Smart PIN: Utility-based Replication and Delivery of Multimedia Content to Mobile Users in Wireless Networks

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Abstract
Next generation wireless networks rely on heterogeneous connectivity technologies to support various rich media services such as personal information storage, file sharing and multimedia streaming. Due to users' mobility and dynamic characteristics of wireless networks, data availability in collaborating devices is a critical issue. In this context Smart PIN was proposed as a personal information network which focuses on performance of delivery and cost efficiency. Smart PIN uses a novel data replication scheme based on individual and overall system utility to best balance the requirements for static data and multimedia content delivery with variable device availability due to user mobility. Simulations show improved results in comparison with other general purpose data replication schemes in terms of data availability.

Keywords
Content management, Non-real-time service, Interactive systems, Mobile systems, Portable and handheld devices.

INTRODUCTION
As users use multiple mobile devices such as mobile phones, digital cameras, laptops, etc, there is a significant challenge to realise the always-connected heterogeneous network environment as envisaged for the Next Generation Networks or 4th Generation Systems (4G). Although most current proposals are based on Internet Protocol (IP), the difference in physical and data link layers among the different mobile technologies makes impossible the existence of cost-free delivery of data which users would want. Consequently, users could get data anywhere and anytime, but need to repay this availability for example with higher battery power consumption, slower connectivity, lower mobility, greater communication charges, etc. [1]. In this context solutions are needed to reduce this user payback and medium and short-range technologies such as Wireless LAN (WLAN) or Wireless Personal Area Network (WPAN) support lower communication charges and relatively high bandwidth when inter-connecting user devices in ad hoc manner.

Wireless network applications are also getting more complex and complement Internet applications by offering similar services such as file sharing, multimedia streaming, etc. Flexibility in connectivity and the diversity of networked devices have transformed users from just consumers of content into providers as well. Terabyte hard disks which can be installed on personal computers can store information covering a person's whole life [2]. Additionally each of the large number of personal or consumer devices owned by users can acquire and store large amounts of rich media data. Following this trend, managing personal information poses an important challenge to users and automated handling solutions are required [3].

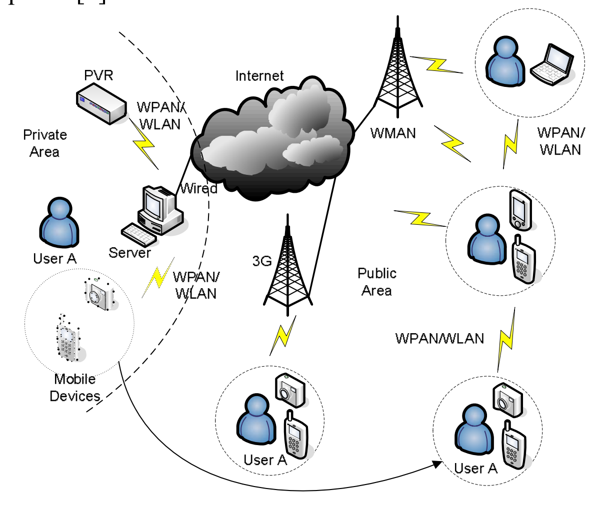

Figure 1. Overall concept of Smart PIN

In order to address both information overload, and the heterogeneity of devices and network connectivity, Smart PIN [4] [5] was proposed as a performance and cost oriented context-aware Personal Information Network, Fig. 1 illustrates Smart PIN which helps mobile users not only to manage personal information stored across various device types, but also to exchange data with other users via heterogeneous networks.

This paper presents a Smart PIN enhancement with a novel utility-based approach for data replication across different devices and adaptive multimedia delivery using a user model, a device profile, and metadata.

The next section presents a literature review of some related works. Section 3 describes Smart PIN and includes details of the proposed data replication scheme. Simulation setup and testing results which involve comparisons with existing schemes are shown in section 4. Conclusions and future work directions are presented in the last section.

