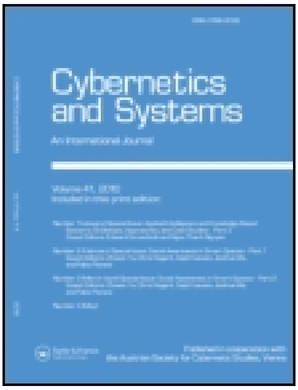

Cybernetics and Systems: An International Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ucbs20

USER ASSIGNMENT AND MOVEMENT PREDICTION IN WIRELESS NETWORKS

Paweł Świątek [a], Piotr Rygielski [a], Krzysztof Juszczyszyn [a] & Adam Grzech [a]

[a] Institute of Computer Science, Wroclaw University of Technology, Wrocław, Poland

Version of record first published: 24 May 2012

To cite this article: Paweł Świątek, Piotr Rygielski, Krzysztof Juszczyszyn & Adam Grzech (2012): USER ASSIGNMENT AND MOVEMENT PREDICTION IN WIRELESS NETWORKS, Cybernetics and Systems: An International Journal, 43:4, 340-353

To link to this article: http://dx.doi.org/10.1080/01969722.2012.678219

Cybernetics and Systems: An International Journal, 43:340–353
Copyright © 2012 Taylor & Francis Group, LLC
ISSN: 0196-9722 print/1087-6553 online
DOI: 10.1080/01969722.2012.678219

User Assignment and Movement Prediction in Wireless Networks

PAWEŁ ŚWIĄTEK, PIOTR RYGIELSKI, KRZYSZTOF JUSZCZYSZYN,
and ADAM GRZECH

Institute of Computer Science, Wroclaw University of Technology, Wrocław, Poland

The article is devoted to the problem of mobility and resource management in heterogeneous wireless networks. It is assumed that in certain areas covered by multiple overlapping wireless networks there are a certain number of mobile clients that consume networks resources by use of the available communication services (e.g., voice or data transmission) delivered by network providers. Moreover, it is assumed that the continuity of communication services may be assured by the use of common handover techniques supporting client mobility (e.g., Mobile IPv6, IEEE 802.21, etc.). The task of mobility and resource management consists of making decisions concerning the moment and the network to which particular clients should be handed over in order to optimize certain quality criterion (e.g., utilization of network resources). In this article we show that gathering knowledge about client movements and prediction of their future positions may significantly improve the overall quality of the services delivered and network resource utilization.

KEYWORDS handover, movement prediction, resources allocation, user mobility, wireless networks

INTRODUCTION

Wireless networking is becoming increasingly popular. Personal device manufacturers equip their laptops and smartphones with every wireless networking technology available, from short-range Bluetooth radios, to

---

Address correspondence to Adam Grzech, Institute of Computer Science, Wroclaw University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland. E-mail: adam.grzech@pwr.wroc.pl

mid-range wireless local area network (WLAN) interfaces, to long-range 3G and worldwide interoperability for microwave access (WiMAX) cards. As a result, the network services provider can deliver its services to mobile users anywhere, anytime.

Providing high-level quality of services (QoS) in mobile wireless environment raises a number of technical problems. The main issues include (1) mobility management in a heterogeneous wireless environment, which allows for seamless handover between different data transmission technologies, and (2) security and trust between different administrative domains, allowing for secure transfer of credentials of a mobile device roaming through different networks.

Considerable research effort has been made to address the aforementioned problems. Intra-technology data link layer handovers are handled with the use of media specific signaling procedures introduced as extensions to particular wireless transmission standards; for example, 802.11r for WLAN (IEEE Standard 802.11r-2008 2008), 802.16e for WiMAX (IEEE Standard 802.16e 2005), etc. Currently, a new standard is being developed to manage inter-technology layer 2 handovers. This proposal, 802.21—"Media Independent Handover" (MIH; Dutta et al. 2008)—provides a set of mechanisms that allows triggering higher layer media-independent handover procedures based on a unified set of commands and media-specific events. Network layer handover is managed by mobility extensions of the IP protocol; that is, MIPv4 (El Malki 2007) and MIPv6 (Johnson et al. 2004). In order to provide service continuity and guarantee required quality of service during handovers, additional modifications to mobility management protocols have been made; for example, Fast Mobile IPv6 (FMIPv6; Koodli et al. 2005) and Hierarchical Mobile IPv6 (HMIPv6; Castelliccia 2000). However, a breakthrough in mobility management has been made by the introduction of a media-independent preauthentication (MPA) mechanism (Dutta et al. 2008), which allows for seamless and secure handovers between different administrative domains.

