EcoRep: An Economic Incentive Scheme for Dynamic Replication in Mobile-P2P Networks

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In mobile ad-hoc peer-to-peer (M-P2P) networks, frequent network partitioning leads to typically low data availability, thereby making data replication a necessity. This work proposes EcoRep, a novel economic model for dynamic replica allocation in M-P2P networks. EcoRep performs replica allocation based on a data item's relative importance, which is quantified by the data item's *price* in terms of a virtual currency. The price of a data item depends on its access frequency, the number of users who accessed it, the number of its existing replicas, its (replica) consistency and the average response time required for accessing it. EcoRep ensures fair replica allocation by considering the origin of queries for data items. EcoRep requires a query issuing user to pay the *price* of his requested data item to the user serving his request. This discourages free-riding and encourages user participation by providing an incentive for users to become service-providers. EcoRep also considers other issues such as load, energy and network topology as replication criteria. Our performance study indicates that EcoRep is indeed effective in improving query response times and data availability in M-P2P networks.

1. Introduction

In a Mobile ad-hoc Peer-to-Peer (M-P2P) network, mobile hosts (MHs) interact with each other in a peer-to-peer (P2P) fashion. Proliferation of mobile devices (e.g., laptops, PDAs, mobile phones) coupled with the ever-increasing popularity of the P2P paradigm strongly motivate M-P2P network applications. Application scenarios, which would facilitate mobile users in sharing information with each other *on-the-fly* in a P2P manner, include tourists in different sight-seeing buses sharing touristic information (e.g., images of castles) with each other (*inter-vehicular communication*). Customers in a shopping mall could share information about the cheapest available `Levis' jeans. They could also exchange shopping catalogues with each other. Similarly, visitors to a museum could request images/video-clips of different rooms of the museum to decide which room they will visit first. They could even request the museum's path information from other visitors as in virtual reality applications. Notably, such P2P interactions among mobile users are generally not freely supported by existing mobile communication infrastructures. The notion of replica consistency in this work is based on the time of the latest update. Our application scenarios do not require absolute replica consistency.

Data availability in M-P2P networks is typically lower than in fixed networks due to frequent network partitioning arising from user movement and/or users switching `on'/`off' their mobile devices. (Data availability is less than 20% even in a wired environment.) To improve M-P2P data availability, replication schemes [4], [9] have been proposed. However, these schemes do not address **fair replica allocation** since they allocate replicas solely based on the read/write access ratio of a data item d without considering the origin of queries for d (e.g., the E-DCG+ approach in [4]). Moreover, existing schemes do not combat **free-riding** [1], [5], which is rampant in P2P systems. Since free-rider MHs do not participate in storing replicas, replication opportunities decrease for existing schemes.

This work proposes EcoRep, which is a novel **economic** model for dynamic replica allocation in M-P2P networks. EcoRep performs replica allocation based on a data item's relative importance, which is quantified by the data item's *price* in terms of a virtual currency. The price of a data item depends on its access frequency, the number of users who accessed it, the number of its existing replicas, its (replica) consistency and the average response time required for accessing it. EcoRep requires a query issuing user to pay the price of his requested data item to the user serving his request. Hence, a user has to provide service to the network to earn enough currency to be able to issue his own queries.

The main contributions of EcoRep are two-fold: (a) It ensures fair replica allocation by considering the origin of queries for data items to determine their relative importance to the network as a whole. (b) It discourages free-riding and provides an incentive for users to become service-providers by virtue of its economic nature. EcoRep also considers other issues such as load, energy and network topology as replication criteria. Our primary focus is **economy-based fair replica allocation**, a pleasant side-effect of which is that of **discouraging free-riding** at no additional cost. EcoRep can also be regarded as an **incentive scheme**, which encourages user participation in M-P2P networks essentially due to its economic nature.

To manage replication efficiently, EcoRep deploys a super-peer architecture. The super-peer (SP) is an MH, which generally moves within the region and which has maximum energy and processing capacity at a given time. In our application scenarios, the tour guides in the sight-seeing buses, the administrators in the shopping mall and the museum administrators would act as SP. Queries need not pass via SP, thereby preserving P2P autonomy. This is possible because every MH periodically sends the list of data items/replicas stored at itself to SP, and SP broadcasts this information to all MHs.