RELATED WORK

Creating multiple replicas of important data in devices is an essential feature of a distributed system and is called data replication. A distributed data processing system uses data replication to enhance performance and reliability using intentional duplication of its data among its member devices. This provides not only improved performance and reliability for mobile computers [6], but also extended data accessibility [7]. Some works focus on numerical analysis of data replication benefits in peer-to-peer (P2P) wireless ad hoc networks. Wang et al [8] define data replication induced gain as the cost reduction caused by data replication. Other works from the literature in relation to data replication focus on consistency and reconciliation issues coping with data changes [9] [10] [11] [12] [13] [14]. Some data replication systems concentrate on data allocation and deal especially with what data and what devices are involved and when the replication is performed.

Cuenca-Acuna et al. [15] propose a novel solution called Autonomous Replication (AR) to achieve high availability of data in P2P file systems based on PlanetP [16], a toolkit for structured P2P applications. It involves fragments of data being replicated randomly on the free space of peers based on periodical measurement of the estimated availability for files and fragments. However, if a node which has a lot of new data joins, the system might need to spend quite long time to achieve target data availability. Many transfers are also performed which reduce the performance of the system. Furthermore, this approach does not consider how data is important to users since replication of data is performed randomly.

In Tempo [17], a proactive method of replication of data during the idle time of devices is proposed. To limit the usage of bandwidth, Tempo introduces a bandwidth budget which defines the maximum data size per unit of time. With this user specified parameter, Tempo removes busty data transfers for repairing data fragments in a reactive way and provides a high level of data durability, with no fluctuation in data transfer. The decision for the transfers is also dependent on the bandwidth budget parameter. This approach does not consider user interest in data, either.

Specifically for multimedia content distribution, having multiple instances of data duplicated across different devices in a wireless environment provide higher accessibility to contents for applications such as streaming. In multiple-sender-based streaming in P2P networks there are two kinds of approaches in terms of division and assembly of content for delivery: interlaced packet assembly and multiple-description code (MDC). Interlaced packet assembly divides a multimedia data into a sequence of multiple packets, transfers those from different devices to one receiver and merge them as a single stream for playout. In contrast, MDC divides a multimedia data into multiple streams with different characteristics. The receiver uses available streams to acquire better quality dynamically.

Nguyen and Zakhor [18] proposed a framework for streaming video from multiple mirror sites simultaneously to a single receiver in the Internet. The scheme is based on receiver-driver protocol which is targeting to achieve higher throughput, to increase tolerance to loss and to reduce delay due to network congestion using rate allocation algorithm (RAA) and packet partition algorithm (PPA). PPA supports interlaced multimedia data delivery from multiple sources for the receiver. They use interlaced packet assembly from multiple source for streaming.

Approaches using MDC include P2P Adaptive Layered Streaming (PALS) [19] and Cooperative Networking (CoopNet) [20]. PALS is a receiver-driven approach based on the adaptive delivery of stored layer encoded streams from multiple sender peers to a single receiver. It uses an own quality adaptation for congestion controlled playback of layer-encoded video over the Internet. CoopNet is a content distribution approach based on data caching, storing delivered data for their ulterior usage. MDC enables CoopNet to provide robust service against disturbance originated from frequent join and leave of clients.

VMesh [21] supports interactive Video on Demand (VoD) service in P2P networks based on a Distributed Hash Table (DHT). VMesh divides videos into variable length segments and stores them in distributed peers over the Internet in a similar manner like caching. The system adopts a locality-aware segment location algorithm providing less stress to server and good quality to the client, and a popularity based segment storage scheme which improves playback continuity. VMesh limitations consist of the fact that it assumes the Internet as the infrastructure for the P2P network and does not consider wireless network-related issues.

Home-to-home online (H2O) [22] is a framework which provides VoD service based on collaborating nodes connected though wired technology. As its replication technique, it uses the worst case expected delay to retrieve a block from one hop away from the current node for the service. Even though there are some simulations with ad hoc networks, H2O does not consider device availability or data availability as substantial dynamic characteristics of the overall system.