Application of the above mechanisms in heterogeneous wireless environment allows provision of truly mobile services on an anywhere, anytime basis (e.g. Grzech et al. 2010; Brzostowski et al. 2012; Świątek et al. 2012). In such scenarios, where users are not bound to use a particular wireless network, network selection and handovers do not affect the user's application performance, and a number of network management and optimization tasks can be performed using network-assisted (network-enforced) handovers. These tasks include, among others, network load balancing, user allocation, resource allocation, network resource utilization optimization, and quality of service provisioning (e.g. Grzech and Świątek 2009b; Tomczak 2012).

In this article, a general concept of network resource assignment optimization assisted by network-enforced handover is proposed. Network optimization tasks that utilize the proposed concept are introduced. Moreover, it is shown that application of even simple methods of prediction of users' movements may significantly improve the efficiency of network management and optimization tasks. The influence of the proposed network optimization concept on the network performance is evaluated by means of computer simulation.

The article is organized as follows. In the following section we present assumed models of wireless networks and user mobility. Then we formulate the problem of assignment of users to networks and propose a solution. The following section is devoted to a description of the experiment and analysis of the results. In the final section we summarize the presented work.

NETWORK AND MOBILITY MODEL

Network Model

Assume that there are N wireless networks net_n ($n = 1, \ldots, N$) covering certain area A. Exemplary area A is depicted in Figure 1. We assume that each network net_n covers a circular area with a center [$net_n(x)$, $net_n(y)$] and radius r_n. Each network net_n is characterized by a maximal amount of available resources U_n. Depending on the amount of free network resources u_n, a client may receive a certain amount of network capacity c_n calculated by function $c_n = f_n\ (u_n, r_n)$, which is specific to each access network net_n.

Assume that area A is divided into $I \times J$ identical square cells. Integers I and J are chosen in such a way that the cells are small enough for the

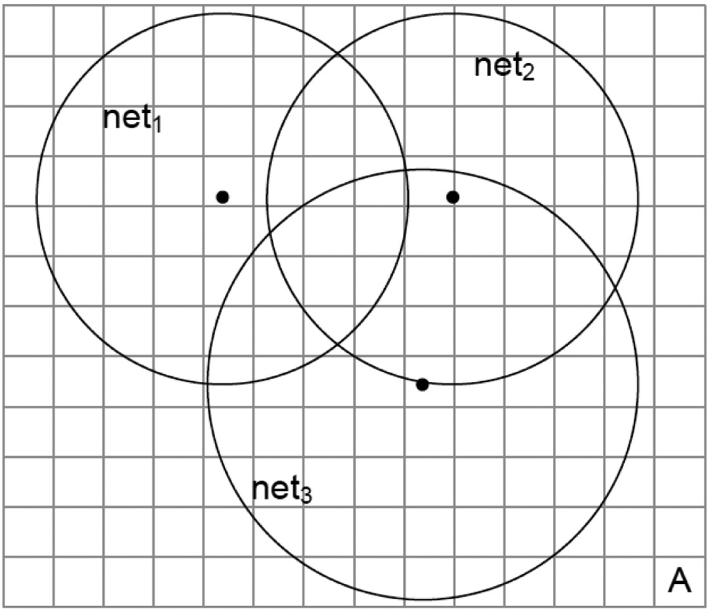

FIGURE 1 Exemplary area A divided into 168 cells with network coverage.

characteristics of each network to be constant across the area of a single cell. Each cell $cell_{ij}$ ($i = 1, \ldots, I; j = 1, \ldots, J$) may contain any number of users and network access points. Coordinates of users and access points lying within a particular cell $cell_{ij}$ are assumed to be equal to the coordinates of the cell. Moreover, we assume that the distance between a certain user and a certain access point is equal to the distance between cells containing user and access point.

