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A seamless context-aware architecture for fourth generation wireless networks

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Abstract The integration of a multitude of wireless networks is expected to lead to the emergence of the fourth generation (4G) of wireless technologies. Under the motivation of increasing the levels of user satisfaction while maintaining seamless connectivity and a satisfactory level of QoS, we design a novel cross-layer architecture that provides context-awareness, smart handoff and mobility control in heterogeneous wireless IP networks. We develop a Transport and Application Layer Architecture for vertical Mobility with Context-awareness (Tramcar). Tramcar presents a new approach to vertical handoff decisions, which is not exclusively based on network characteristics but also on higher level parameters which fall in the application and transport layers. Tramcar is tailored for a variety of different network technologies with different characteristics and has the ability of adapting to changing environment conditions and unpredictable background traffic. Furthermore, Tramcar allows users to identify and prioritize their preferences. Tramcar is a smart and practical system, which is more capable of dealing with 4G challenges. Simulation results demonstrate that Tramcar increases user satisfaction levels and network throughput under rough network conditions and reduces overall handoff latencies.

Keywords 4G Mobility management · Vertical handoff · Seamless communications

1 Introduction

Interest in the fourth generation (4G) of wireless communications is continuously increasing as wireless networks grow at an astonishing rate. 4G will integrate homogeneous technologies; the outcome of this integration is a heterogeneous wireless network. This would result in broader coverage areas, lower access costs, the convenience of using a single "all-in-one" mobile device and more dependable wireless access even with the loss or failure of one or more networks. 4G will offer user involvement and context-awareness as well. 4G mobile devices are expected to eventually replace landline phones, Personal Digital Assistants (PDAs), Global Positioning Systems (GPS), digital cameras, audio players, radios and even gaming devices just to mention a few! The future of wireless communications is very exciting and promises to bring

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about many enhancements and enrichments into our daily lives.

The outer appearance of future Mobile Hosts (MH) may not change within the next few years, but what these MHs will enable users to do is expected to drastically improve. The hi-tech market research company In-Stat [9] predicts that heterogeneous networking, high-speed data rates, high-quality multimedia services and user control are just some of the expected future features for MH users. Nokia, the world's leading mobile phone supplier, predicts a "millennium of total mobility" [13]. Improvements in hardware and software are making mobility less of an option and more of a necessity for even the most basic computing users. Wireless PDAs, notebooks with high-speed wireless connections, and smartphones all have the ability to stretch the work-desk, making the world smaller for everyone. All of these factors combined will pave the way for a strong emergence of 4G technologies.

Criterion of a vertical handoff is one of the chief challenges for seamless mobility. Traditional handoff detection operations and policies, decision metrics, radio link transfer and channel assignment are not able to acclimatize to dynamic vertical handoff conditions or varying network availabilities. Furthermore, traditional handoff does not allow for device selection of networks since it assumes that there is only one type of network. In a mixed networking environment, user choice is a desirable enhancement.

This paper provides an extended version of our work in Refs. [7,8] Our previous work on Tramcar consisted of the abstract framework with proposed ideas of how each module could be tackled. In this paper a more thorough solution is given and Tramcar's modules are extended. The aim of this work is to design a smart 4G system for wireless heterogeneous networks that has the ability of providing context-awareness while maintaining high levels of QoS. Furthermore, the system should meet user preferences and support seamless handover among heterogeneous wireless networks. In this paper, we present a novel cross-layer framework for smart vertical handover control and mobility management, Tramcar (Transport and Application Layer Architecture for vertical Mobility with Context-awareness). Tramcar utilizes the application and transport layers and avoids making any changes to the network layer.This fully operable architecture periodically collects various host parameters and network information as inputs and enforces the best handover strategy. This strategy is selected based on user defined policies and network conditions. By doing so, Tramcar becomes more context-aware and consequently achieves higher user satisfaction. Tramcar's design supports:

- Seamless vertical handoff: the ability of Tramcar to handoff between different network interfaces and thus access services from different networks is an imperative functionality. Seamless universal handoff is also a fundamental concern.
- Context-awareness: Tramcar's behaviour should be governed by its surroundings. Context-awareness exploits user, device, and network information to improve connectivity, QoS and maintain a high level of user satisfaction.
- User preferences: Tramcar should allow users to identify and prioritize their preferences. These should then be translated into policies that other system modules can understand.
- Graceful degradation: in the case of a deficiency in resources or unavailability of a required feature, Tramcar should be able to react in such a manner as to continue to transfer data, but provide a reduced level of QoS.
- Feasibility: being able to practically implement and deploy Tramcar is a must. Our proposed system should balance economical and business constraints with technology constraints to produce a cost effective feasible solution.

A cross-layer framework, that integrates application layer user interaction merits and transport layer multi-homing and end-to-end connectivity features, provides a fine potential for supporting our design goals. Our system extends the Stream Control Transmission Protocol (SCTP) which is defined in RFC 2960 [17] and utilizes its multi-homing features. By extending SCTP, transport layer transparent mobility becomes a reality [6]. Among many of SCTP's positive features, its ability to support seamless handover has unlocked an exciting new research area that pledges to have a great impact on heterogeneous wireless networking in the upcoming years [1,18,21]. We utilize this power in Tramcar in order to achieve very low-handoff latencies and hence meet Tramcar's ultimate objective of high-user satisfaction levels.

The rest of this paper is organized as follows. Tramcar, Sect. 2 discusses related work and our novel contributions. Section 3 then presents Tramcar's framework. This is then followed by performance evaluation in Sect. 4. Finally, Sect. 5 concludes the work by referring to some future research directions.

