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User-centric Utility-based Data Replication in Heterogeneous Networks

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***Abstract*—Information overload and convergence of devices aggravate the difficulties of accessing data distributed among various user devices especially when this is performed by mobile users and over heterogeneous wireless networks. Existing data replication systems help increase the performance of the distributed data system, but they do not consider users' different levels of interest in various pieces of data and neither heterogeneous wireless connectivity issues. This paper presents the Smart Personal Information Network (Smart PIN), a performance and cost-aware personal information network which uses a novel user-centric utility-based data replication scheme to exchange content automatically, based on both network performance and user interests. The proposed user-centric data replication scheme's evaluation, through simulation, shows improved results in comparison with existing solutions.**

***Keywords:* Data replication, Utility Function, Heterogeneous Network.**

I. Introduction

Over 90% of information these days is stored and transferred in digital format and the amount of generated digital content increases significantly every day. As both information diversity and quantity grows, significant pressure is put on the limited capacity of any individual person to store and handle this data [1]. In terms of storage there are already systems that can save one person's lifetime of data in the form of e-mails, video, audio, etc. (estimated at roughly 1 GB/month) [2]. However selecting data relevant to users' interests, transferring it via heterogeneous networks and displaying it on diverse user devices still causes problems.

In terms of transferring data, the latest advances in wireless communications enable the generalisation of the always-connected paradigm via heterogeneous networks [3], [4], [5]. This allows for content transfers to mobile users located almost anywhere at anytime, but significant bandwidth limitations exist. Regarding presentation of data to users, there is a trend of user device convergence towards three main categories: personal computers, consumer electronics and mobile phones. These devices differ in terms of characteristics such as battery power, processing capacity, memory, associated screen size, mobility support, etc., affecting user experience [6], [7]. Most of these devices have a primary network connection (e.g. fixed, wireless or cellular) and also secondary networking capabilities such as WLAN (e.g. IEEE802.11) or wireless personal area networks - WPAN (e.g. Bluetooth). This network connectivity can be used to establish a personal information network which would enable users to have easy access to desired services via various devices.

Information exchange can also be performed between different users based on their interests. One could imagine a user (User A) interested in the Irish music scene and having his favourite music and pictures saved on his mobile phone when meeting their friends (Users B and C). User B and C are interested in pop and rock music respectively and have stored their favourite contents on their portable devices. If users choose to share their data with friends, but do not want to do so manually, they would benefit from automatic data exchange based on their interests. This would see Irish pop and Irish rock music being transferred among users A and B and A and C respectively. The proposed Smart PIN relies on this principle which is illustrated in Fig. 1. Existing solutions such as network file systems [8] and P2P file sharing systems [9] can only provide restricted access to contents and users need to manually manipulate devices to access data.

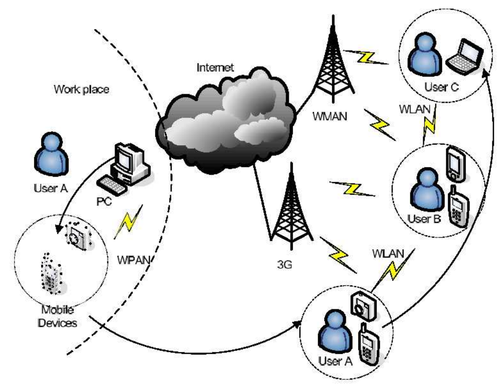

Fig. 1. General Concept of Smart PIN

This paper presents the Smart Personal Information Network (Smart PIN), a performance and cost-aware personal information network which uses a novel user-centric utility-based data replication scheme to exchange data automatically based on both network performance and user interest. The paper is structured as follows. In the next section, a literature review of related work is presented. Section 3 presents Smart PIN and the proposed user-centric data replication scheme. Simulation setup and testing results which involve comparison with existing schemes are shown in section 4. Conclusions and future work directions are presented in the last section.