SMART PIN

Smart PIN [4] [5] is a performance and cost-oriented context-aware personal information network and focuses on efficient user access to information located on remotely distributed devices. Smart PIN operates in a heterogeneous network environment. To achieve its requirements, Smart PIN supports a utility function-based data replication and adaptive multimedia delivery. In order to handle data of large size, Smart PIN employs segmentation in fixed length segments (FIX_SEG) or variable length segments (VAR_SEG). Small size data is not segmented and is labelled NO_SEG.

Smart PIN bases its operation on information gathered from user modelling, device profiling, and metadata associated with each piece of data present in the distributed system. A user model collects information on users' interests and by analysing this information [23]. Smart PIN can draw conclusions about a particular user interest in any given piece of data. Device profiles like those built by the User Agent Profile (UAProf) [24] describe the features of the devices from the system and Smart PIN uses the information available on the different capabilities of mobile devices to perform data replication and distribution. Smart PIN makes use of metadata, enabling the mitigation of the data management overhead for users.

Utility Function

In order to take data replication decisions, Smart PIN evaluates a utility function U_i for each piece of data content i. The utility function includes two main components: the private utility which reflects the user individual interest in the content i and the global utility which expresses the overall utility of the content in relation to its popularity.

The private utility component formula includes the content i's associated benefit (B_i) and its cost (C_i) to the user. In addition, the user interest on the particular data item i (I_i) (e.g. relevance of data to the user) 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 private utility (PU_i) for item i is computed as in Eq. 1 and as it was normalised, it has values from 0 to 1. The basic version of Smart PIN described in [5] uses the private utility function for data replication.

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

Smart PIN also uses a global utility function (GU_i) which involves the popularity of multimedia streaming segments (G_i) [21] as described in Eq. 2.

$$GU_i = \frac{1 + B_i \cdot G_i - C_i}{2} \qquad (2)$$

The overall utility function which includes both PU_i and GU_i is presented in Eq. 3. Different weights are used depending on the data type (T) and its segmentation-related characteristics (i.e. NO_SEG, FIX_SEG and VAR_SEG).

$$U_i = w_{1,T} \cdot PU_i + w_{2,T} \cdot GU_i \qquad (3)$$

Utility-based Data Replication

As discussed in many wireless ad hoc routing solutions [25], a wireless node has different characteristics to a wired node and one of the most important properties is its higher mobility. This highly affects the distributed application system as nodes storing shared data can get out of range and become suddenly unavailable. Therefore, data replication is the main solution in order to achieve high data availability.

The overall algorithm for data replication in Smart PIN is divided into two steps: data selection and data delivery and employs the utility function previously described. During data selection, data is classified into three categories based on two thresholds depending on their utility to the users. An example with high, intermediate and low utility groups is presented in Fig. 2. Data from the high utility group will be replicated into devices along with associated metadata. In order to achieve Smart PIN's performance targets, the content from the other two groups is not replicated. However as a user might want to access information with an intermediate utility value, the metadata will be replicated onto the devices along with information on the actual location of the content, allowing fast ulterior access to data.

Smart PIN uses a proactive way based on the introduced utility function to control network usage. When the system selected data which will be replicated, it also decides data delivery based on the utility function. Smart PIN calculates the transfer duration with the target bandwidth consumption and schedule next data replication accordingly. A more detailed description of this algorithm can be found in [5].