2 Contributions and related work

This section presents our contributions and compares Tramcar to related research work. To get the most out of heterogeneous networks based on network and host conditions, a context-aware intelligent mobility and handover scheme is preferable. This smart handover control mechanism could offer flexible adaptive service based on varying requirements of traffic flow, network performance and user requirements. Due to the highly potential success of such an idea, we designed Tramcar, a cross-layer mobility solution for the next generation of heterogeneous networks. Tramcar has been inspired by the currently ongoing research in the areas of 4G wireless networks and more specifically cross-layer (application and transport) mobility and user policies.

Unlike previous work, Tramcar's novel cross-layer architecture makes use of the application layer to meet user preferences, enhances the transport layer to reduce handoff delays and avoids modifying the network layer to provide end-to-end connectivity. This is also the first attempt at utilizing SCTP's multi-homing features to provide context-awareness and user preferences.

The SCTP is a fairly novel transport protocol and for that reason very few research projects worldwide have had the opportunity of utilizing SCTP's power. Nonetheless, a number of research projects have been undertaken in order to test the various SCTP features and try to expand upon them. Jungmaier et al. [10]tested the performance of networks in the presence of both TCP and SCTP connections and have concluded that SCTP does not degrade the quality of connections and maintains a high level of fairness. Conrad et al. [4] present experimental results that demonstrate the advantages of employing SCTP's multi-streaming and partial ordering in terms of reducing latency when streaming multimedia in a lossy environment. Regrettably, they only consider streaming in a homogenous networking environment. Tramcar on the other hand concentrates on providing future solutions to heterogeneous wireless network environments. Mobile SCTP (also known as mSCTP) has been getting a great deal of attention recently [11,12]. Ma et al. [14] propose a method to facilitate seamless vertical handoff between Universal Mobile Telecommunications System (UMTS) and Wireless Local Area Networks (WLANs) using SCTP but they do not assess the impact of SCTP's improved performance on meeting user satisfaction levels. With Tramcar, we modify and utilize mSCTP in order to increase user satisfaction. To the best of our knowledge, no research has been conducted on integrating these two areas and utilizing the transport layer for increasing the levels of user satisfaction.

There are currently several prominent research projects in the area of context aware vertical handoff. A Policy-based Solution for Future 4G devices (Proton) [24] demonstrates how a flexible policy-based approach is suitable for 4G scenarios, and how to incorporate richer context into policies and still maintain a light weight solution appropriate for mobile devices. In order to make use of Proton, modifications to the network layer, "lower level", may be necessary. Tramcar avoids these changes by utilizing mSCTP in the transport layer. This can lead to a much faster deployment of such a context aware network. Service providers are reluctant to spend huge sums of money on modifying the current infrastructure when a more economical solution is possible. Chen et al. [2] present a smart decision model that tries to perform handoff to the highest quality network at the most suitable time. Their proposed model is able to make vertical handoff decisions based on the properties of available network interfaces such as link capacity, power consumption and link cost. In another project [3], they propose a Universal Seamless Handoff Architecture (USHA) to deal with both horizontal and vertical handoff scenarios. Unlike Tramcar, only signal strength is used for the handoff decision and no clear explanation is given as to when and where this decision is made.

3 TRAMCAR's framework

In this section, we present Tramcar's framework and describe the behaviour and functionalities of all of its components.

3.1 System overview

The presented system consists of application and transport layer modules. Tramcar's architecture together with other relevant components is illustrated in Fig. 1. The Connection Manager (CM) operates in the transport layer and is responsible for managing the MH connectivity through a modified version of SCTP. As a MH moves across different networks, its IP will most likely change resulting in connection breakdown. For example, suppose that a MH with IP address IP1 is communicating with a server. The server uses the MH's IP address in order to communicate and identify that host. When the MH roams into a new network it will get assigned a new IP address IP2. Consequently, several problems would occur: when the MH uses IP2 to send packets to the server, that server cannot identify the sender and therefore does not accept the packet. Moreover, when the server sends a packet to the MH, it will use the old IP address IP1 and therefore the packet will not be delivered. The technique used to solve these problems in Tramcar is multi-homing. By means of multi-homing, hosts can be reached through multiple IP addresses. Multi-homing permits an association between two end points to span across heterogeneous networks. CM deploys multi-homing in a more sophisticated way in order to support context-awareness as well as seamless mobility. Its modules and functionalities are explained in detail in Sect. 3.2.

Unlike the CM, the Handoff Manager (HM) is responsible for providing mobility and location management. It triggers handoff decisions and plays a major role in increasing Tramcar's intelligence. HM collects information from different sources such as the MH, available networks, etc. It also collects user preferences, translates these preferences into a handoff policy and then decides which of the available networks should be considered as possible handoff candidates. The HM's modules as well as the full Tramcar architecture are described in detail in Sect 3.2

3.2 Detailed description of Tramcar's architecture

In this section we describe Tramcar's detailed architecture. Section 3.2.1 identifies the handoff decision parameters. Sections 3.2.2–3.2.8 explain the architecture in detail.

3.2.1 Handoff decision parameters

Handoff decision parameters help Tramcar determine which network should be chosen for data transfer. Because of their importance, we choose the following network parameters for the vertical handoff decision: Cost of service (C): the cost of the different services to the user is a major issue, and could sometimes be the decisive factor in the choice of a network. Security (S): when the information being exchanged is confidential a network with high encryption is preferred. Power consumption (P): vertically handing off to a high-power consuming network is not desirable if the MH's battery is nearly exhausted or if the battery's lifetime is relatively short. Network conditions (D): available bandwidth is used to indicate network conditions and is a major factor especially for voice and video traffic. Network performance (F): in some cases interference or potentially unstable network connections might discourage a handoff decision. For more information on the abovementioned parameters please refer to [5].