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II. Related Work

Data replication involves a distributed data processing system to enhance overall system performance and reliability using intentional duplication of its data among the member devices. Hara [10] classified data replication system issues in data relocation, data consistency, and data search. Data consistency [11], [12], [13] and data search [14] were very well studied by many researchers in recent years. This section focuses on some important data replication schemes and data relocation issues.

A. Data Replication Schemes

Fundamentally, data replication schemes could be categorised into manual and autonomous approaches. In manual schemes, the selection of data, location and delivery is dependent on user activity as is the case in Roam [11]. In this system, users pick up the data needed to be carried and stored to their devices. If there is too much data to handle, autonomous data replication should be involved. Autonomous data replication schemes could be classified into static and dynamic solutions [15]. Static replication indicates that the data replication is determined at system deployment time and only changed with administrative control. In other words, no adaptive data replication properties are provided during system's operation. Even though the static schemes do not consider dynamic characteristics of traffic and network, the situation is similar to static file assignment problem which is NP-complete. The dynamic replication schemes measure objective metrics for network, user behaviour and other performance parameters and provide adaptation to achieve specific requirements. In comparison with the static schemes, they require continuous monitoring of performance parameters, but also provide better results.

B. Data Relocation Issue

Data availability or durability is defined as the ratio of successful data accesses over total requests. Data relocation affects critically the data availability. Related to this issue, data allocation and delivery are the main aspects to be considered.

1) Data Allocation Approaches: OceanStore [16] is a replication system based on a large network and considers data either as a changing active object or as a read-only deep archival object. The system uses random data allocation for load distribution. It provides a unique id for each server and distributes data using the server id as a portion of data id to data. Specifically, OceanStore uses an approach which uses a fixed number of erasure coded fragments for the archival data. The erasure coded fragments are small pieces of data which have redundant codes for forward error correction. However, the devices considered are not mobile devices and the system does not deal with characteristics of different network technologies.

Wayfinder [17] is a P2P file system supporting optimistic consistency based on PlanetP [18], a toolkit for medium-scale P2P applications. Cuenca-Acuna et al. [19] propose the Automated Replication (AR) scheme to achieve high availability of data in P2P file system based on PlanetP. For this, the erasure coded fragments are replicated randomly on the peers' free space. The estimated availability for a file and fragment is measured periodically. Wayfinder supports a middle-scale data system: if a node which has a lot of new data joins, the system needs to spend a quite long time to achieve target data availability.

2) Data Delivery Approaches: The approaches for data delivery involve scheduling of data delivery for replication among the devices. These could be categorised as reactive and proactive approaches. Reactive approaches initiate data delivery when it is required, whereas proactive solutions initiate it in advance. This section discusses delayed delivery as a reactive approach and periodic and budget-based delivery as proactive approaches.

Delayed delivery manages a queue for delivery request and waits until the connectivity between devices is available. OmniStore [13] adopts schemes which are similar to a computer's cache memory. Specifically, push caching used for transferring files to mobile devices from repositories, and a backup scheme used for replicating files from mobile device to repositories, are performed on this basis. Although OmniStore considers various connections such as WPAN and Internet, the different costs of each connection are not considered.

Periodic delivery works with some conditions for determining whether there is a need to transfer the data. The scheme used in OceanStore [16] and AR scheme [19] are periodic approaches using erasure coded fragments distribution. OceanStore uses a very low rate such as once a month and the scheme is just for repairing the fragments which are considered as deep archival files. The AR scheme measures the estimated availability for a file. Based on measured data availability, a randomly generated fragment of file is distributed to a randomly chosen node to achieve target availability. Since the system randomly chooses data to transfer, this approach does not consider how data is important to user.

In Tempo [20], a proactive method of replication of data during idle time of devices is proposed. To limit the usage of bandwidth, it introduces a bandwidth budget which defines the maximum data size per unit time. With this user specified parameter (bandwidth budget), Tempo removes busty data transfer for repairing data fragments in a reactive way and provides the same level of durability as previous implementations, without fluctuations of the data transfer. The decision for the transfer is also related to the bandwidth budget. A major problem with this approach is that it does not consider user interest in data.

