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A SCALABLE ROUTING FOR DELAY-TOLERANT HETEROGENEOUS NETWORKS

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Abstract. *A Delay Tolerant Network (DTN) is an intermittently connected mobile wireless network in which the connectivity between nodes changes frequently, due to the nodes' movement. Recently, there have been a lot of researchers working in this area. However, to the best of our knowledge, no work has addressed itself specifically to DTN routing within heterogeneous network environments. In this work, we propose a prediction-based routing protocol for heterogeneous delay tolerant networks, wherein edge servers are distributed over the borders of the different network domains. First, a location prediction algorithm based on user online logs is used to intelligently estimate the most probable future location of a destination, if the destination is currently unavailable. Then, an edge server selection algorithm, based on fuzzy logic, is employed to select a close-by intermediate node along the path to the destination, so that messages can be saved temporarily once the destination's location has been predicted. The experimental results show that the proposed routing protocol can efficiently deliver a message under limited buffer space, compared with other two representative delay tolerant network routing protocols found in the literature. The scalability of the proposed model is also confirmed in the simulations.*

Keywords: Heterogeneous network, Delay tolerant network, Edge server, Routing, Fuzzy logic

1. **Introduction.** A Delay Tolerant Network (DTN) is an intermittently connected mobile wireless network in which the connectivity between nodes changes frequently, due to the nodes movement. Typical examples of DTNs include interplanetary networks, wildlife tracking and habitat monitoring sensor networks [1-3], etc. In DTN routing, messages are sent in an extended store-and-forward manner, and nodes may cache messages for considerably long periods of time before getting the opportunity to send them to the next hop nodes.

In recent years, service providers are interested in owning and operating overlaid heterogeneous wireless systems, which integrate multiple wireless technologies with partially overlapped coverage areas and provide ubiquitous network service to mobile users. In order to access various wireless technologies, the mobile host may be equipped with one or multiple programmable wireless interface cards which are based on the programmable radio technology [4,5] or employ an approach similar to mobile access routers. Optimized data delivery can thus be achieved via the flexibility of selecting one of multiple available wireless access technologies at a particular location, or by using different access technologies when data travel in the network and arrive at different locations covered by various wireless networks.

In this paper, a prediction-based DTN routing protocol is proposed to deliver messages through heterogeneous all-IP wireless networks. Reliable network environments such as wire-lined or cellular networks are employed to pass the messages as closely as possible to the location where the target is expected to appear. A series of simulations were conducted to demonstrate the feasibility of the proposed algorithm. Our simulations showed that the prediction-based DTN routing protocol can effectively deliver messages in heterogeneous networks.

The remainder of this paper is organized as follows: Section 2 gives a brief overview of the related work in the literature; Section 3 presents the proposed DTN routing scheme for heterogeneous networks; the simulation results are set out in Section 4; and conclusions comprise Section 5.

2. **Related Work.** In a heterogeneous all-IP wireless network, the interconnection of different wireless access technologies supports IP transport. An essential aspect of service delivery in a heterogeneous all-IP wireless network environment is the selection of an optimal access network. Network selection in such an environment is influenced by several factors, and currently there is no comprehensive solution available to solve this problem. Selection of a non-optimal network [6] can result in undesirable effects, such as higher costs or poor service experiences.

Considering the store-and-forward routing in non-internet-like disconnected networks, numerous research contributions have arisen recently. In [7], Vahdat and Becker proposed an epidemic routing protocol for intermittently connected networks. The epidemic routing protocol uses a flooding method to disseminate the message over the entire network. Hence, messages are quickly distributed through the connected portions of the network. However, it was reported that the performance of epidemic routing depends greatly on both a mobile node's buffer size and network bandwidth [8]. In [9], a relay-based approach used to combine with traditional ad-hoc routing protocols is proposed. This approach, which makes use of node mobility to disseminate messages to mobile nodes, is called the Mobility Relay Protocol (MRP). The MRP integrates traditional ad-hoc routing and message storage in the network. The basic idea of MRP is that if the node does not know a route to a destination, it delivers a relay request to its immediate neighbor nodes. Each node upon receiving this relay request, then checks whether it has a route that is shorter than a pre-defined hop to the destination. If so, the node forwards the packet; alternatively, it stores the packet if it does not have a valid route for the request. The performance of this approach also depends greatly upon the mobile node's buffer size.