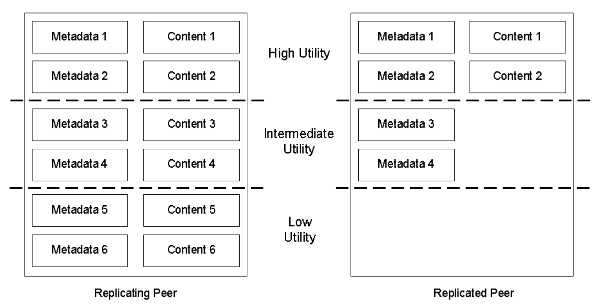

Figure 2. Data replication using classification

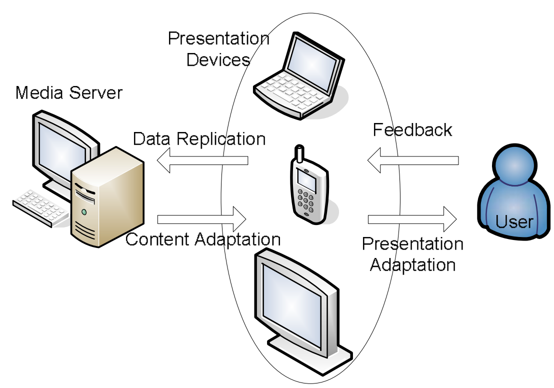

Figure 3. Adaptive multimedia presentation in Smart PIN

Adaptive Multimedia Presentation

As devices vary significantly in characteristics, different multimedia presentation environments can be envisaged at different times. A user can see a movie clip on a mobile phone when he leaves from the office and then he might want to see the clip again on a HDTV when he arrives home. For this, adaptive multimedia presentation should be supported in Smart PIN, performing background and foreground procedures as depicted in Fig. 3.

The foreground procedure refers to the multimedia presentation and involves streaming the data among the nodes, adapting the user model and different device profiles. Interactive feedback such as control commands for multimedia adaptation (i.e. fast forward and rewind) and pre-defined feedback such as device profile and parameters can be used to fine tune the streaming to the network conditions. In consequence, the user achieves a good multimedia presentation. Furthermore, content adaptations such as digital item adaptation [26] and video summarisation, help the data be reduced to an affordable amount for the mobile environment since these enable the control of run time and quality factor, maximising the user's satisfaction.

The background procedure for the adaptive multimedia presentation performs data replication. To handle large size non-real time data items, fixed-length segmentation (FIX_SEG) is used in a similar fashion to OceanStore [10], Wayfinder [27] and BitTorrent [1]. For multimedia data, variable-length segmentation (VAR_SEG) is employed to enable distributed streaming in a similar fashion with that of VMesh [21].

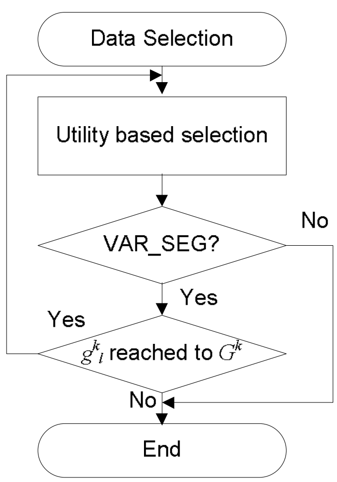

Figure 4. Updated data selection scheme

Data Caching vs. Replication

Sometimes, data replication and data caching are used to indicate the same operation. However, they show different characteristics depending on the system architecture. Usually, data caching has more benefit when a server exists in the system which supplies clients with data. In this context, multimedia streaming can benefit of data caching after several successful deliveries to other devices. Data replication term is often used when data is available at distributed devices and their availability differs. The process refers to making copies of data in order to increase their availability to the overall system. In this context, it is not possible to guarantee a successful multimedia streaming process if there is not at least a full set of stable segments of multimedia data available. Therefore to have data availability closest to 1 is desirable.

The availability of a device (P_j) is defined as in Eq. 4. The average data availability is defined in Eq. 5 with the availability of the segment l of the multimedia data item k in a device j as $s^k_{l,j}$, device availability P_j, total number of segments of the multimedia data k, L and total number of devices J.

$$P_j = \frac{\text{Device } j \text{ available time}}{\text{Total time}} \qquad (4)$$

$$D^k_{avg} = \frac{\sum_{l=1}^{L}\sum_{j=1}^{J}\left(s^k_{l,j}\cdot P_j\right)}{L\cdot J} \qquad (5)$$

It can be mathematically shown that the system availability of the replicated segment l of the multimedia data k across all devices (g^k_l) is always greater than or equal to $s^k_{l,j}$ as Eq. 6 indicates. By combining Eq. 5 and 6 the relationship from Eq. 7 results.