III. Utility-based Data Replication in Mobile Devices over Wireless Networks

A. Smart PIN

Smart PIN [21] is a performance and cost-oriented context-aware personal information network targeting efficient user access to information located on remote devices. Smart PIN operates on a heterogeneous network environment as illustrated in Fig. 2. As in any context-aware system, Smart

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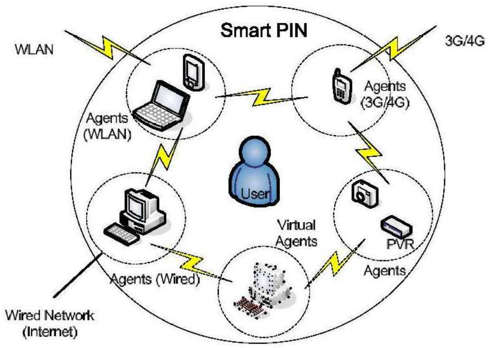

Fig. 2. Topology of Smart PIN

PIN uses context information for internal usage [22], context annotation [23] and replication of context annotated content [13]. Context information enhanced with specific performance-related data is considered as metadata (data about data). Since metadata could exist separately from the associated content, Smart PIN assumes data will be stored in context-content data pairs. Consequently, Smart PIN focuses on replication of context annotated content.

B. User Interest Modelling

The data replication strategy in Smart PIN is automatic rather than manual. In addition, Smart PIN supports mobile devices, heterogeneous networking and large amounts of data. Since most mobile devices cannot store and transfer all data, important data to user needs to be selected, delivered and stored in mobile devices. In this context, Smart PIN uses results of user modelling which indicates the level of user interest in the content and stores this information as part of the content's metadata.

Smart PIN assumes a user profile exists with a set of keywords given by the user as in [24]. Starting from these keywords, devices can evaluate how important each piece of data i is to the user. Information Retrieval (IR)-related techniques are used for document-query pair relevance assessment [24]. The IR solution can provide a relevance value starting from keywords and a piece of data: (I_i). The data with high relevance score obtained from the query keywords associated by the user model to a particular user will be considered more important to that user than the one which yields a low relevance score. Alternatively a user model such as proposed in [25] could be used by Smart PIN to collect different user interest-related information via users' previous queries in a specific environmental context such as location and time of day. The user model would then be represented as context-keyword pairs.

C. Utility Function

Utility functions are mainly used in the field of Economics for presenting the relative satisfaction from consumption of goods. However recently they were also used in other areas including networking to reflect users' satisfaction with services based on measurable metrics from the system. For data application systems, some approaches present utility functions and use them [26], [27].

Smart PIN uses a utility function which is evaluated for each piece of data content i. The function includes two main components: benefit (B_i) and cost (C_i). In addition, the user interest (I_i) (e.g. relevance value of data) for specific items is used to increase or decrease the relative influence of the benefit in comparison with that of the cost. Including normalised values of these metrics, the utility (U_i) for item i is computed as in Eq. 1 and has values from 0 to 1.

$$U_i = \frac{1 + B_i \cdot I_i - C_i}{2} \quad (1)$$

Smart PIN uses separate utility functions for data selection and delivery respectively and consequently the benefit factor used (B_i) will differ. For data selection, the relevance score of content item i is used as the benefit factor (B_{RL_i}) representing perceptual quality of information. In contrast, for data delivery, the required bandwidth for the delivery of data item i is used (B_{BW_i}) divided by the total available bandwidth for content delivery (B_{BW}). Consequently, the benefit function is defined as in Eq. 2.

$$B_i = \begin{cases} B_{RL_i} & \text{For data selection} \\ \frac{B_{BW_i}}{B_{BW}} & \text{For data delivery} \end{cases} \quad (2)$$

A utility function's cost component considers the storage and delivery cost relative to the size of data as Eq. 3. To normalise this factor, maximum data size (S_{MAX}) and minimum data size (S_{MIN}) are measured in a node which performs data replication to another node. The data selection and delivery scheme adopts the following cost factor for the utility function, where (S_i) is the size of item i.

$$C_i = \frac{S_i - S_{MIN}}{S_{MAX} - S_{MIN}} \quad (3)$$

D. User-centric Utility-based Data Replication Scheme

Based on the proposed utility function, the overall algorithm for data replication is illustrated in Fig. 3. Firstly, a replicating device checks whether there is a recently joined device and/or newly generated data. If this is the case, the replicating device needs to perform data replication. Currently, this scheme supports only shared contents, a single mobile device per user and no segmentation of data.