To the best of our knowledge, no work has specifically addressed itself to DTN routing with a focus on heterogeneous network environments. Unlike the above-mentioned routing protocols, this study proposes a prediction-based routing protocol, which exploits the user's online logs to choose the most satisfactory forwarding node to successfully deliver the messages. Meanwhile, a deployment of edge servers at the intersections of different network domains is proposed in this work. The purpose of the distributed edge server deployment is to effectively eliminate the possible impacts of buffer size limitation and inefficiency of network bandwidth utilization caused by DTNs routing within a heterogeneous network.

3. **Prediction-Based Routing Protocol for Heterogeneous Delay-Tolerant Networks.** Figure 1 illustrates the architecture of the proposed heterogeneous delay-tolerant network. The proposed architecture supports all-IP wireless heterogeneous networks. Each mobile device can connect to the internet through the base station in a cellular/WiMAX/WiFi network, or through a nearby edge server in a mobile ad-hoc network (MANET). We first deploy the edge servers supporting the distributed computing technology at the intersections of any two network domains. An edge server is able to collect the online history logs of mobile nodes through cellular base stations, WiMAX base stations, WiFi APs or MANETs. Meanwhile, a location prediction algorithm that considers each user's online history logs is proposed to calculate the probability of the appearance frequency of the destination in a specific network domain. In addition, we run the proposed fuzzy logic based edge server selection algorithm to select the edge server that has the greatest chance of successfully delivering this message to the destination, and transmit the message to the selected edge server. Once the destination is connected to the networks, it can receive the message from the selected edge server, as expected.