3.2.2 User interface (UI)

The User Interface (UI) is part of the HM and is simply the method through which the user interacts with the MH. The user does not specify the handoff policy directly to the Handoff Decision Maker (HDM) but instead, he defines simple preferences which are then rendered by the Policy Translator (PT). The user has an option of entering up to ten different inputs to aid Tramcar in making a handoff decision that meets his preferences. Five values consist of the priority of each of C, S, P, D and F to the user; the user is allowed to enter each value as a percentage. UI ensures that the total percentage

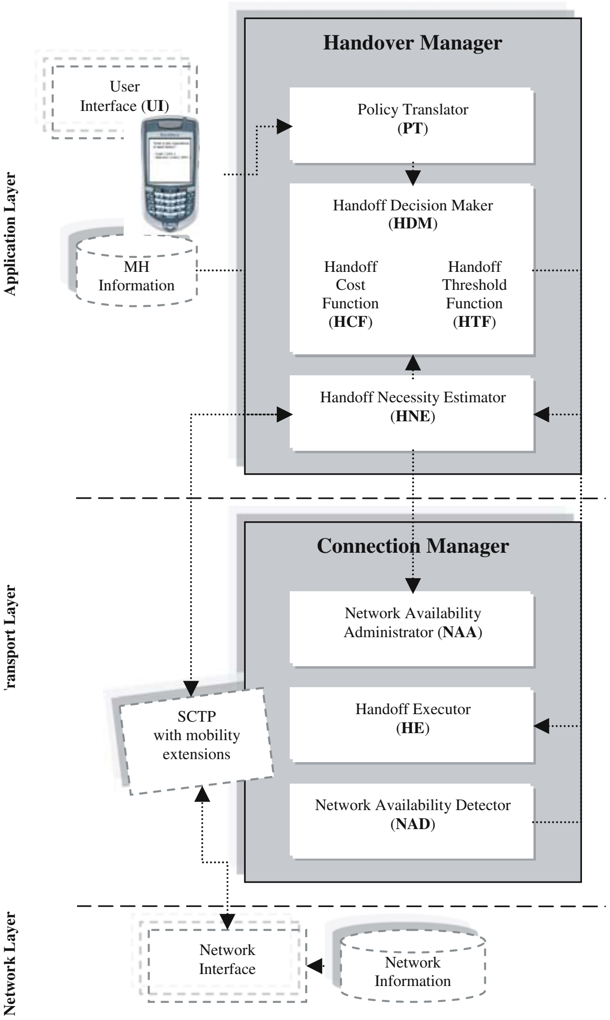


Fig. 1 Tramcar's architecture

adds up to 100%. The other five inputs consist of predefined threshold values for each of C, S, P, D and F.

3.2.3 Policy translator (PT)

Once the user finishes inputting new values through the UI, these values are further interpreted by the PT. PT uses these input values to generate weights for the Handoff Cost Function (HCF) and threshold values for the Handoff Threshold Function (HTF). Each of the network parameters is given a weight $\omega_c, \omega_s, \omega_p, \omega_d, \omega_f$ and a threshold value $\tau_c, \tau_s, \tau_p, \tau_d, \tau_f$.. The use of these weights and threshold values are explained in Sect. 3.2.5 PT's objective is to simply translate the ten user inputs into these ten values.

The following is an example that demonstrates how PT works. PT checks the MH's remaining battery power. If the battery power is critically low, ω_p is given a much higher priority (let's assume 0.6 of 1.0 for the sake of clarity). The remaining 0.4 is then shared amongst the weights based on the input user percentages. If the battery power is above the critical low threshold value, the percentages input by the user are directly converted to decimal values which total to 1.0. The final calculated weights are sent to HCF to aid in the handoff decision. The threshold values $\tau_c, \tau_s, \tau_p, \tau_d, \tau_f$ are directly assigned from the five threshold values input by the user. These thresholds are also sent to HCF to aid in the handoff decision.

3.2.4 Handoff necessity estimator (HNE)

The Handoff Necessity Estimator (HNE) helps in providing context-awareness. The aim of context-awareness is to acquire and utilize MH and network information to provide services that are appropriate to a particular user, place, time, event, etc. In other words, adapting to the user's current position or environment will make the MH more intelligent and will yield better results and this is precisely what HNE aims for. HNE's objective is to avoid handoffs in scenarios similar to A in Fig. 2. HNE achieves its objective by communicating with the transport layer and only adding relevant networks to the multi-homing network list. Many effective mobility solutions have been proposed in the literature [19,22,23,25]. We design HNE in such a way as to make use of these solutions.

3.2.5 Handoff decision maker (HDM)

The HDM decides on which of the candidate networks is best suitable for handoff. HDM plays a vital role in Tramcar and is a main contributor to context-awareness and user satisfaction. HDM consists of two main functions: HCF and HTF. HCF is a measurement of the improvement gained by handing over to a particular network n. HTF aims at controlling user budgets or other requirements in order to further improve user satisfaction levels. HCF is evaluated for any network that has been approved for consideration by the HNE. The network with the highest calculated value for HCF is the most desirable for the user based on his specified preferences (which were obtained through the UI and translated by PT). The network quality Q_i, which provides a measure of the appropriateness of a certain network i, is measured via the function:

$$Q_i = f\left(\frac{1}{C_i}, S_i, \frac{1}{P_i}, D_i, F_i\right). \tag{1}$$

In order to allow for different circumstances, there is an apparent necessity to weigh each factor relative to the magnitude it endows upon the vertical handoff decision. Therefore, a different weight is introduced as follows:

$$Q_i = f\left(\omega_c\frac{1}{C_i}, \omega_s S_i, \omega_p\frac{1}{P_i}, \omega_d D_i, \omega_f F_i\right), \tag{2}$$

where $\omega_c, \omega_s, \omega_p, \omega_d, \omega_f$ are weights for each of the network parameters. The values of these weights are fractions, i.e. they range from:

$$0 \leqslant \omega_c, \omega_s, \omega_p, \omega_d, \omega_f \leqslant 1 \tag{3}$$

and total of the weights must equal 1.0:

$$\omega_c + \omega_s + \omega_p + \omega_d + \omega_f = 1.0. \tag{4}$$

Each weight is proportional to the significance of a factor in the vertical handoff decision. The larger the weight of a specific factor, the more important that factor is to the user and vice versa. These weights are obtained from PT as explained in Sect. 3.2.3 Even though we could add the different factors in the vertical handoff decision function to obtain network quality Q_i, i.e.