$$s^k_{l,j} \le \sum_{j=1}^{J} s^k_{l,j} = g^k_l \qquad (6)$$

$$D^k_{avg} \le \frac{\sum_{l=1}^{L}\sum_{j=1}^{J}\left(g^k_l\cdot P_j\right)}{L\cdot J} = \left(\frac{\sum_{l=1}^{L} g^k_l}{L}\right)\cdot\left(\frac{\sum_{j=1}^{J} P_j}{J}\right) \qquad (7)$$

Denoting $P^J_{avg} = \frac{\sum_{j=1}^{J} P_j}{J}$ and $G^{L,k}_{avg} = \frac{\sum_{l=1}^{L} g^k_l}{L}$, Eq. 7 is simplified as Eq. 8.

$$D^k_{avg} \le G^{L,k}_{avg}\cdot P^J_{avg} \qquad (8)$$

$G^{L,k}_{avg}$ represents the average availability of multimedia data k in Smart PIN and is dependent on the number of multimedia segment sets in the system. As data availability cannot exceed 1 and it is desired that the availability to be as high as possible, Smart PIN aims to find the minimum number of sets of segments from the multimedia data k such as for a given average device availability P_{avg} to have the relationship as defined in Eq. 9. From the equation, G^k target is derived as in Eq. 10.

$$1 = G^k \cdot P_{avg} \qquad (9)$$

$$G^k = \left\lceil \frac{1}{P_{avg}} \right\rceil \qquad (10)$$

To use this concept, Smart PIN processes segmented multimedia data separately from the other data pieces and processes them according to the algorithm illustrated in Fig.

[1] BitTorrent.org, http://www.bittorrent.org/

4. Smart PIN replicates each segment of the VAR_SEG data in order to have the average availability of multimedia data k reaching the target value of G^k and therefore provide maximum data availability of data given certain level of device availability. The transfer of segment is based on the utility function. For non-segmented data, Smart PIN performs regular data replication based on the utility function as described in details in [5].

MODELLING AND SIMULATION

Network Model and Scenarios

The proposed Smart PIN data replication scheme is evaluated via network simulation using Network Simulator 2 (NS-2)[2]. 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. A grid-like topology is used for simulations with a simple mobility scenario as depicted in Fig. 5. Totally, 6 mobile nodes are involved, numbered from 0 to 5. The data node (labelled as D0) includes movie fragments as segmented (VAR_SEG) data, and some non-segmented (NO_SEG) data. Empty nodes (marked as E1, E2 and E3) do not store any data initially. Because of communication range limitations, E1, E2 and E3 cannot transfer data directly between themselves. However, connecting nodes R4 and R5 enable this connectivity between the Smart PIN nodes (i.e. E1, E2 and E3) when D0 leaves away.

The test scenario includes periodic movement of node D0 in and out of the network range (i.e. trips). The simulation is assessed with different numbers of such trips: 20, 40, 80 and 120. Approximately 20 trips take an hour to complete. The data node has a device availability of 0.4 due to the movements whereas the other devices have device availability of 1 in this scenario. The currently used P2P communication protocol is simplified to focus on the data replication and supports node join and leave, data query and response. Furthermore, device availability information measurement and broadcasting is also included in this simplified P2P implementation.

Smart PIN (SPIN), Smart PIN without G^k enhancement (SPIN-NG), AR and Tempo are modelled with NS-2 and a comparison based assessment is envisaged. No metadata only replication is considered in this paper.

Data Models

Data context 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 NO_SEG content used a size uniformly distributed between 400 Kbytes to 3 Mbytes which is consistent with that of the size distribution of still images taken with a 5M pixel digital camera. The relevance value of each data for users and popularity value for variable length segmented data are generated with uniform distribution and have values between 0 and 1.

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

The simulations used VAR_SEG multimedia sequences from the "Die Hard 1" movie encoded at a high quality (4 Mbps MPEG2 stream). This is divided into 102 segments and each segment includes up to 5 GOPs. Data context for each segment is generated with the same assumption made for NO_SEG data metadata. During the simulation, $w_{1,T}$ and $w_{2,T}$ in the utility function (see Eq. 3) are assumed 1 and 0 for NO_SEG data and 0 and 1 for VAR_SEG data, respectively.