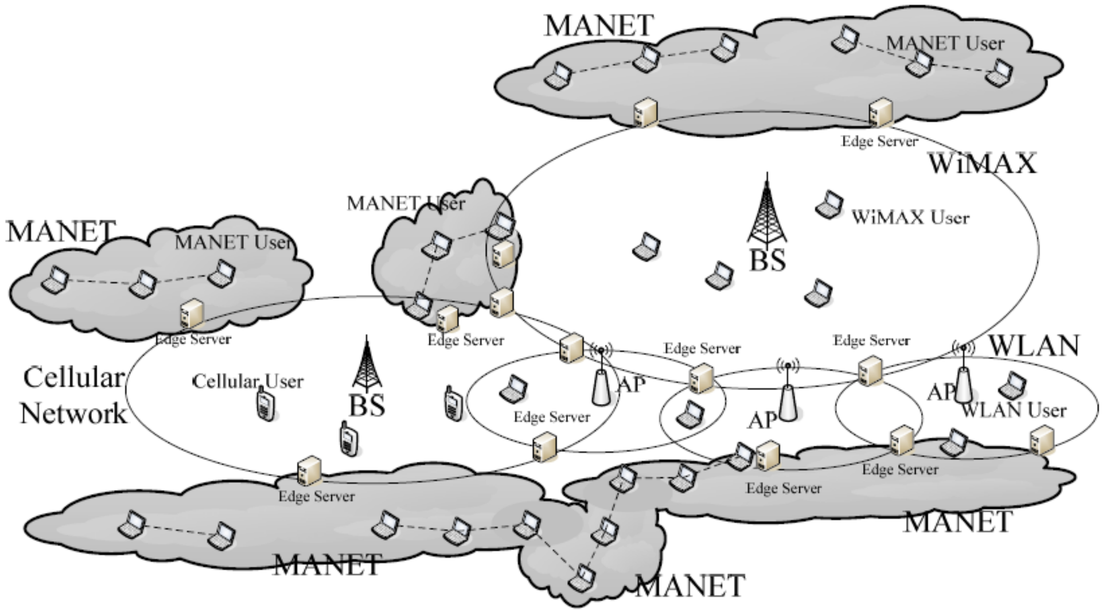

FIGURE 1. An example of heterogeneous delay-tolerant networks

The proposed protocol provides a more stable message delivery mechanism than the aforementioned algorithms presented in Section 2, for two reasons. First, most of the latter use a flooding method to disseminate the message over the network, which is impractical in the real world, because both the buffer size of a mobile device and the network bandwidth are limited. In this work, we use a location prediction algorithm based on online user history logs to intelligently estimate the most probable future location of the destination. If the destination is currently unavailable, a fuzzy logic-based edge server selection method is used to select an edge server that the destination has the most probability of connecting with. Second, when considering the forwarding routing, there are two major problems that need to be addressed, namely the lack of a guarantee of link availability between two successive nodes, and the need for the source to know the location of the destination. The assistance of online user history logs allows the edge server to select a more probable network domain. In addition, we specifically consider heterogeneous networks, rather than evaluating other methods only applied in single network environments.

Notably, for the mobile devices and the edge servers that are attached to multi-homing access networks, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [10] is adopted to address the issue of how to select the best network interface to transmit data [11-13]. TOPSIS is chosen here because it uses a comprehensive decision making process to rank candidate networks for service delivery to the terminal. TOPSIS is based on a unique decision making process that uses compensatory and non-compensatory multi-attribute decision making algorithms, jointly, to assist the terminal in selecting the top candidate network.

3.1. **Distributed computing technology supported by the edge servers.** In all-IP wireless heterogeneous networks, distributed database involves the query processing and the result coalescing. Distributed computing technology is supported by the edge servers in the proposed architecture. The edge servers act as the role of the post offices and can be used in a number of distributed computing applications that are capable of accessing network resources to obtain the user online history logs that correspond to the characteristic of deployed network domain to assisting in the decision making for the routing path. In this work, a distributed computing technology, Raymond's algorithm [14,15], is used to maintain online history logs in real-time and serialize the distributed concurrent requests such that the scheduling can be updated in a consistent way. Raymond's algorithm is chosen in this work owing to its suitability in terms of minimal message exchange for assuring serializability, deadlock freedom, no starvation, and fault tolerance. In short, Raymond's algorithm uses efficient mechanisms to process queries by breaking the qualification into separate pieces using a few simple heuristics. The cost criteria that were considered are minimum response time and minimum communications traffic.

3.2. **Prediction of destination location based on user online logs.**

3.2.1. *Primitive location prediction algorithm.* We first calculate the probability of appearance frequency of the destination in a specific network domain in a straightforward way,

$$P_i(D) = \frac{N_i(D)}{\sum\limits_{j=1}^{m} N_j(D)}, \tag{1}$$

where m is the number of network domains in the heterogeneous network environment, $N_i(D)$ is the appearance frequency of the destination D connecting to a specific network domain in the past, which is indexed by i, and the denominator represents the destination's total number of appearances in all network domains.

The most probable location at which the destination D will appear can be determined by,

$$L(D) = \arg \max_j \{P_j(D)\}. \tag{2}$$

3.2.2. *Improved location prediction algorithm.* We observe that people are generally accustomed to using their PCs and connecting to the network within some time period every day. For example, office workers turn on their PCs while on duty, from 9:00 to 17:00, during the work day. This observation motivates us to attempt to derive the appearance frequency of the destination in a more realistic manner.

Consider the case where the destination connects to a specific network at t_{Start} and leaves at t_{End}. We record both its connecting and disconnecting time in the database. Based on the recorded history of the appearance of each node, as saved in the database, say, for the past month in each network domain, the cumulative number of times that the destination showed up during a narrow time window, for example, between 9:00 and 10:00 during the past month, can be expressed by,

$$Pt_{i,t=[9:00,10:00]}(D) = \frac{N_{i,t=[9:00,10:00]}(D)}{\sum_{j=1}^{m} N_{j,t=[9:00,10:00]}(D)}, \tag{3}$$

where D represents the destination, and i is the index for the network domain in which it appears, and $N_{i,t=[9:00,10:00]}(D)$ is the frequency that the destination D connects to a specific network domain that is indexed by i between 09:00 and 10:00 during the past month.