$$Q_i = \omega_c\frac{1}{C_i} + \omega_s S_i + \omega_p\frac{1}{P_i} + \omega_d D_i + \omega_f F_i \tag{5}$$

each network parameter has a different unit which leads to the necessity of normalizing Eq. 5. The final normalized equations for n networks are:

$$\begin{aligned} Q_i = {} & \frac{\omega_c(1/C_i)}{\max((1/C_1),\ldots,(1/C_n))} + \frac{\omega_s S_i}{\max(S_1,\ldots,S_n)} \\ & + \frac{\omega_p(1/P_i)}{\max((1/P_1),\ldots,(1/P_n))} \\ & + \frac{\omega_d D_i}{\max(D_1,\ldots,D_n)} + \frac{\omega_f F_i}{\max(F_1,\ldots,F_n)}. \end{aligned} \tag{6}$$

The HTF the second HDM module assists in meeting user budget limits. It deploys a static strategy aimed at not exceeding user budget limits. In this strategy, HTF sets a strictness percentage $\lambda\%$ for dealing with user threshold requests. The larger the value of λ the more aggressive HTF is at meeting the user's requested threshold values. HDM then monitors the parameter as it increases. For the sake of clarity let's say the user requested a threshold on cost τ_c of $ 3.50. As the user roams about and connects to different networks the cumulative cost c_c starts increasing. HDM executes the algorithm shown in Fig. 3.

where ρ is a positive integer number, $1 < \rho < \infty$. As the user roams about c_c continuously increases and approaches τ_c. When c_c is within $\lambda\%$ of τ_c the weights of all five network parameters $\omega_c, \omega_s, \omega_p, \omega_d$, ω_f are changed. This change puts more emphasis onto the cost by giving ω_c a much larger value. The larger the value of ρ the more emphasis is

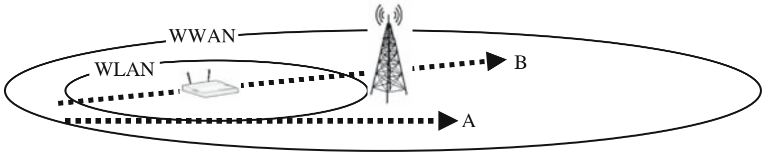


Fig. 2 Different mobility scenarios

$$
if\left\{c_c > \left(1-\frac{\lambda}{100}\right)\times\tau_c\right\} then \left\{\begin{array}{l}
\omega_c = \left(1-\frac{1}{\rho}\right)+\frac{\omega_c}{\rho}\\
\omega_s = \frac{\omega_s}{\rho}\\
\omega_p = \frac{\omega_p}{\rho}\\
\omega_d = \frac{\omega_d}{\rho}\\
\omega_f = \frac{\omega_f}{\rho}
\end{array}\right\}
$$

Fig. 3 HTF cost algorithm

put onto the cost. Consequently, Tramcar becomes more aware of the importance of that parameter and searches for the network that most suitably helps bound it. The algorithm shown in Fig. 3 can be applied to any other network parameter as well.

3.2.6 Network availability detector (NAD)

The Network Availability Detector (NAD) is part of the CM and is responsible for the prompt detection of the availability or unavailability of different networks. NAD lies in the transport layer and acts as a middleware between the application and network layers. It obtains information from the network layer, processes it and forwards relevant information to the application layer.

When the MH moves into the coverage of a new network it detects the availability of that network and obtains a new IP address. The availability of a new network is recognized by the receipt of advertisement messages from that network's base station. This new IP address however has no effect whatsoever on the routing of data. Once the new network is realized by the system, NAD then notifies HNE of the availability of that network. The new network's IP address is not bound to the MH's address list until HNE decides that the network is a suitable handoff candidate. The unavailability of a network is more critical and should be detected quickly. Rapidly decaying signal strength is a strong indication that a network is on the verge of becoming unavailable. Zhang et al. [26] propose a Fast Fourier Transform (FFT)-based decay detection scheme. This signal strength decay scheme is integrated into our framework for fast prediction of approaching network unavailability.

3.2.7 Network availability administrator (NAA)

The Network Availability Administrator (NAA) is an integral part of the CM. It is responsible for executing the addition and deletion of IP addresses from the host's address list and notifying the server of these changes. Unlike conventional multi-homing methods, detecting a new network does not necessarily guarantee its binding to the address list. As explained in previous sections, NAD is responsible for discovering currently available wireless networks and notifying HNE of them. HNE in turn decides on which of the available networks are possible handoff candidates. Once a new network is detected by NAD and then approved for handoff candidacy by HNE its information is forwarded to NAA. NAA is then responsible for including that network's information in the MH's address list and notifying the server of its existence. NAA is also responsible for removing networks that are no longer (according to HNE) suitable candidates.

