Effects of network scale and domain scale on delay performances

The former is defined on the principle of the closer to the data object identifier the higher benefit, and the latter is defined on the principle of the smaller link delay the higher benefit.

If $d(i, oID) > \min_{i_m \in M} \{d(i_m, oID)\}$, and $d(i, oID) > d(a, oID)$, $f_o(s, a)$ represents the benefit that MA gains in the terms of distance by choosing action a in state s:

$$f_o(s, a) = \frac{d(i, oID) - d(a, oID)}{d(i, oID) - \min_{i_m \in M} \{d(i_m, oID)\}}, \qquad (3)$$

else $f_o(s, a) = 0$. Where $d(i, j)$ is the overlay distance between MA i and MA j. $f_d(s, a)$ represents the benefit that MA gains in the terms of delay by selecting action a in state s:

$$f_d(s, a) = \frac{\min_{i_m \in M} \{d_{i_m}\}}{d_a}. \qquad (4)$$

As a result, the total benefit function is given by:

$$r(s, a) = \omega_1 \cdot f_o(s, a) + \omega_2 \cdot f_d(s, a), \qquad (5)$$

where $\omega_1, \omega_2 > 0$, are two weight factors for adjusting the proportion of the two benefit functions in the reward function.

IV. MARKOV DECISION ROUTING ALGORITHM

In this section, we present the problem formulation and describe how to obtain the optimal policy. Then, the backward induction algorithm MDR are introduced.

A. Optimality Equations

A decision rule is a regulation specifying the action selection for each state at a particular decision epoch. It can be expressed as $f : S \to A(s)$. A policy $\pi = (f_0, f_1, f_2, ..., f_N)$ is a sequence of decision rules to be used at all N stages.

According to the definition of the reward function, in order to minimize the *query delay*, i.e. maximize the expected total reward, we obtain the finite-horizon total reward model of the query process. Let $V_\pi(s)$ denote the expected total reward between the first decision epoch and the query termination, given that policy π is used with initial state s. That is,

$$V_\pi(s) = \mathbf{E} \left\{ \sum_{k=0}^{N_\pi(s)} r(s_k, a_k) \right\}, s \in S. \qquad (6)$$

We can state the MDP optimization problem as:

$$\max V_\pi(s) = \max \mathbf{E} \left\{ \sum_{k=0}^{N_\pi(s)} r(s_k, a_k) \right\}. \qquad (7)$$

Then, the optimality equations are given by:

$$u_k(s_k) = \max_{a \in A(s_k)} \left\{ r_k(s_k, a) + \sum_{s \in S} p(s|s_k, a) u_{k-1}(s) \right\}, \qquad (8)$$

where function u_k is the the expected total reward from the decision epoch 0 to the decision epoch k.

Since the optimization problem is to maximize the expected total reward, we define a policy π^* to be optimal in Π if $u^{\pi^*}(s) \geq u^\pi(s)$ for all $\pi \in \Pi$. Note that the MDP optimal policy $\pi^*(s)$ indicates the decision as to which next hop MA to choose from given that the current state is s.

B. Backward Induction Algorithm

Backward induction algorithm is usually used to solve the finite-horizon MDP problem. Considering the characteristics of the mapping query, we improve this algorithm and present a

Markov decision routing (MDR) algorithm. Algorithm 1 shows the pseudo code of MDR, which includes four main steps:

1) Initialization. The algorithm implements forward iteration from the last state, i.e. the destination of routing. Set the node ID item to be destination's nID, and set the initial expected reward function $u_0^*(s)$ to be zero.

2) Decide whether can end the iteration. If we have not find all possible routing paths between source and destination, i.e. if $\exists i \neq$ source's nID, keep on the iteration and execute step 3); else the corresponding policy π is the optimal path, then end the algorithm.

3) Compute the Bellman optimality equation $u_k^*(s_k)$ for each optional next hop node, and determine the decision rule f_k^*. Here, we need to eliminate the effect of loop, so we will not compute the nodes which have already been on the corresponding paths.

4) Return to step 2), and do the next iteration.