Similar to Equation (2), the most probably network domain in which the destination D might appear between 09:00 and 10:00 is determined by,

$$L_{t=[9:00,10:00]}(D) = \arg\max_{j} \left\{ Pt_{j,t=[9:00,10:00]}(D) \right\}. \tag{4}$$

3.3. **Fuzzy logic based-edge server selection algorithm.** We employ edge servers as temporary message holding stations for MANETs. These edge servers are distributed over the border areas between a MANET and other kinds of networks. When a mobile device connects to the Internet via a MANET, it can receive its message from one of the edge servers that the MANET is connected to. An efficient edge server selection algorithm is required, since there might be multiple edge servers distributed in a multi-hop MANET, and a proper choice of an edge server to act as an intermediate node can result in better message delivery.

A fuzzy logic based-edge server selection algorithm is proposed and employed to select an edge server from among those located at the most probable network domain that is determined by Equation (4). The basic function of each component in the fuzzy edge server selection module is described as follows:

- **Fuzzifier**: The fuzzifier performs the fuzzification function that converts three inputs into suitable linguistic values which are needed in the inference engine.
- **Fuzzy rule base**: The fuzzy rule base is composed of a set of linguistic control rules and the attendant control goals.
- **Inference engine**: The inference engine simulates human decision-making, based on the fuzzy control rules and the related input linguistic parameters.

Defuzzifier: The defuzzifier acquires the aggregated linguistic values from the inferred fuzzy control action, and generates a non-fuzzy control output, which represents the predicted priority.

Figure 2 shows the input-output mapping for the fuzzy edge server selection algorithm. There are three input parameters used in the fuzzy logic inference system. The first parameter is the normalized cumulative time for the destination node connected to the candidate edge server, which is expressed by,

$$F_i = \frac{\sum_{j} D_{j,i}}{T_i}, \tag{5}$$

where $D_{j,i}$ represents the length of the jth time period that the destination connected to the ith edge server, and T_i denotes the total cumulative time period since the ith edge server started operating. Notably, we assume that the destination node intermittently connects and disconnects from the ith edge server. Three linguistic term sets, "small", "medium" and "large" are used for this input.

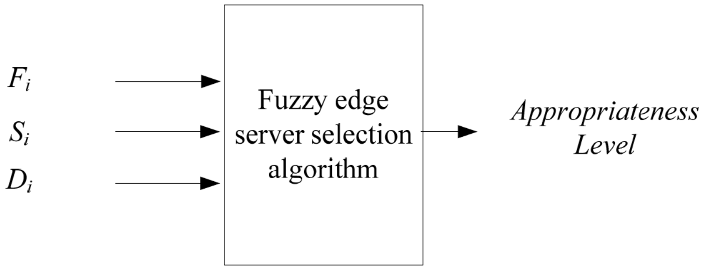

FIGURE 2. Input-output mapping of fuzzy edge server selection algorithm

The second input parameter for the fuzzy logic system is the ratio of the size of the transmitted message to the buffer size of the ith edge server,

$$S_i = \frac{M}{B_i}, \tag{6}$$

where M denotes the size of the transmitted message, and B_i is the buffer size of the ith edge server. Notably, S_i is set to 1 if S is equal to or larger than B_i. Three linguistic term sets, "low", "medium" and "high" are used for this input.

The last parameter used in this work is the normalized delivery ratio for the data sent to the destination node via the ith edge server,

$$D_i = \frac{R_i}{\sum\limits_{j=1}^{n} R_j}, \tag{7}$$

where R_i represents the cumulative data size transmitted to the destination node via the ith edge server, and n denotes the total counts of the edge servers located at the network domain derived by Equation (4). Notably, the denominator represents the total data size transmitted to the destination via the n edge servers. Three linguistic term sets, "small", "medium" and "large" are used for this input.