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Our performance study indicates that EcoRep is indeed effective in improving query response times and data availability in M-P2P networks, while incurring relatively low communication costs for replication. To our knowledge, this is the first work to propose an economic model for data replication in M-P2P networks.

2. Related Work

Economic models for resource allocation in distributed systems have been discussed [2]. Such models do not address the unique issues associated with the M-P2P environment such as frequent network partitioning and mobile resource constraints. Incentive schemes to combat free-riding have been proposed in [3], [5], [6]. However, these works are orthogonal to M-P2P replication issues.

The proposal in [4] considers limited memory space in MHs for storing replicas, access frequencies of data items and the network topology, to improve data accessibility in mobile ad-hoc networks. The **E-DCG+ approach** [4] is among the most influential replica allocation approaches. By creating groups of MHs that are biconnected components in a network, E-DCG+ shares replicas in larger groups of MHs to provide high stability. However, it does not consider economic issues such as incentives and prices of data items. Furthermore, the architecture in [4] is not suitable for our application scenarios since it does not consider load sharing and tolerance to weaker consistency.

3. EcoRep: An Economic Model for Data Replication in M-P2P networks

This section discusses EcoRep, which is an economic model for dynamic replica allocation in M-P2P networks. In EcoRep, each data item has a price ρ (in terms of a virtual currency) that quantitatively reflects its relative importance to the M-P2P network as a whole. Whenever an MH MI accesses a data item d stored at an MH MS, it pays the price ρ of d to MS since MS serves its request. Thus, MI spends the amount ρ, while MS earns ρ. We define the **revenue** of an MH as the difference between the amount of virtual currency that it earns and the amount that it spends. EcoRep provides an incentive for MHs to provide service to the network so that they can earn more revenue in order to be able to issue their own queries. An MH can provide service to the network either by storing data items/replicas that are accessed by other MHs or by forwarding messages e.g., queries, query results (i.e., relay functions). Storage of data items and replicas is assigned higher priority than relay functions. When an MH joins the M-P2P network, SP provides the MH with a small amount of revenue to start with.

Each MH maintains recent read-write logs (including timestamps) of its own data items and the read-logs of the replicas stored at itself. As we shall see shortly, each MH uses this information for computing the prices of the data items and replicas stored at itself. Furthermore, each data item d is owned by only *one* MH, which can update d autonomously anytime; other MHs cannot update d. Memory space of MHs, bandwidth and data item sizes may vary. We define the load of an MH M as the job queue length of M normalized w.r.t. its available bandwidth and service capacity to address heterogeneity.

Table 1: Summary of Notations

Notation	Significance
d	A given data item
M	A given MH
ρ_{rec}	Price of d during most recent period
ρ	Moving average price of d
N_{MH}	Number of MHs
w_i	Weight coefficient for MH i
n_i	Number of queries for d from MH i
C_i	Consistency of queries answered on d
BA_i	Bandwidth allocated by MH i for d
PA_M	Probability of availability of M
N_R	Number of replicas of d
J_M	Job queue of MH M
σ_M	Service capacity of MH M

An MH M, which stores a data item d, computes d's price in two steps. First, M computes ρ_{rec}, which is the price of d based on the accesses to d at M during the most recent replica allocation period. Second, M uses moving averages of ρ_{rec} over a fixed number of replica allocation periods to compute the price ρ of d. This is necessary because ρ_{rec} may not always be able to reflect the true importance of d to the network (e.g., when spurious `spikes' in d's access frequency occur). Table 1 summarizes the notations, which we shall henceforth use in this paper.

Computation of ρ_{rec}: M first sorts the MHs in descending order of their access frequencies for d during the most recent replica allocation period i.e., the first MH in this order made the most accesses to d. Given this order and using the notations in Table 1, M computes ρ_{rec} of d.