The simulation starts with the data node containing 2000 data items (i.e. 1898 NO_SEG data and 102 VAR_SEG segments). Simulation parameters used are shown in Table 1.

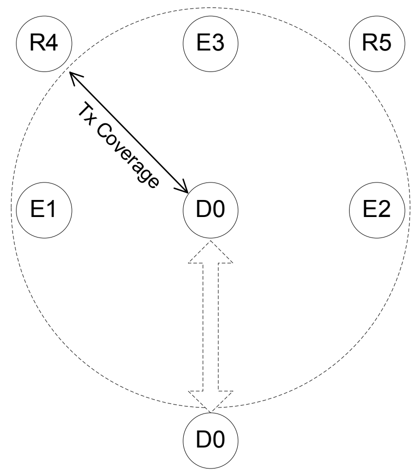

Figure 5. Simulation topology

Results and Analysis

One of the metrics for performance assessment is data availability which is measured with average online rate of device in the range of communication and ratio of data residing duration over total test time on a specific device as described in Eq. 11 and Eq. 12 of this paper. Network resource usage is measured by the rate of data received by each device. Loss is measured by the rate of data dropped in all devices.

$$R_{l,j} = \frac{\text{Data } l \text{ residing time in device } j}{\text{Total test duration}} \quad (11)$$

$$D^k_{avg} = \frac{\sum_{l=1}^{L}\sum_{j=1}^{J}\left(s^k_{l,j} \cdot P_j \cdot R_{l,j}\right)}{L \cdot J} \quad (12)$$

As shown in Table 2, Smart PIN without consideration of G^k shows superior data availability to other approaches such as AR and Tempo since it limits replicated data based on utility in the view of overall data. However, it does not consider the minimum data sets of VAR_SEG data to be replicated in order to support wireless P2P data streaming. Smart PIN with G^k=2 in this test scenario shows small difference in the overall data availability and better data availability of the VAR_SEG segments. Especially, VAR_SEG segments availability increases with the increase in the number of trips the data item perform as shown in Fig. 6. Because of the movement of the data node, data availability in the overall system is quite low. However, data availability when only empty nodes, which are not moving, are considered is about 0.87 overall and 0.97 for VAR_SEG data only.

Considering the total replicated sets of multimedia data segments, Smart PIN achieves 1.92 sets stored on average across devices when the target for ideal data availability was G^k=2, representing the number of sets of segments to be replicated.

Table 1. Simulation parameters

	Parameter	Value
Smart PIN (SPIN and SPIN-NG)	Transfer utility threshold	0.75
	Selection utility threshold	0.75
	Storage size	2 Gbytes
	Target Bandwidth (B_{BW})	1.95 Mbps
AR	Replication Interval	10 secs
	Device availability	0.4
	Target data availability	0.8
	Storage size	2 Gbytes
Tempo	Target Bandwidth (B_{BW})	1.95 Mbps
	Storage size	2 Gbytes

Table 2. Data replication results in terms of data availability (DA) when having 2000 data items in the system

	Total data		NO_SEG data		VAR_SEG data		
	Num	Avg. DA	Num	Avg. DA	Num	Avg. DA	Achieved $G^{L,k}_{avg}$
SPIN	2656	0.59	2460	0.58	196	0.73	1.92
SPIN-NG	2632	0.60	2466	0.59	166	0.65	1.63
AR	3452	0.51	3278	0.51	129	0.51	1.26
Tempo	3470	0.51	3293	0.51	177	0.50	1.73

Fig. 7 illustrates network load when each scheme was employed in turn. Since the actual target changes according to the utility function, Smart PIN uses 562 Kbps on average, whereas Tempo uses an average of 1.03 Mbps, which is twice as much. Since the AR scheme is based on a periodic time (i.e. 10 sec. is the inter-replication interval), network load depends on the amount of data which is transferred in the duration. The AR scheme uses on average 982 kbps in terms of network bandwidth, which is almost double the load caused by Smart PIN.