The output of the fuzzy logic system is the estimated appropriateness level of the edge server acting as the temporary message holding station. The appropriateness level of each candidate edge server is collected by the request node to determine the most appropriate edge server to hold the temporary message. The fuzzy linguistic variables used for the output membership function are "low", "medium" and "high".

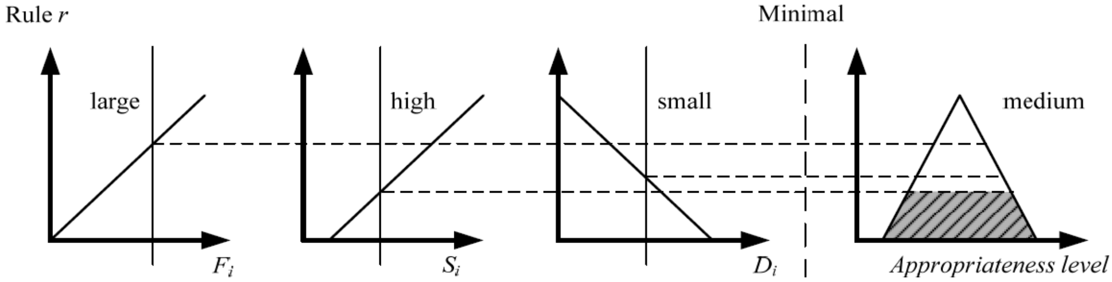

FIGURE 3. The reasoning procedure for Mamdani fuzzy model

Figure 3 illustrates the Mamdani reasoning procedure employed in this work. An example rule is given by:

IF the normalized cumulative time for the destination node connected to the candidate edge server is “large”, **AND** the ratio of the size of the transmitted message to the buffer size of the ith edge server is “high”, **AND** the normalized delivery ratio for the data sent to the destination node via the ith edge server is “small”.

THEN the estimated appropriateness level of the edge server is “medium”.

There are 27 inference rules generated in the Mamdani fuzzy inference system. The non-fuzzy output of the Mamdani fuzzy inference system can then be obtained by computing the centroid of the area for the aggregated output membership function.

4. **Simulation Results.** We ran a series of simulations to evaluate the performance of the proposed prediction based routing (PBR). Two representative DTN routing schemes found in the literature, including epidemic routing (ER) [7] and mobile relay protocol (MRP) [9] are compared with the PBR. The detailed simulation parameters are shown in Table 1. The Attractor-point-based mobility model [16] is adopted as the mobility model in this work because it is observed that users are influenced to move toward particular attraction points depending on the time of day. Each mobile node first chooses a location randomly and moves toward that location. Once it reaches the location, it then chooses the next location, and the process repeats until the end of the simulation.

Table 1. Simulation parameters

Parameter type	**Parameter value**
Simulation time	200 hours
Simulation terrain	40 km $\times$ 40 km
Mobility model	Attractor-point-based mobility model
Number of nodes	4500
Mobility	$0 \sim 20$ m/s
Network types	WiFi/MANET/WiMAX/Cellular
Mac protocol	802.11/802.16/HSPDA
Transmission range	100 m/10 km/6 km
Number of data sessions	1000

4.1. **Performance metrics.** In the comparison and analysis of the DTN routing algorithms, the following performance measures are adopted:

- Average delay latency: The delay latency is the period which elapses between the time the source sends the message to the time that the destination receives the message. Only those messages that are successfully delivered to the destination are considered in the latency time measure.
- Transmitted bytes: The total size of messages the source transfers.

Data delivery ratio: This is the ratio of the number of receiving data messages to the total number of sending data messages for data sessions.