The service of the network that can be delivered to multiple clients may have various interpretations in different access networks. In networks based on a time-division multiplexing (TDM) medium-sharing technique, the allocated resource is interpreted as the number of time slots in which a client is allowed to transmit data. In contrast, in networks based on frequency-division multiplexing (FDM), a certain amount of bandwidth is allocated to each user.

The form of function f_n (u_n, r_n) depends, among others, on the type of network it is associated with. Another important factor is the International Organization for Standardization/Open Systems Interconnection (ISO/OSI) layer at which network capacity is measured. At the physical layer, capacity c_n, measured as the number of bits send per second, is roughly proportional to the amount of allocated resources and does not depend on the distance from the network access point. At the data link layer, where, due to transmission errors, datagram retransmission may occur, the user's distance from the antenna plays an important role. At higher layers of the ISO/OSI model, protocol-specific mechanisms requiring data retransmissions may further decrease delivered network capacity. In general, it may be assumed that effective network capacity c assigned to a user is proportional to the amount of allocated resource u and inversely proportional to the distance r from the network access point:

$$c_n = f_n(u_n, r_n) = C_n \cdot \frac{u_n}{U_n} \cdot \frac{r_n - r}{r_n}, \tag{1}$$

where C_n is the maximal achievable effective capacity under assumption that a user is assigned with all available resources $u_n = U_n$ in a near-zero distance from the network access point. For such a general model we add some assumptions and formulate mobility management tasks, which are presented in the Problem Formulation section.

User's Mobility Model

The quality of services and performance of wireless networks highly depend on the position and movement trails of humans who operate the various types of communication devices. Most of these devices are small, handheld equipment attached to their operators. It is rather difficult to deploy large-scale wireless networks for testing purposes, so various mobility models are used for simulations and performance evaluations. Mobility models, which reproduce the movement patterns of humans, are applied to make their behavior predictable and support the algorithms used for network management (Song et al. 2010). We consider three mobility models, reflecting various statistical features observed in human activity patterns: random walk (RW), truncated Levy flight (TLF), and self-similar least action walk (SLAW).

The RW model does not require much explanation—we assume stochastic movement with the maximum distance limit. The TLF model was based on the proposal discussed in Injong et al. (2008), where the applicability of the Levy walk model was proved for human mobility patterns. In particular, this result is especially interesting because the model verification in Injong et al. (2008) was carried out on data gathered in mobile telecommunication networks. Typically, Levy exponents for flight length distribution and pause time distribution are equal to 1 and 5 .

SLAW was based on the model proposed in Kyunghan et al. (2009). It is the most advanced approach and covers several distinctive features observed in human mobility patterns. First, it provides truncated scale-free distributions of flights (elementary movement actions) and pause times (time intervals between movements). This feature is also addressed by the TLF model. Moreover, SLAW simulates the influence of individual mobility areas that typical for each user. The individual character of movement patterns was confirmed in Brockmann et al. (2006). The next feature modeled by SLAW is intercontact times. It is assumed that the movements of individuals are correlated, and people tend to move in spontaneously formed groups that have a truncated power law time distribution. The last feature is the characteristic movement destination points, which have a fractal-type geographical distribution. This is used to simulate that some destinations are preferred and visited more often than the others. Following the results from Rhee et al. (2008), it is a characteristic feature observed in many scenarios, especially in urban and industrial environments. The geographical space (area A) in our experiments is a 30×30 square mesh with a *reflection boundary* (where points crossing the boundary turn back instead of returning on the other side of the mesh, which is a *wrap-around boundary*). According to the state-of-the-art, we use the SLAW model in our experiments.

PROBLEM FORMULATION

A number of mobility management tasks can be performed to improve quality of service delivered in wireless networks. Each mobility management task can be formulated as an optimization problem that, in general, is NP-hard. In this section we focus on the problem of maximization of the number of connected users. Then we consider the simple prediction mechanism in order to minimize the overall number of handovers.