$$\rho_{rec} = \Sigma\ (\ (w_i \,.\, n_i \,.\, C_i \,.\, BA_i\,)\,.\ PA_M)\ /\ ((N_R+1)\,.\ J_M\,/\,\sigma_M\,)\ (1)$$

where the weight coefficient w_i equals (i/N_{MH}), thereby ensuring that more the number of MHs served by d, the more its price will be. C_i reflects the (replica) consistency with which d was answered for queries by MH i. C_i= 1 for queries answered by M's own data items since such queries are always answered with absolute consistency. For queries answered by replicas, we consider three different levels of replica consistency, namely *high*, *medium* and *low*. C_i is assigned values of 1, 0.5 and 0.25

for high, medium and low consistency respectively. Each MH maintains a table TC, which contains the following entries: (x%, high), (y%, medium), (z%, low), where x, y, z are error-bounds, whose values are application-dependent and pre-specified by the system at design time. Thus, C_i is computed using TC, which is replicated at each MH and is the same for each MH. BA_i equals (TB / Na), where TB is the sum of all the bandwidths that M allocated to MH i over each of the times when MH i accessed d at M. Na is the total number of access requests that MH i made for d. The total number of copies of d in the M-P2P network equals the number of replicas in addition to the original data item itself, which explains the term (N_R+1).

Computation of the moving average price ρ: M computes the Exponential Moving Average (EMA) price ρ of d as follows:

$$\rho = (\rho_{rec} - EMA_{prev}) \cdot 2 / (N+1) + EMA_{prev} \qquad (2)$$

where EMA_{prev} represents the EMA that was computed for the previous replica allocation period, and N represents the number of replica allocation periods over which the moving average is computed. Preliminary experiments show that N = 5 is a reasonable value for our applications.

Algorithm *AReL*
Rep: List of data items that are candidates for replication

(1) Sort data items in Rep in descending order of ρ
(2) for each data item d in Rep
(3) FLAG R = FALSE
(4) Identify list LA of MHs which have recently accessed d
(5) for each MH M in LA
(6) Compute the number Φ of M's 1-hop neighbours that accessed d
(7) Sort the MHs in descending order of Φ into a list LB
(8) while (FLAG R != TRUE)
(9) for each MH M in LB
(10) Add M and its 1-hop neighbours to a list LC
(11) Delete MHs with inadequate memory space from LC
(12) Delete MHs with low remaining energy from LC
(13) Delete overloaded MHs from LC
(14) Delete MHs with low probability of availability from LC
(15) if (LC is not an empty list)
(16) From LC, select the MH with lowest λ for storing the replica of d
(17) Delete all entries from LA, LB and LC
(18) Recompute ρ of d
(19) FLAG R = TRUE
(20) break
end

Figure 1: AReL replica allocation algorithm

4. AReL: An Adaptive Revenue-Load-based Replica Allocation Algorithm for EcoRep

This section discusses the AReL (Adaptive Revenue-Load) replica allocation algorithm deployed by EcoRep. AReL uses a parameter λ that can be tweaked to adjust the relative importance of revenue and load. Let us designate the normalized revenue of an MH as R and the normalized load of an MH as L. When revenue and load are both assigned equal weight, λ = R + L. When revenue is assigned higher weight than load, λ = 2R + L. If revenue is assigned lower weight than load, λ = R + 2L.

Figure 1 depicts the AREL replica allocation algorithm, which is executed by SP. Periodically, each MH sends its current (x,y) coordinates, its revenue value ω, the prices of items stored at itself, its load, energy and available memory space status to the corresponding SP in its region. The list Rep in Figure 1 comprises items that are candidates for replica allocation i.e., all items whose prices exceed the average price. Observe how AReL facilitates both revenue-balance and load-balance by allocating replicas of relatively higher-priced data items to MHs with low values of λ (see Line 16). The AReL algorithm is repeatedly executed until none of the MHs have adequate memory space.

5. Performance Evaluation

Our experiments consider 50 MHs and 1 SP. A total of 200 data items are uniformly distributed among 50 MHs i.e., each MH owns 4 data items. Each query is a request for one of the data items. MHs move within a region of area 1000 metre by 1000 metres according to the *Random waypoint model* since our application scenarios consider random movement of users. Periodically, every 200 seconds, SP decides whether to perform replica allocation. In all our experiments, 20 queries/second are issued in the network, the number of queries directed to each MH being determined by the Zipf distribution with zipf factor = 0.9. Communication range of all MHs (except SP) is a circle of 100 metre radius. Bandwidth between MHs varies between 28 Kbps to 100 Kbps, while probability of MH availability is between 50% to 85%. Data item sizes vary between 50 Kb to 350 Kb, while memory space of each MH is between 1 MB to 1.5 MB. MH service capacity varies between 1 to 5 service capacity units, while MH speed varies between 1 metre/s to 10 metres/s.