4.2. **Simulation results and analysis.** We first investigated the performance of the three routing schemes under ideal conditions. That is, the simulations were run under the assumptions of infinite buffer size and unlimited bandwidth. All of the routing schemes, PBR, ER and MRP, achieve 100% data delivery ratios under ideal conditions. Since ER uses a flooding method to transmit the messages, the messages are quickly distributed to entire network. The destination can easily receive the messages once it connects to the networks. MRP combines one-hop broadcasting and traditional ad-hoc routing to

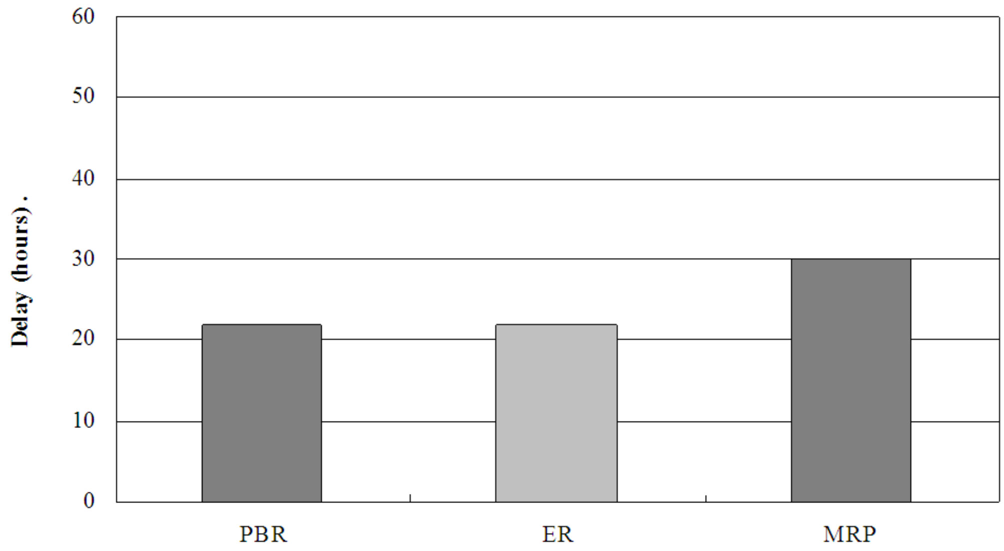

FIGURE 4. Average delay for PBR, ER and MRP under ideal conditions

transmit the messages. It can transmit the message to the closest nodes and the destination can receive the messages via these nodes. The proposed PBR first uses a location prediction algorithm to predict the network domain that the destination will connect to, then runs the edge server selection algorithm to forward and store the messages to the selected edge server, and finally, waits for the destination to receive the messages.

The average delay latency under ideal conditions is shown in Figure 4. The result showed that, the average delay latency is very long when successfully delivering the message with the MRP scheme. This is because the MRP scheme uses one-hop broadcasting and traditional ad-hoc routing to forward the message without considering users' history logs, and thus, the selected edge server may not be located at the right network domain, but instead may be at a location that is far from the destination. Hence, the MRP scheme