Next the most important stages are presented:

1) Data Selection Algorithm: Based on utility function values, during data selection, data is classified into three categories based on three thresholds: high utility (U_{HU}), intermediate utility (U_{IU}), and low utility (U_{LU}). Data with high utility ($U_i \geq U_{HU}$) will be replicated onto the devices as a metadata-content pair. As a user might want to access information with intermediate utility levels ($U_{HU} > U_i \geq U_{IU}$), in this case only the metadata will be replicated onto the device, offering information about the location of data if it needs to be transferred. Data with low utility values ($U_i < U_{IU}$) will trigger no operation, saving network and storage resources.

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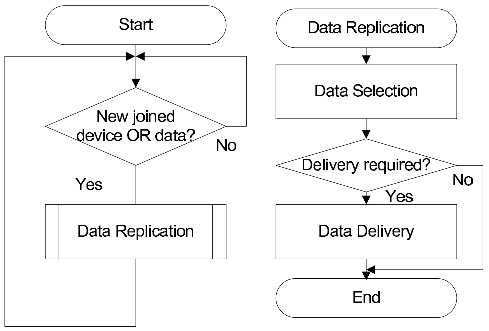

Fig. 3. User-centric Utility Data Replication Algorithm

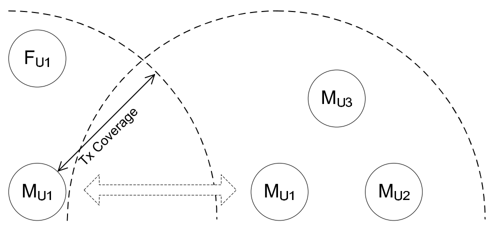

Fig. 4. Simulation network topology

2) Data Delivery Algorithm: In this paper, a proactive way based on introduced utility function is proposed. Similar to data allocation, target utility (T_r) is specified for scheduling data delivery. This parameter involves estimating the duration of delivery (T_{dur_i}). Since B_{BW_i} is represented as S_i/T_{dur_i}, the utility function derives T_{dur_i} as described in Eq. 4.

$$T_{dur_i} = \frac{S_i \cdot I_i}{B_{BW}(2 \cdot T_r + C_i - 1)} \tag{4}$$

IV. Modelling and Simulation

The proposed scheme is evaluated via network simulation using Network Simulator 2 (NS-2) [1].

A. Network Topology

An IEEE 802.11g WLAN model was used with maximum transmission rate of 54 MBps which operates in the 2.4 GHz band and uses DSDV for ad-hoc routing. The topology used for simulations is depicted in Fig. 4 and involves 4 mobile nodes and 3 users. User 1 controls two devices (F_{U1} and M_{U1}) and the other users have a single mobile device each. The test scenario includes movement of user 1's mobile device into the neighbourhood of the other users. Peer-to-peer communication protocols supporting node join and leave, data query and response are simulated in a simplified manner. The focus of the simulation is on Smart PIN data selection and transfer.

B. Performance Assessment

The metrics for comparison are data availability and network usage. Data availability for each data item is measured with the average online rate of device in the range of the user. When a user leaves the fixed device with his mobile device, the data on fixed devices is considered non-accessible. Network resource usage is measured by the rate of data transmitted by each device. The comparison is done with AR and Tempo schemes implemented with NS-2. All models used employ no data segmentation.