MDR has the main characteristics and advantages: 1) Because the reward function synthetically considers the delay information of overlay network and physical network, the policy selection based these information can reduce the effects of topology inconsistent in a certain extent. 2) Comparing with local greedy routing methods, we can get the global optimum strategy using the MDP theory. 3) The algorithm has the characteristics of distributed computing, so it can balance and reduce the complexity of time and space, and effectively avoid the loops and a large number of redundant calculations.

V. DMDRMM: DHT AND MDR-BASED MOBILITY MANAGEMENT SCHEME

In this section, we design DMDRMM scheme based on the MDR algorithm. The design is corresponding to the three parts in the analysis framework [18], i.e. index structure, update operation and query operation. The index structure uses the domain-level DHT-based mobility management structure.

A. Update Operations

Update operations of DMDRMM involve movement detection (MD), address configuration or duplicate address detection (DAD), and registration or binding update (BU).

When an MN moves into the area of a new AR, discovery of the new AR and determination of movement is performed through the messages exchange between MN and AR①. Then, through the address configuration and DAD procedure to obtain a new unique CoA②. The MN's AR reports the new mapping information to its bootstrap mobility agent (aMA), which is the nearest MA to the AR in physical distance③. Finally, according to MN's HoA, the aMA obtains its oID, and performs binding update to the home mobility agent (hMA), whose nID is the nearest to the MN's oID, through the overlay network. The MDR algorithm is used to achieve efficient routing, in which the source node is aMA, the destination node is hMA.④ In addition, DMDRMM adopts route optimization procedure. In Mid-Call mobility, BUs are sent to all active correspondent nodes (CNs) by the MN, so that the CNs can direct, timely know the MN's new mapping.

Algorithm 1 MDR procedure

1: Initialization. $k = 0$, $i = $ destination's nID, $u_0^*(s) = 0, \forall s \in S$
2: **if** $\exists i \neq$ source's nID **then**
3: $\quad k = k + 1$, run line 7
4: **else**
5: $\quad \pi = ($source's $nID, f_1^*($source's $nID)$, $f_2^*(f_1^*($source's $nID)), ...,$ destination's $nID)$ is the optimal path , algorithm end.
6: **end if**
7: for each $s_k \in S$,which is not on the corresponding path (eliminate the effect of loop), to compute
$$u_k^*(s_k) = \max_{a \in A(s_k)} \left\{ r_k(s_k, a) + \sum_{s \in S} p(s|s_k, a) u_{k-1}^*(s) \right\},$$
8: and sign the set
$$A_k^*(s_k) = \arg \max_{a \in A(s_k)} \left\{ r_k(s_k, a) + \sum_{s \in S} p(s|s_k, a) u_{k-1}^*(s) \right\},$$
and arbitrarily choose $f_k^*(s_k) \in A_k^*(s_k)$, i.e. f_k^* is the decision rule at stage k.
9: return to line 2.

B. Query Operations

Due to DMDRMM uses the route optimization, the query operations execute in Pre-Call mobility. The procedure of the first query is as follows: ① The CN knows the MN's HoA. The destination address in the packet which the CN sends to the MN is MN's HoA. ② After the correspondent router (CR) receives the first packet, correspondent mobility agent (cMA) sends the mapping query request message to the overlay network. Overlay query process calls the MDR algorithm, in which the source and destination nodes are cMA and hMA respectively. ③ After receiving the query response message which includes the MN's mapping information, CR replaces the destination address of the data packets with MN's CoA, and directly delivers the packets to the MN.

VI. PERFORMANCE EVALUATION

In this section, we analyze the basic performances of DMDRMM using the analysis framework in [18], and compare DMDRMM with dDHT using the simulation system in [14].

A. Performance Analysis

Our analyses are based on the following assumptions. Firstly, ignore the delays and merely consider the packet delivery delays and overheads. Secondly, the distance parameters between any network nodes are the number of hops packets travel. Thirdly, assume that all packets have the same delays and overheads if their destination and source are identical.