Maximization of the Number of Connected Users

It is assumed that there are M users in area A, each accessing one of the wireless networks. The task is to find such an assignment of M users to N networks for which the maximum number of users is connected with the network.

Let matrix $\mathbf{R}_{N\times M}$ ($R_{n,m} \in \{0, 1\}$) model the possibility of connecting users to the networks in moment t. Value $R_{n,m} = 1$ means that the mth user is located within the range of the nth network, and $R_{n,m} = 0$ means that such a connection is impossible at the tth moment of time. Assuming that all variables are considered in moment t we can formulate the following optimization problem:

$$\text{Maximize} \quad \sum_{n=1}^{N}\sum_{m=1}^{M} P_{n,m} \tag{2}$$

$$\text{subject to}: \quad \underset{n=1,\ldots,N}{\forall}\ \underset{m=1,\ldots,M}{\forall} P_{n,m} \in \{0,1\} \tag{3}$$

$$\mathbf{R}\cdot\mathbf{P} = \mathbf{P} \tag{4}$$

$$\underset{m=1,\ldots,M}{\forall} \exists! P_{n,m} = 1 \tag{5}$$

$$\underset{n=1,\ldots,N}{\forall} \sum_{m=1}^{M} P_{n,m} \leq c_n. \tag{6}$$

It can be shown that the problem formulated above is in general an NP-hard optimization problem. The proof can be shown by transformation to a multidimensional multiple-choice knapsack problem (MMKP; Martello and Toth 1981). Therefore, the above formulation cannot be utilized in real-life applications where the number of users and networks may be large. In the next section we simplify the problem by assuming that each user requests the same amount of network resources. For such an assumption we present a polynomial-time exact algorithm.

Minimization of Resource Assignment Error

The situation when the user is not assigned with desired amount of resources we call the *resource assignment error*. The method presented in this subsection works if and only if all of the users in the considered area request the same amount of resources (e.g., the same maximum bandwidth). We can identify this as the situation when the mobile operator guarantees the equal throughput, say 1 Mbps, for each mobile device with a contract.

The solution for this task is obtained by transformation of the original problem to the classic assignment task. Assuming that each user demands equal network capacity $c = c_n$ (for $n = 1, \ldots, N$) we create virtual wireless networks in the following way. Each nth real network with total capacity U_n is divided into $\mathrm{Floor}\left(\frac{U_n}{c}\right)$ virtual networks. After such transformation we know that each of the $K = \sum_{n=1}^{N} \mathrm{Floor}\left(\frac{U_n}{c}\right)$ virtual networks can handle exactly one user.

In the next step we build a square binary matrix $\mathbf{R}'$ of size max $\{K,M\}$ in the following way. If the mth user can be connected (is located within the range) to virtual network k then $R'_{m,k} = 1$; otherwise, $R'_{m,k} = 0$. If $K > M$ we add $K - M$ artificial users with the possibility to connect each network. If $M > K$ we add $M - K$ artificial virtual networks where each virtual network can be accessed by any user in area A.

When the matrix $\mathbf{R}'$ is filled with the proper values, we produce the assignment cost matrix denoted **CR**, which defines the apparent cost of the assignment of the users to the virtual networks. The size of matrix **CR** is the same as the size of $\mathbf{R}'$. The cost matrix **CR** is calculated in the following way: If $R'_{m,\,k} = 1$, then $CR_{m,\,k} = 0$; if $R'_{m,\,k} = 0$ and $m < M,\ k < K$, then $CR_{m,\,k} = b_1$; otherwise, $CR_{m,\,k} = b_2$. The b_1 and b_2 are any high numbers such that $b_1 > b_2$. In our experiments we take $b_1 = 1{,}000$ and $b_2 = 500$. Such a cost matrix puts preference on the connection of users that are within the range of any real wireless network. If the user is not within the range of any network, the assignment cost is very high, so the connection is unlikely to be preferred. The cost of assignment of an artificial user or assignment to the artificial network is also high, but it is lower than in the case when no network is available. This does not impact the overall solution because the artificial users are not going to be connected for real. The connection of a real user to the artificial network will cause the resource assignment error (the user will remain not connected) but will satisfy the general problem constraints (Eqs. (3)–(6)).