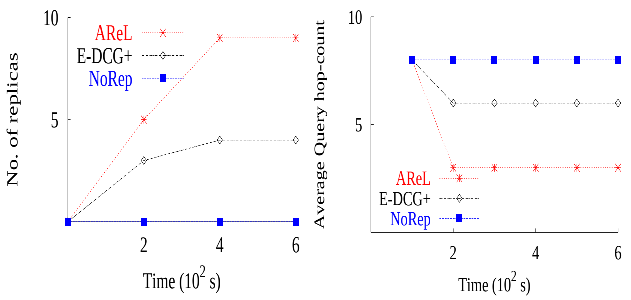

Figure 2: Effect of fair replica allocation

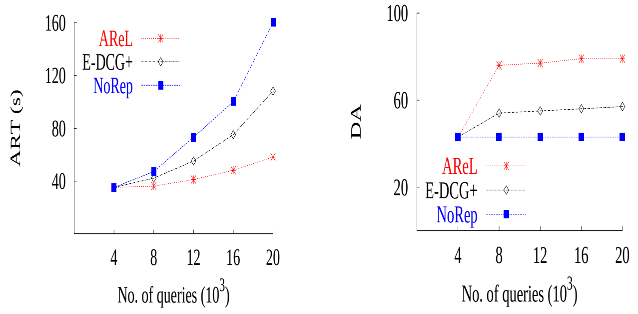

Figure 3: Performance of AReL

Performance metrics are **average response time (ART)** of a query, **data availability DA** (the percentage of queries answered successfully) and **traffic TR** (total hop-count) for replica allocation. As reference, we adapt the **E-DCG+** approach [4] (discussed in Section 2) to our scenario. E-DCG+ is executed at every replica allocation period. We also compare our proposed AReL algorithm with an approach **NoRep**, which does not perform replica allocation. Incidentally, AReL showed comparable performance for different values of λ, hence we present here the results of AReL corresponding to equal weight for both revenue and load i.e., λ = R + L (see Section 4).

Effect of fair replica allocation: We observed the number of replicas created by AReL and E-DCG+ for a single `hot' data item d, which was selected randomly from the top 10% hottest data items. Figure 2a shows that AReL creates more replicas of d than E-DCG+ because AReL's economic model encourages higher MH participation, hence total available memory space and available bandwidth are more for AReL than for E-DCG+. Figure 2b indicates that AReL requires lower number of hops than E-DCG+ to answer queries on d since AReL creates more replicas for d, which increases the likelihood of queries being answered within lower number of hops. E-DCG+ outperforms NoRep essentially due to replication.

Performance of AReL: Figure 3 depicts the performance of AReL, which can be explained partly by the reasons discussed for Figure 2. Additionally, AReL allocates replicas only to underloaded MHs, while it is possible for E-DCG+ to allocate replicas to overloaded MHs.

6. Conclusion

We have proposed EcoRep, which is a novel economic dynamic replica allocation model for improving the typically limited data availability of M-P2P networks. EcoRep ensures fair replica allocation by considering the origin of queries for data items. EcoRep's economic nature discourages free-riding. EcoRep also considers load, energy and network topology as replication criteria. Our performance study demonstrates that EcoRep is indeed effective in improving query response times and data availability in M-P2P networks. We plan to extend this work by considering a bidding-based economic model for M-P2P networks.

[References]

[1] E. Adar and B. A. Huberman. "Free-riding on Gnutella.". Proc. First Monday 5(10), 2000.

[2]. C. Grothoff. "An excess-based economic model for resource allocation in peer-to-peer networks.", Proc. Wirtschaftsinformatik, 2003.

[3] P. Golle, K.L. Brown and I. Mironov. "Incentives for sharing in peer-to-peer networks." Proc. Electronic Commerce, 2001.

[4] T. Hara and S.K. Madria. "Dynamic data replication using aperiodic updates in mobile ad-hoc networks." Proc. DASFAA 2004.

[5] S. Kamvar, M. Schlosser, and H. Garcia-Molina. "Incentives for combatting free-riding on P2P networks." Proc. Euro-Par, 2003.

[6] N. Liebau, V. Darlagiannis, O. Heckmann and R. Steinmetz. "Asymmetric incentives in peer-to-peer systems." Proc. AMCIS, 2005.

[7] O. Wolfson, S. Jajodia, and Y. Huang. "An adaptive data replication algorithm." Proc. ACM TODS, 22(4):255--314, June 1997.

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