When NAA is required to include a new network for handoff candidacy, it uses multi-homing and starts the process of acquiring a new secondary IP address. It is then necessary for NAA to bind this new IP address and notify the server of its existence. This can be achieved by employing SCTP's Dynamic Address Reconfiguration (ASCONF) feature. Dynamic Address Reconfiguration defines two chunk types (ASCONF and ASCONF-ACK) and several parameter types such as "Add IP Address", "Delete IP Address", "Set Primary Address", etc. NAA notifies the server of its new IP address by sending an ASCONF message to the server with two parameters: "Add IP Address" and the new network's IP address. When the server receives the message it will add the new IP address to its local network information but will not set the new IP as primary. The server will then confirm receipt of the message and the successful addition of the new IP address by sending an ASCONF-ACK back to the MH. At this point the newly added network is ready to exchange messages with the server, nonetheless the current primary network maintains its connection state and the newly added network only becomes a handoff candidate. It is HDM's responsibility as to which network the MH should use.

3.2.8 Handoff executor (HE)

Once a decision to handoff is made by HDM, it sends a handoff trigger message to the Handoff Executor (HE) with the identity of the network to handoff to. When HE receives a handoff trigger it carries out the vertical handoff process. HE sends an ASCONF message to the server asking it to redirect data traffic to the new IP address. The ASCONF parameters are "Set Primary Address" and the new network's IP address. When the server receives this message it sets its primary destination address to the MH as the new IP address and sends an acknowledgment (ACK) back to the MH. Once HE receives this acknowledgment from the server, the new network becomes the primary IP address and the messages between the MH and server are exchanged though the new network.

3.3 Summary

A flowchart of the proposed system is shown in Fig. 4. In Sect. 4 we shall present a simulation model to evaluate the performance of this architecture.

4 Performance evaluation

The performance of Tramcar is evaluated in this section. The simulation model is described in Sect. 4.1 and the results are presented and discussed in Sect. 4.2.

4.1 Simulation model

A simulation model for Tramcar has been developed in Network Simulator (NS-2) [16]. All experiments were performed with University of Delaware's NS-2 SCTP extension [15]. This NS-2 extension currently supports the core features (including multi-homing) of the "Stream Control Transmission Protocol" RFC2960 [17]. We utilize this SCTP extension in order develop SCTP aware applications. The extension was modified in several ways as discussed in Sect. 3.

The simulated network topology is illustrated in Fig. 5. This network topology is setup in NS-2 such that the MH and stationary server are both wirelessly connected via two heterogeneous network interfaces. A multi-homed SCTP association is setup between the MH and two overlaid networks. Network A, represents cellular Wireless Wide Area Networks (WWAN) and has a low bandwidth of 384 kb/s. Network B, on the other hand has a higher bandwidth of 1Mbps and represents a WLAN. Nonetheless, each connection is independent of the other.

The MH shares the networks' bandwidth with various other background traffic sources. As the MH moves about, the amount of background traffic may vary and consequently the performance of both networks will also vary. Therefore, it is impossible to predict which of the two networks will provide higher bandwidth or lower cost, etc. In fact, remaining connected to a single network will not necessarily provide the best possible performance. Network B has a larger capacity and can therefore, better tolerate background traffic and maintain higher performance. In a real-life implementation, Network B would most likely be the more expensive of the two networks due to its higher QoS. NS-2's expo-traffic (exponential traffic) [17] source is used to generate background traffic. Separate traffic is generated for each of the two networks. We classify the traffic into "none", "light", "heavy" and "oscillating". The MH has several connection strategies: it can operate without context-awareness by remaining connected to network A or handing off to network B, or it can employ Tramcar. Initially, the MH is connected to the server through network A's interface, i.e. the primary path is the path from the MH to the interface on network A. The

Fig. 4 Flowchart of the Tramcar architecture

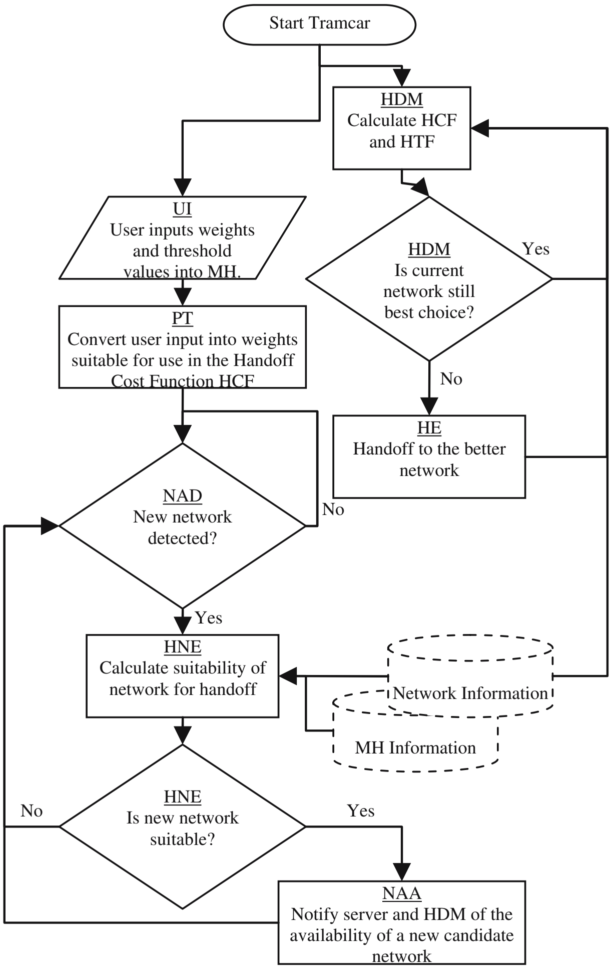
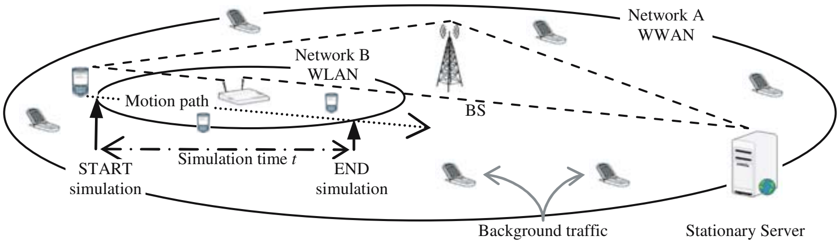


Fig. 5 Simulated network topology



secondary path is from the MH to network B's interface.