Fig. 8 illustrates data loss for each scheme during the simulation. Smart PIN shows a 2.5% loss of data in average, which is similar with what AR and Tempo have achieved in the same conditions. However as Fig. 8 shows the burstiness of loss is much higher for the other schemes in comparison with Smart PIN, more severely affecting the eventual perceived quality.

These results show much better performance in terms f data availability, network load and loss rate when using the proposed Smart PIN in comparison with when AR and Tempo were used.

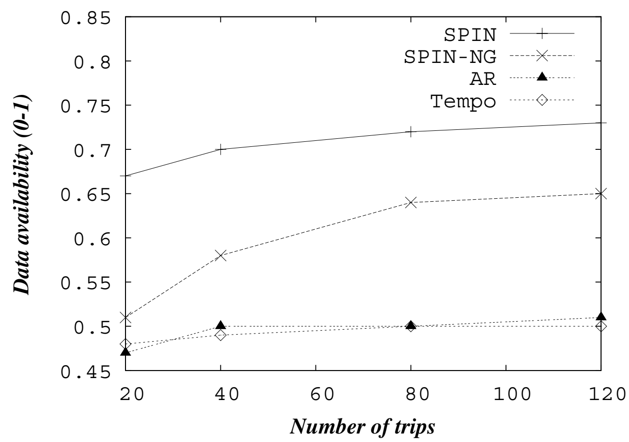

Figure 6. VAR_SEG data availability

CONCLUSION

Smart PIN is a performance and cost-oriented context-aware Personal Information Network which helps mobile users not only to manage personal information stored across various device types, but also to exchange data with other users via heterogeneous wireless networks. Smart PIN uses a utility-based data replication and adaptive multimedia presentation. It categorises data into three interest groups based on a novel utility function and performs data replication accordingly. Smart PIN performance assessment was performed via simulations and testing results show better data availability, loss and network load when using Smart PIN in comparison with when other data replication schemes were used.

Future work will examine a combination between the general purpose data replication approaches and distributed streaming applications in P2P wireless network. Balancing background and foreground data delivery will also be addressed in the future.

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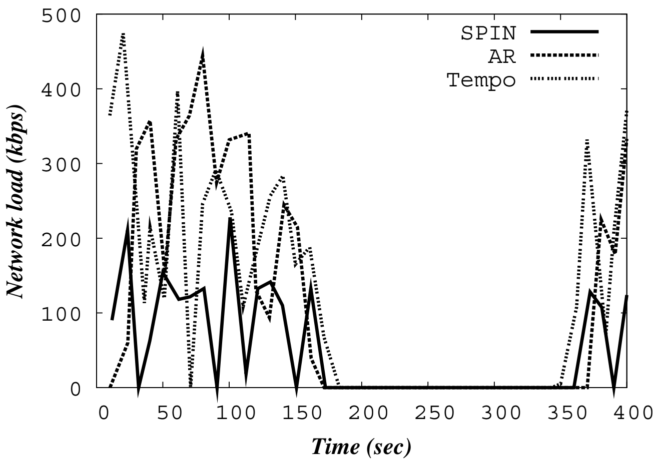

Figure 7. Network usage graph

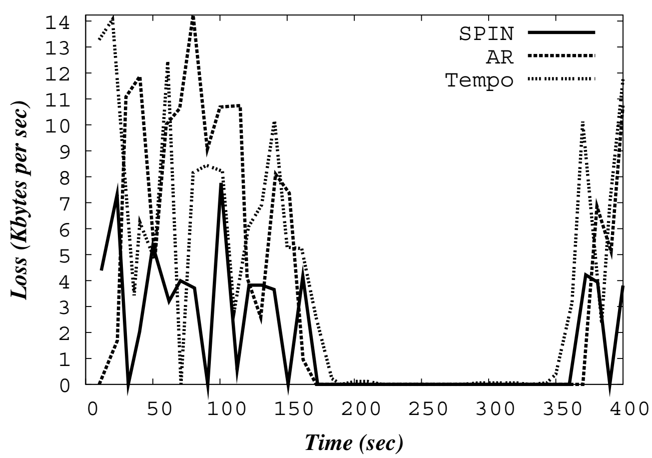

Figure 8. Data loss graph

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