Such a cost matrix is the only parameter of an algorithm solving the stated assignment problem. We use the Hungarian method (Munkres 1957) with a cost minimization objective.

Minimization of Movement Prediction Error

In this subsection we consider the minimization of prediction error problem, which is a further extension of the resource assignment error minimization problem (Eq. (2)). We assume that the user location can be predicted for the next step; thus, we want to minimize the overall number of handovers throughout the experiment.

As the movement prediction error we define a situation in which the handover of a user occurred when it was not necessary. This means that the handover would not have occurred if the previous assignment decision was correct. The handover operation is not without cost, so we want to minimize the number of handovers in order to manage the wireless system resources properly.

In order to consider the prediction in the assignment algorithm we introduce the following changes to the cost matrix **CR**. Consider the *t*th moment of time. If the *m*th user is within the range of the *k*th virtual network and will remain in the range of this network at moment $t+1$, the cost equals $CR_{m,\ k}=5$. The cost equals $CR_{m,\ k}=10$ if the *k*th network will be unavailable at moment $t+1$ but is available at *t*. Moreover, if the *m*th user is connected to the *k*th network at moment *t* and this network will be available at moment $t+1$, the cost is $CR_{m,\ k}=0$. The solution is obtained using the Hungarian algorithm with a cost minimization objective.

EXPERIMENTAL RESULTS AND DISCUSSION

In order to evaluate the efficiency of the proposed movement prediction methods, a dedicated simulation environment was developed in *C++*. The developed simulator simulates the set of users moving over a square area covered with wireless networks. The area *A* was split into 900 (30 × 30) square cells in which a defined number of wireless radio stations and users were placed. Each user located within area *A* behaves in the following way. At every time step the user makes a movement from one cell to another one according to the mobility model. When the user moves between cells the assignment decision is being made. The decision concerns an assignment of users to particular wireless networks. After each step the number of disconnected users was counted.

The experiments executed in the simulation study consisted of running a number of simulation rounds, each with a constant number of networks but with an increasing number of users and using various assignment algorithms. The results for each simulation round contain statistics about the values of the following parameters: *connection errors*, or how many times the user's requirements were not satisfied (user was not connected), and *prediction errors*, or how many times a handover occurred even if there was such an assignment possible earlier such that the handover would not occur.

We examined four assignment algorithms:

- *USR1*: The user makes a decision regarding which network to connect depending on the signal strength.
- *USR2*: The user chooses the network with the lowest ping.
- *HEU1*: The heuristic algorithm presented in Rygielski et al. (2011).
- *OPT1*: The optimal assignment solution for a problem given with Eqs. (2)–(6).

The results of the first experiment are presented in Figure 2. Each simulation run was executed with a different number of users in area *A*. There were 600

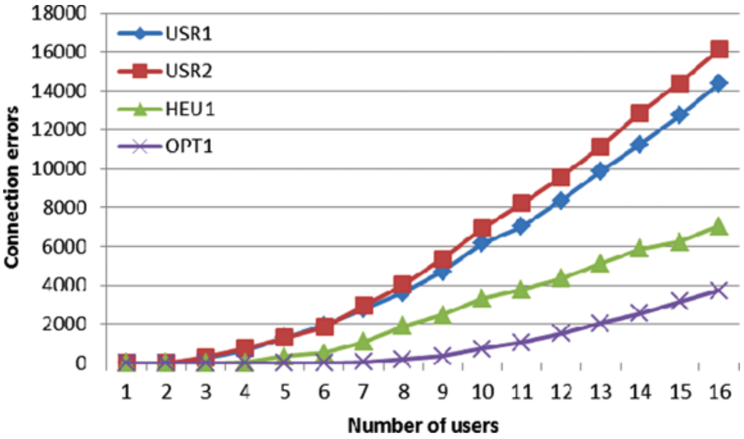

FIGURE 2 Number of network resource assignment errors under control of various assignment algorithms for increasing number of users present in area *A* (color figure available online).

time steps for the simulation. In each time step every user made a movement according to the mobility model. Algorithms *USR1* and *USR2*, where the user makes an assignment decision, caused the largest number of connection errors. Both *USR* algorithms were used to show the waste of wireless networks resources when the user makes the decision, which is the most common practice. In the heuristic *HEU1* the networks make a decision which user to connect. This method outperforms methods *USR1* and *USR2*. The optimal method *OPT1* presented in this article maximizes the number of users that have connectivity to the network.