4.2 Simulation results

4.2.1 Bandwidth in unpredictable network conditions

In this set of experiments the user's preference is to get the highest possible QoS by receiving the maximum amount of bandwidth, irregardless of other factors such as usage cost, security, power consumption and network performance. Therefore, the user sets the HCF to:

$$Q_i = f((0\times C_i), (0\times S_i), (0\times P_i)(1.0\times D_i), (0\times F_i)).$$

The results of this experiment are presented in Fig. 6. Tramcar manages to increase throughput by up to 57.9% in individual cases. Tramcar increased throughput by 99.1% compared to the non context-aware scheme which remains connected to network A and by 21.0% compared to the non context-aware scheme that hands off to network B. With no background traffic the non-context-aware scheme (which hands off to network B) performs rather well since network B has a high bandwidth. Tramcar's performance is very high as well in that case. When the background traffic varies, Tramcar shows a significant improvement over non-context-aware schemes. This is due to Tramcar's ability of handing off several times with low- handoff latency. In general, it is apparent, from the results obtained, that Tramcar has significantly helped in bringing about smarter handoff decisions and boosting the network throughput.

Figure 7 presents a specific scenario with background traffic oscillating on both networks. All three schemes (Remain on network A, handoff to network B and use Tramcar) are plotted on the same graph (Fig. 7b) in order to easily compare each scheme's performance in terms of throughput, packet drops and disconnections. The background traffic rates are also provided (Fig. 7a). The results show that Tramcar was able to transfer more packets, had a very low delay and suffered from very minor packet losses. The non-context-aware schemes on the contrary got connection disruptions and in fact got completely disconnected several times during the transmission. These disconnections occurred because the background traffic was high and consequently, there was not enough bandwidth available for the non context-aware systems to complete the transfer without disconnection. These disconnections are completely unacceptable in wireless roaming systems. Furthermore, without context-awareness the throughput was much lower and therefore user satisfaction is much less. The lower throughput is caused by the sudden boost in traffic that is not met by a handoff in the non-context-aware schemes. On the contrary, Tramcar handed off when needed and avoided crowded networks.

4.2.2 Utilization of bandwidth and usage cost

In this set of experiments a charge is added to each network. Network A which still has a capacity of 384 kb/s and it charges 1 ¢/s. Network B's capacity is 1 Mb/s. and it charges 2 ¢/s. These charges are *fixed* per second irregardless of the amount of data transferred during the connectivity period. Consequently, a network with high-background traffic would lead to low-network utilization due to the fixed network cost per minute no matter what amount of data transferred.

The user's preferences in this set of experiments is to receive the maximum possible QoS for the lowest cost, i.e. increase network utilization and pay least possible charge for each bit of data transferred. Therefore, the user sets the HCF weight parameters to:

$$Q_i = f\big((0.5\times C_i), (0\times S), (0\times P_i), (0.5\times D_i), (0\times F_i)\big). \tag{7}$$

Once again, different levels of background traffic are generated on each network. The results of this experiment are graphically presented in Fig. 8.

The bar graph in Fig. 8 (left *y*-axis), displays the amount of data transferred per unit cost under different background traffic levels. The points in Fig. 8 (right *y*-axis), present the amount of data transferred in each case. Tramcar is able to meet user requirements and achieve higher context-awareness by smartly handing off to the network with best conditions. Tramcar did not always

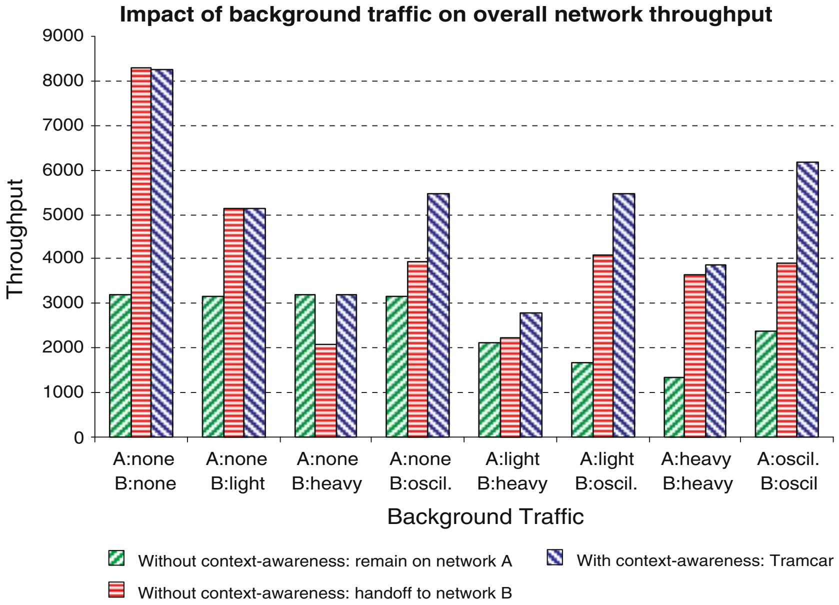


Fig. 6 Impact of background traffic on overall network throughput

perform the best—especially in static background traffic scenarios. This is because non-context-aware schemes achieved the ideal performance in these cases. Nonetheless in about 88% of the experiments, Tramcar outperformed non context-aware schemes. When Tramcar did not perform best it still remained within 1.5% of the best scheme and always outperformed the worst scheme. In summary, Tramcar underperformed in static cases but with random and unpredictable traffic, Tramcar demonstrated a stable confident performance, that is clearly outstanding.