In [18], we select the basic performance metrics combining both user and network perspectives, and update and query processes. Here, update delay is defined for an MN as the time that elapses between the connection reestablishment with a new access point (AP) and the arrival of the first packet on the new subnet. And update overhead is defined by the cost of network-layer signaling messages necessary to complete a

Symbol	Description
α	Latency or signaling cost of a packet delivery through a wireless medium between MN and AP
β	Latency or signaling cost of a packet delivery between AP and AR
γ	Latency or signaling cost of a packet's hop delivery in wired medium
b	The physical hop distance between AR and CN
d	The physical hop distance between AR and aMA
k	The physical hop distance between CR and cMA
h'	The physical hop distance between aMA and hMA which is determined by MDR algorithm
j'	The physical hop distance between cMA and hMA which is determined by MDR algorithm
ζ	The ratio between the length of query signal message and the length of data packet, which reflects the impact of separating mapping query and data delivery on overhead performance
$t_R = \alpha + \beta$	Latency or signaling cost of a packet delivery between MN and AR
$t_N = t_R + b\gamma$	Latency or signaling cost of a packet delivery between MN and CN
$t_M = t_R + d\gamma$	Latency or signaling cost of a packet delivery between MN and MAP
$t_{ah'} = t_M + h'\gamma$	Latency or signaling cost of a packet delivery between MN and aMA through overlay network using MDR algorithm
$T_{MD_{n+l}}$	Average period to complete the MD procedure
T_{DAD_n}	Average period to complete the address configuration and DAD

handover. As a result of route optimization, we only focus on the query delay and query overhead of the first query process. Based on the system architecture and performance parameters, we obtain unit update delay, unit update overhead, unit query delay, and unit query overhead for DMDRMM, respectively:

$$U_{L_{DMDRMM}} = T_{MD_{n+l}} + T_{DAD_n} + \max\{2t_{ah'}, \max_i\{2t_{N_i}\}\},$$

$$U_{S_{DMDRMM}} = 3t_R + 2t_{ah'} + \sum_i \{t_{N_i}\},$$

$$Q_{L_{DMDRMM}} = t_N + 2k\gamma + 2j'\gamma,$$

$$Q_{S_{DMDRMM}} = t_N + 2k\gamma\zeta + 2j'\gamma\zeta.$$

Table I shows the instructions about the parameters in these expressions. The basic performances of dDHT is given in [14].

B. Simulation System

We construct the simulation system according to the parts of mobility model in the analytical framework [18].

1) Topology model. The subnet in Internet is an abstract conception. The analytical framework has no restrictions on shape or location of the subnets. So we use a simple two-tier grid structure, in which each domain contains a certain number of subnets. 2) Movement model. Establish Random roaming model, and assume the subnet residence time follows an m-order Erlang distribution [19]. 3) Session model. Assume the session arrival process follows a Poisson distribution, and the session duration process follows a Pareto distribution [20].

For our analysis, the following parameters are used: $\alpha = 6ms$, $\beta = 4ms$, $\gamma = 2ms$, $T_{MD_{n+l}} = 0.15s$, and $T_{DAD_n} = 0.5s$. The mean and variance of the subnet residence time are $60s$ and $600s$, respectively. The mean of the inter-session arrival time is $30s$, and the mean and variance of the session duration time are $80s$ and $8000s$, respectively. Statistical analyze the performances for 1000 MNs. The user distribution follows random distribution. Total simulation time is $10000s$.

C. Simulation Results

The only difference between DMDRMM and dDHT is the overlay routing algorithm, and the mobility management structure and the distribution of mapping relation information are the same. Therefore, DMDRMM inherits the load balance and user scalability of dDHT. And in this paper, we mainly focus on the effects of the network size and the weight factor ω_1 on the basic performances. Here, we study three cases in which weight factor ω_1 takes 0.2, 0.4, 0.6, respectively.

Fig. 3 (a) and (b) show the delay performances for different network sizes and weight factors, where every domain contains 16 subnets and the number of subnets increases from 64 to 576. Fig. 3 (c) and (d) show the delay performances for different domain sizes and weight factors, where the number of subnets is 576 and the number of subnets in each domain increases from 16 to 144.