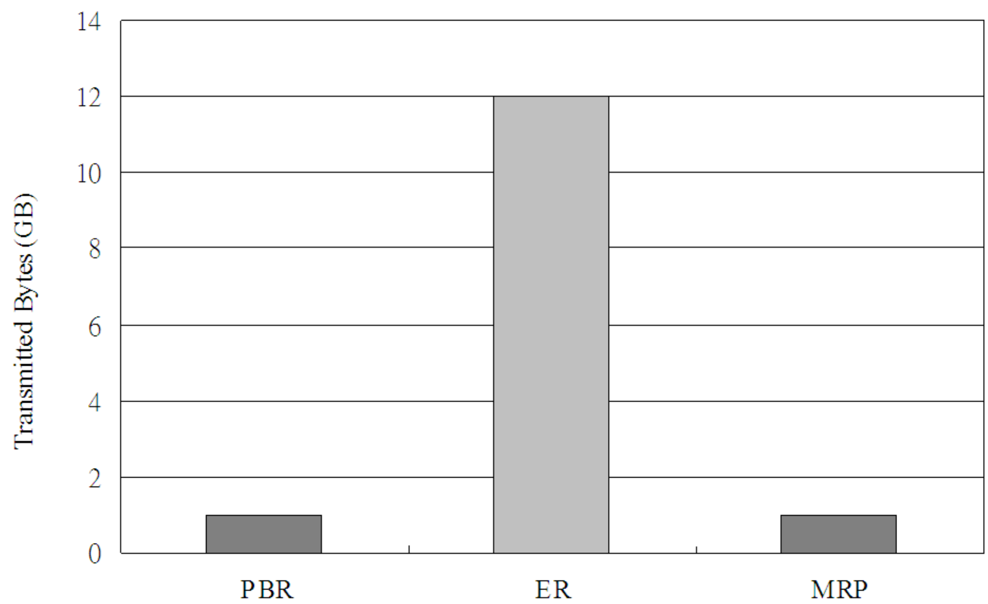

FIGURE 5. Transmitted bytes for PBR, ER and MRP under ideal conditions

usually successfully delivers the message to the right destination only after the user logs in. The ER scheme delivers messages to each edge server at all network domains, so no matter which network domains the users enter, they can successfully receive the messages. Although the average delay latency of the ER scheme is close to that of our proposed PBR scheme, the former reduces delay via generating massive numbers of copies, which causes a high amount of bandwidth consumption. On the other hand, our proposed scheme can achieve low delay latency without such massive forwarding of messages in the networks.

The comparison of the cumulative volumes of the messages spread over the networks is given in Figure 5. The result showed that, the volume of required transmitted messages is very large when successfully delivering messages with the ER scheme. As mentioned above, the ER scheme uses the strategy of letting users receive messages wherever they are, at some network domains, by wasting precious bandwidth. However, the PBR scheme and the MRP use different mechanisms to select the specific edge servers, and both successfully deliver messages without incurring the massive message replication problem.

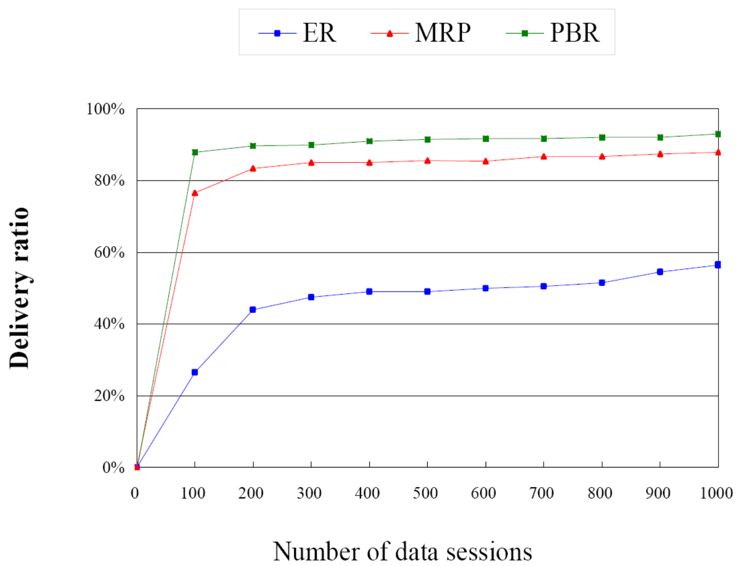

FIGURE 6. Data delivery ratio vs. number of data sessions in PBR, ER and MRP

The comparison of the data delivery ratios for delivering fixed size messages among the three schemes is illustrated in Figure 6. The ER scheme automatically deletes the temporary messages in every edge server, and then re-sends the messages. It is thus possible that the user enters the network domain, but the saved messages in the edge servers have been removed owing to the ER algorithm. Hence, the data delivery ratio of the ER scheme is much lower than those of the MRP scheme and the proposed PBR scheme. Furthermore, the proposed PBR scheme has a higher data delivery ratio than the MRP scheme because in the former, the messages are very often sent to the edge servers which are closer to the destinations via the location prediction algorithm and the edge server selection algorithm. Conversely, the MRP scheme always transmits the message only when the holding nodes have a shorter route to the destination. However, it is rare that every node has complete route information in DTNs, especially in a heterogeneous environment. Thus, it is difficult for MRP to successfully find a route to the destination. This results in a poor data delivery ratio with the MRP scheme.