4.2.3 Experiments with different network applications

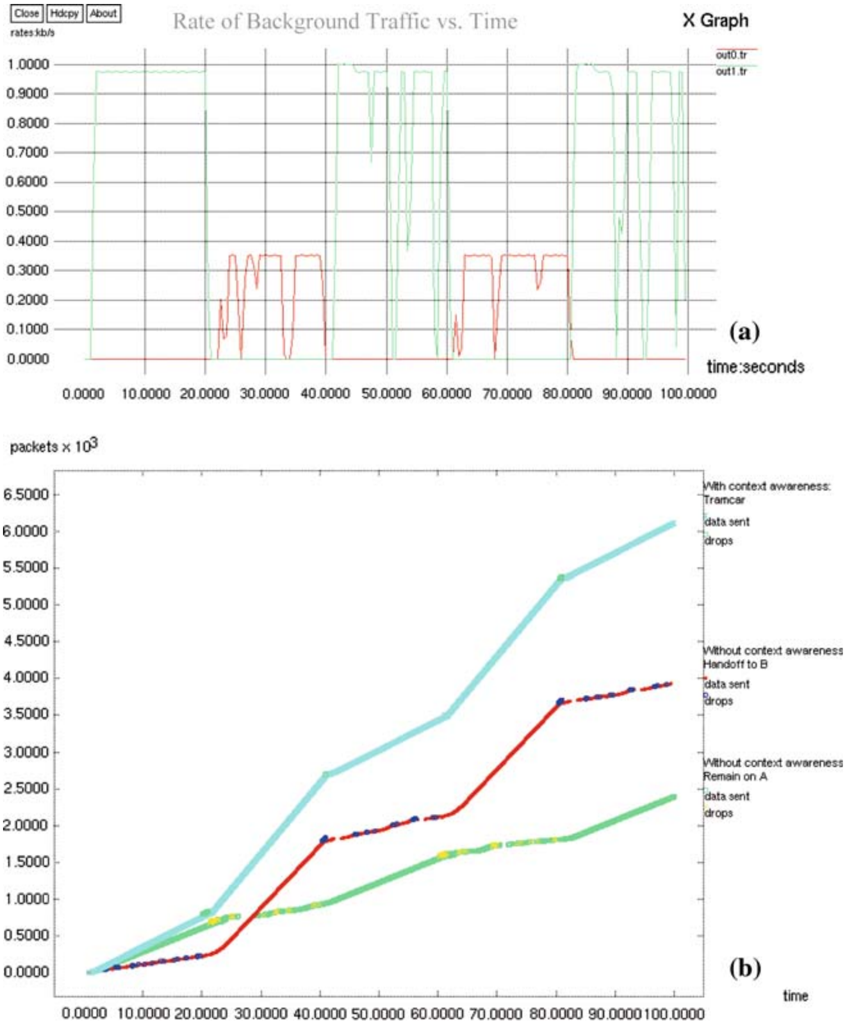
In this set of experiments, different application protocols are simulated to test Tramcar's performance in transmission of bursty and non-bursty data. Bursty data (high-bandwidth consumption) is represented by FTP while Telnet is used to simulate non-Bursty data (low-bandwidth consumption). The Ns-2 classes used in these simulations are: application/FTP and application/Telnet. In these scenarios, both Telnet and FTP applications are used but in each experiment the application ratios are varied. Furthermore, random background traffic is generated in both networks. The results are graphically presented in Fig. 9.

The graphs show that Tramcar has a greater ability in adapting to different application protocols. As the percentage of FTP traffic approaches 0 or 100% the non-context-aware scheme that hands off to B performs as well as the context-aware Tramcar. On the other hand, as the ratio of FTP to Telnet data approaches 50:50% Tramcar shows a significant improvement. This is most likely due to Tramcar's ability to handover several times depending on the bulkiness of the data being transmitted. It is also apparent that as the data becomes more bursty, the schemes are able to utilize that data more and thus, the amount of data transferred per unit cost increases.

4.2.4 Management of user budgets

In this set of experiments our objective is to show that, by deploying Tramcar, the user is allowed to provide an approximation to the amount of money he wishes to spend, i.e. a specific budget can be specified by the user. It is practically impossible to guarantee that a user will not exceed a specified budget since the system is also trying to maintain a reliable steady QoS, as well as avoid disruption or disconnection of the active connection. Nonetheless, the best scheme should have the ability of achieving the highest level of user satisfaction under any given situation. The network topology remains unchanged and the background traffic is

Fig. 7 Oscillating / oscillating background traffic. (**a**) Background traffic (**b**) Network throughput and packet drops



once again randomized in an attempt to reproduce a real life scenario. The cost threshold value t_c for HTF is given a value such as \$ 1.00. User satisfaction is calculated as:

$$\text{User satisfaction}(\%) = \frac{\text{Preferred cost }(\text{¢})\text{-Actual cost }(\text{¢})}{\text{Actual cost }(\text{¢})} \times 100$$

where the value of preferred cost is varied in the experiments and the actual cost is calculated experimentally. The results are plotted in Fig. 10.