[1]Network Simulator 2, http://www.isi.edu/nsnam/ns/

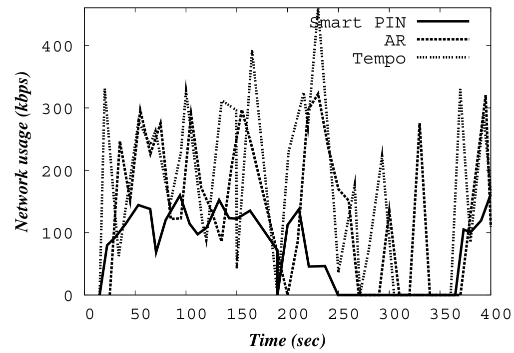

Fig. 5. Network usage graph

C. Data Models

For data context, the assumed size was uniformly distributed between 1 and 10 Kbytes. As no real measurement analysis of annotated metadata was available, it was assumed that the size of metadata is similar to that of regular web pages. The model used during simulations is adopted from the modelling of web content [28]. The generation of content used a size uniformly distributed between 400 Kbytes to 3 Mbytes based on the size of several hundreds of still images taken with a 5M pixel digital camera. The relevance value of each data for users is generated with uniform distribution and has values between 0 and 1. Furthermore, the perceptual quality of information is assumed 1 as constant value.

D. Results and Analysis

The storage size of each mobile device was assumed to be 2 GBytes. For the AR scheme, the device availability value used was 0.4 and target availability was 0.8. The time duration of each replication is 10 sec. Tempo used 1.95 Mbps as target throughput. Smart PIN target utility for data selection and delivery used was 0.75 and target throughput was set as 1.95 Mbps. Data replication considered data only and no metadata was delivered.

Fig. 5 illustrates network usages when each scheme was employed in turn. Since an actual target changes according to utility function as designed, Smart PIN uses 67 kbps in average, whereas Tempo uses an average of 144 kbps. The AR scheme is based on a periodic time and network usage depends on the amount of data which is transferred in the duration. The AR scheme uses on average 143 kbps in terms of network bandwidth.

Table I and Fig 6 present data availability against the total number of data items stored on devices. With the assumption that device availability are similar, data availability could be measured as the duration for which data existed on the mobile

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TABLE I
DATA AVAILABILITY STATISTICS

Data item	Smart PIN		AR		Tempo	
	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
200	0.991	0.006	0.620	0.283	0.624	0.275
500	0.981	0.014	0.565	0.285	0.553	0.289
1000	0.953	0.037	0.550	0.283	0.536	0.285
1500	0.921	0.057	0.527	0.289	0.548	0.283

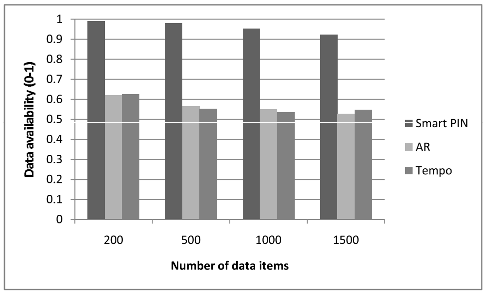

Fig. 6. Data availability chart

devices over the total test time (i.e. about an hour). The AR scheme shows a 15% decrease of data availability with a 650% increase in the number of data items. When Tempo was used, data availability was lower mostly due to the fact that it focuses on network usage only. In contrast, Smart PIN shows much higher data availability than the other schemes regardless of the number of items and it is maintained above 90%. In particular it is very significant to note that when there are 200 data items, Smart PIN data availability is 37% higher than when both other schemes are used. For 1500 data items, Smart PIN achieves data availability with 40% higher than AR and with 38% higher than Tempo. To increase further data availability supporting a large number data, the selected data set should be static rather than dynamic.

V. CONCLUSION

This paper presented the Smart Personal Information Network - Smart PIN, a novel performance and cost-aware personal information network. Smart PIN uses an innovative user-centric utility-based data replication scheme to exchange content automatically based on both network performance and user interests. The proposed scheme was tested via simulations and significantly better results were obtained in comparison with existing approaches such as Automated Replication (AR) and Tempo. Future work will involve enhancing the proposed solution to support segmentation of data delivery. The scheme will be extended to support perceptual quality assessment and exchange of multimedia-based content. As current version focuses on a single device per user, a multiple mobile devices environment will also be considered.

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