Figure 7 illustrates the required buffer size for the three schemes while successfully delivering the messages. The required buffer size with the ER scheme is always the largest, owing to its massive packet-forwarding reliance. Moreover, the ER scheme deletes

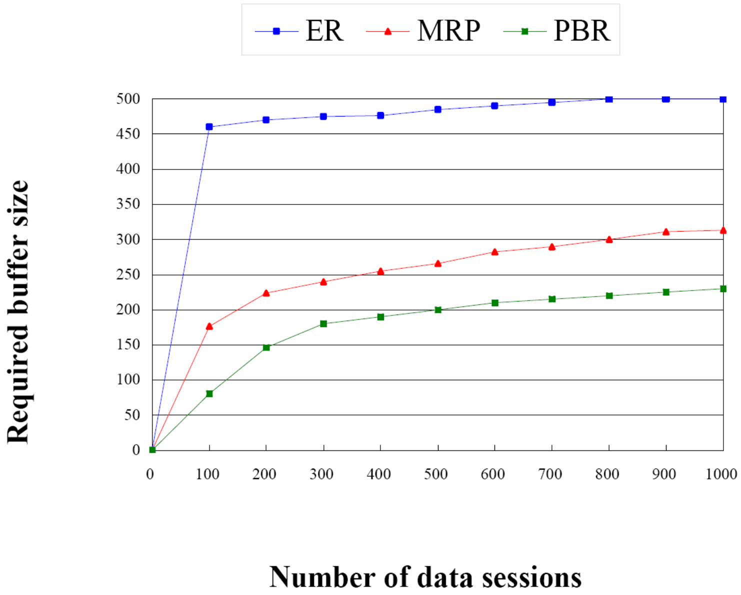

FIGURE 7. Required buffer size vs. number of data sessions in PBR, ER and MRP

the temporary messages in a fixed period, thus causing the successful transmission rate to deteriorate. Therefore, the ER scheme not only needs more buffer size, but also has a poor data delivery ratio. The MRP scheme has to select more adjacent edge servers to improve the successful transmitted rate, so the required buffer size is much larger than that required by our proposed PBR scheme.

The prediction accuracy comparison for PBR, MRP and ER under varied buffer sizes is given in Table 2. It can be seen that PBR has a higher accuracy rate than MRP and ER because the location prediction algorithm and the edge server selection algorithm effectively forecast the possible locations of the mobile hosts. The data delivery ratio and required buffer size comparison, as shown in Figures 6 and 7, provide further evidence that PBR indeed outperforms both MRP and ER, owing to the effectiveness of the proposed algorithms.

TABLE 2. The prediction accuracy comparison for PBR, MRP and ER under varied buffer sizes

Schemes \ Buffer size	50	100	150	200	250	300	350	400	450	500
PBR	68.3%	78.3%	75.0%	75.0%	77.3%	76.6%	80.0%	83.3%	85.0%	91.6%
MRP	24.1%	27.5%	46.66%	52.5%	71.6%	64.1%	79.1%	81.6%	85.0%	90.0%
ER	4.1%	5.8%	22.50%	25.8%	42.5%	39.1%	46.6%	44.1%	50.0%	51.6%

5. **Conclusions.** A prediction-based DTN routing protocol, which consists of a location prediction algorithm and a fuzzy logic-based edge server selection method, is proposed in this work. A heterogeneous architecture for DTNs is presented in which edge servers are distributed at the intersections of network domains, to help message delivery. User online logs are used in the location prediction and edge server selection algorithms, to determine the intermediate node that saves the messages for the destination. The impact of buffer space is analyzed in the simulations. The experimental results show that the proposed prediction-based DTN routing protocol can efficiently deliver messages, with

limited buffer space, when the performance metrics take the data delivery ratio, average delay latency and transmitted bytes into account. The scalability of the proposed work is thus confirmed. Finally, there are some limitations to our proposed method. First, although the utilization of edge servers can efficiently improve the overall performance as stated above, it could increase the computation overhead required to calculate the possible network domain and choose an appropriate edge server to temporarily store the message. Second, the server needs more storage space to record online user history log data, and this might increase maintenance costs.

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