Figure 10 shows that the highest user satisfaction is achieved by Tramcar no matter what budget is specified by the user. The figure shows that Tramcar manages to maintain a user satisfaction that is consistently above 80%. These elevated user satisfaction levels might however decrease under extensively high-background traffic levels. It needs to be also noted that Tramcar's performance approaches non-context-aware performance as the user requests more extreme (too low or too high) costs. Overall, the results indicate that Tramcar's context-awareness can once again increase the users' satisfaction and help manage their budget or other requirements.

5 Conclusion and future work

In this paper, Tramcar, a novel context-aware architecture and mobility control mechanism was fully developed. This architecture allows adaptation of handoff mechanisms to specified user preferences, unreliable environment conditions and QoS requirements. To support our proposed system, an

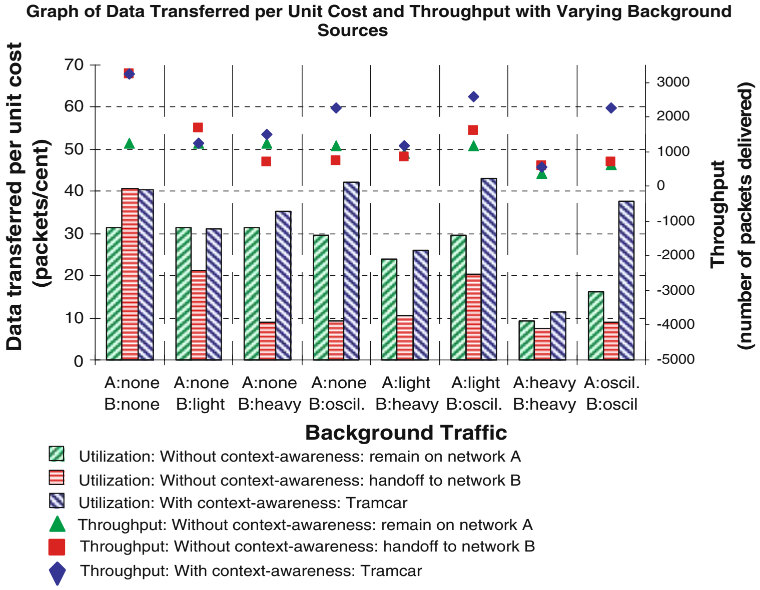


Fig. 8 Impact of various background conditions on the overall number of packets transferred per unit cost

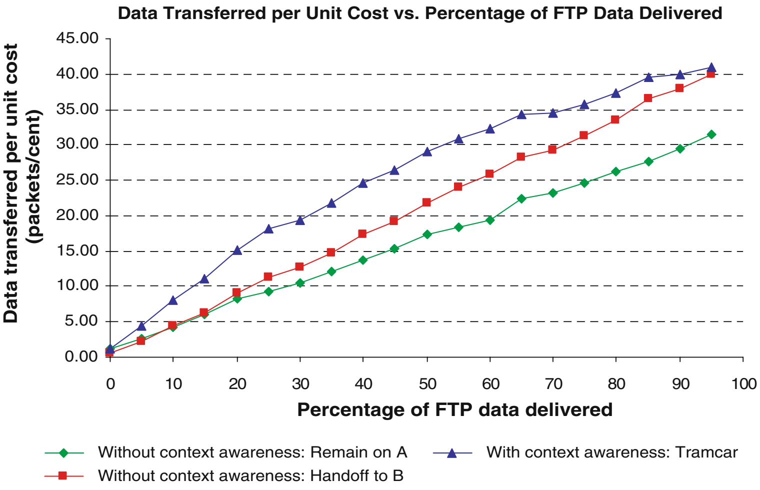


Fig. 9 Impact of different application data on data transferred/unit cost

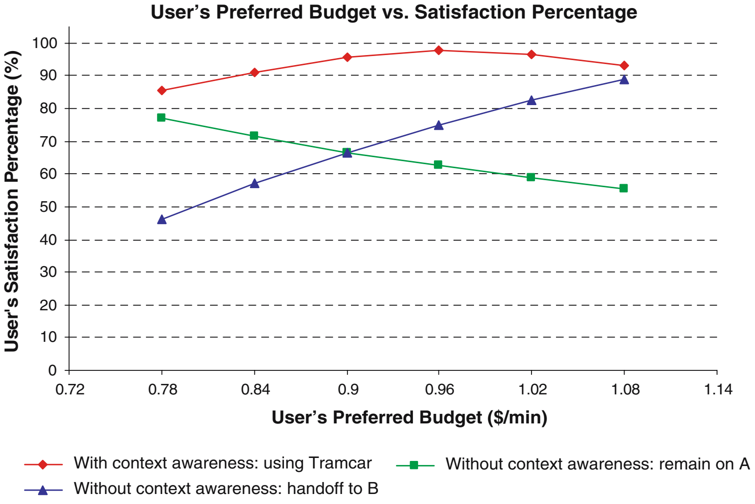


Fig. 10 Impact of schemes on managing user budgets

NS-2 simulation model of Tramcar was developed. The simulation results were then used to analyze the merits of individual Tramcar modules as well as their interaction and functionalities. Tramcar's context-aware performance was compared to non-context-aware schemes. Through our simulations, we have proven the viability and implementability of our context-aware and adaptive architecture. Using the presented context-aware and mobility control system, we were able to overcome the inadequacies, limitations and weaknesses of individual non context-aware mechanisms.

An issue that will be considered in future research work is the application of the handoff decision module to multimedia applications. We shall address the fact that a better network quality Q_i does not necessarily mean better multimedia service. For example, a WLAN network might have a high Q_i, however because Voice over WLAN (VoWLAN) still provides poor voice quality, vertical handoff from a cellular WWAN might be an appalling choice.

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