In the next three experiments we investigate the quality of the exact method and the influence of the amount of available knowledge regarding users' movements on the quality of prediction and decision making by comparing the number of prediction errors when using the following prediction assumptions:

- No prediction of user location
- Low-quality predictor: only partial information about users' past movements was available
- High-quality predictor: we know all the history of the past movements
- Ideal predictor one step ahead: we assume that we know the exact position of the user in the next step
- Ideal predictor two steps ahead: we assume that we know the exact position of the user in the next two steps

Each of the experiments consisted of 16 simulation runs (for an increasing number of users) for each prediction scheme. Figures 3–5 present the results

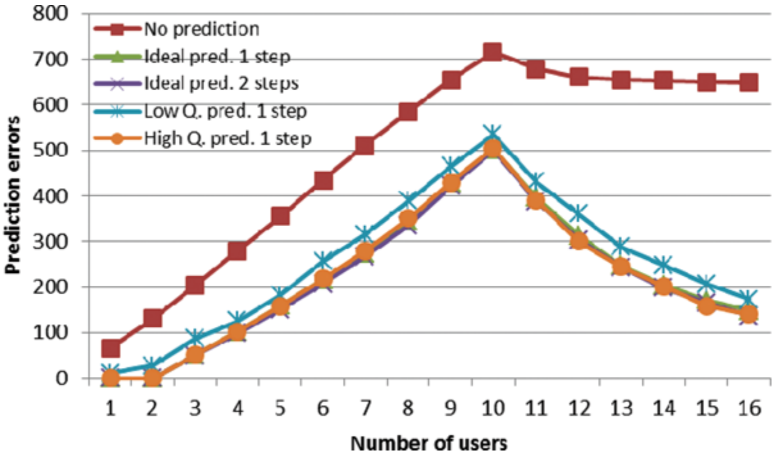

FIGURE 3 Number of prediction errors under control of predictors with various quality using exact assignment algorithm for increasing number of users present in area *A* moving according to the RW mobility model (color figure available online).

of the experiments for various mobility models; that is, RW, TLF, and SLAW, respectively. The results concern the number of prediction errors for each mobility model and various prediction methods assuming the optimal assignment of users to networks (algorithm *OPT1*).

Each simulation series (for each mobility model) in this experiment provides an equal number of connection errors—the same as in the first experiment for algorithm *OPT1*. This means that the modifications to the algorithm do not change the optimality in the sense of the optimization criterion (Eq. (2)) chosen for minimization of connection errors. In this

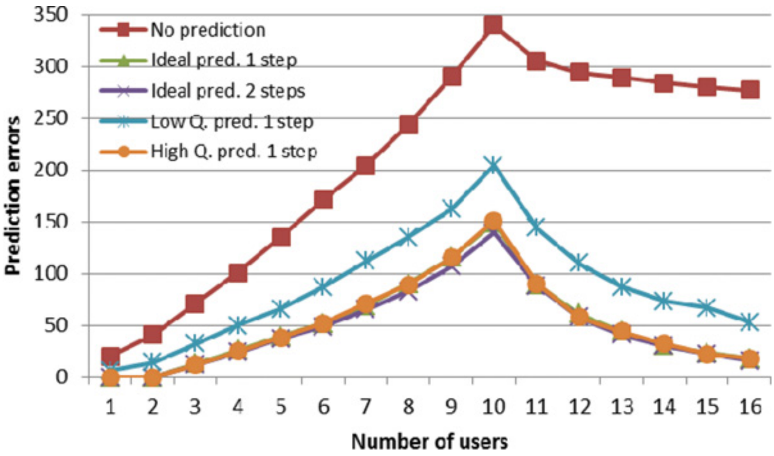

FIGURE 4 Number of prediction errors under control of predictors with various quality using exact assignment algorithm for increasing number of users present in area *A* moving according to the TLF mobility model (color figure available online).