Simulation results show that the update and query performances of DMDRMM are better than dDHT. The advantages are more obvious especially when the network size is larger or the domain size is smaller, i.e. the overlay network size is relatively larger, and the performance of dDHT can be optimized by about 10%. This is because when the overlay network size is larger, the inconsistency of logical and physical topologies is relatively larger too. So using MDR algorithm which combines the physical information with the overlay information can gain more benefits. In addition, the weight factor ω_1, which reflects the proportion of the distance benefit function in the reward function, is not the smaller the better. For example, when the subnet number = 400 and $\omega_1 = 0.4$, or when the subnet number = 576 and $\omega_1 = 0.2$, the performances are better. If according to different scenarios to choose the optimum weight factor, the advantages of the MDR can be better reflected.

VII. CONCLUSION

In this paper, we designed mobility support based on the domain-level DHT-based management structure, to reduce the effects of inconsistency of logical and physical topologies on mobility management. We modeled the overlay mapping query problem to a finite-horizon MDP, and presented the Markov decision routing algorithm called MDR. The algorithm improves backward induction to get the global optimal strategy, and effectively avoids loops and a large number of redundant calculations. And the algorithm has the characteristics of distributed computing, so it can balance and reduce the complexity of time and space. Therefore, the MDR algorithm is suitable for large-scale mobility management.
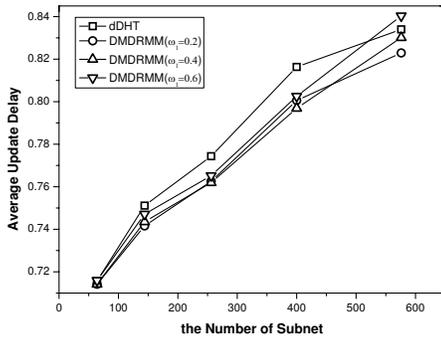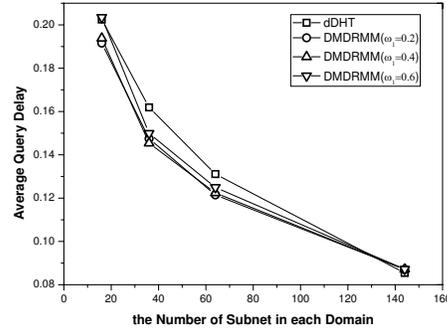
(a) Effects of network scale on average update delay
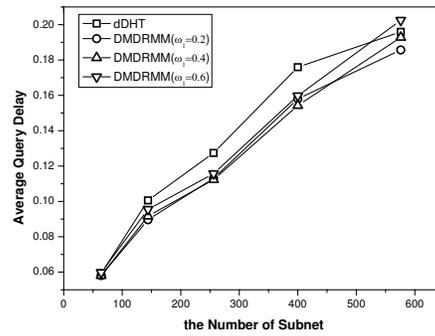
(b) Effects of network scale on average query delay
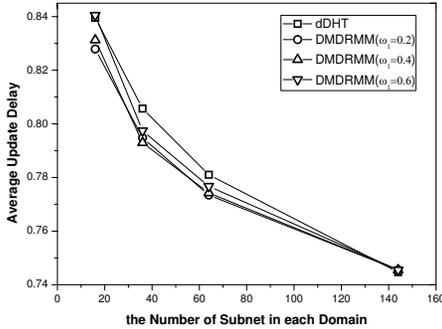
(c) Effects of domain scale on average update delay

(d) Effects of domain scale on average query delay

Fig. 3. Effects of network scale and domain scale on delay performances of dDHT and DMDRMM

Moreover, we proposed the DHT and MDR-based mobility management scheme called DMDRMM. The scheme inherits the advantages on load balance and user scalability of the DHT-based management structure. And because of combining physical layer information with application layer information, the scheme optimizes the update and query performances, especially for a large-scale network. The choice of the weight factors in the reward function is very important for developing the scheme performances better. We will study the optimal weight factor selection criteria in future works.

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