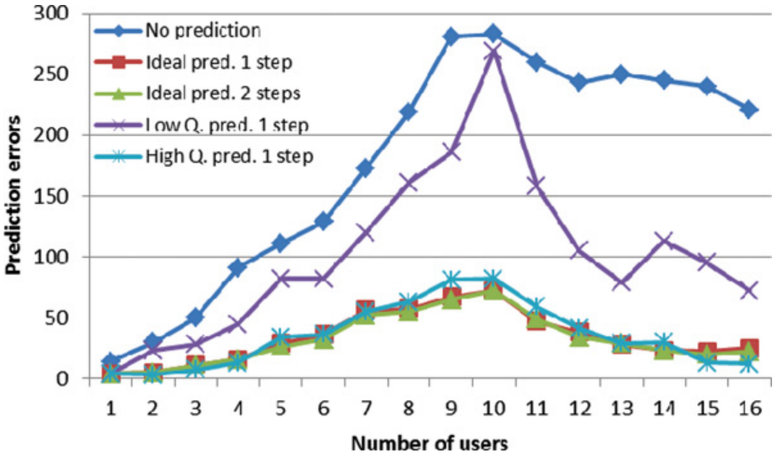

FIGURE 5 Number of prediction errors under control of predictors with various quality using exact assignment algorithm for increasing number of users present in area *A* moving according to the SLAW mobility model (color figure available online).

experiment we change the optimization criterion and compare the number of prediction errors against the optimal algorithm.

The results show that prediction of future user location is worth the effort. Even the low-quality prediction provides significant improvement in the number of prediction errors. Using more sophisticated methods of prediction improves the wireless network resources usage, assuming that each handover impacts the load of the network. In this case, the high-quality predictor provides satisfying results. A more interesting observation is that using the ideal predictor with a longer prediction horizon does not significantly improve the results compared to the ideal predictor with a shorter horizon. This may suggest that (for example) in densely populated areas the assessment of short time trends in user mobility may be sufficient for handover management.

In general, a one-step-ahead high-quality prediction is good enough for near-optimal decision making for each assumed mobility model. In our experiments we assumed very simple predictors, namely, autoregressive moving average (ARMA) predictors, where the amount of available knowledge about users' movements (predictors quality) was modeled with the number of previous steps taken into account by ARMA. Because even such a simple predictor provides very good results in terms of the quality of decision making, it is not necessary to provide more sophisticated ones, at least for the mobility models considered in this article.

Considering the graphs in Figures 3–5 one can notice that the number of prediction errors varied for different mobility models. Optimal assignment solutions for the ideal predictors yielded less than 500, 150, and 70 prediction errors for RW, TLF, and SLAW, respectively. The difference between RW and

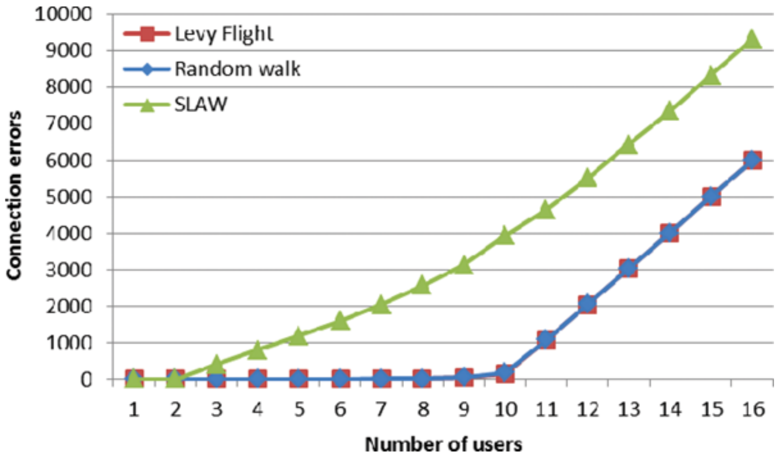

FIGURE 6 Influence of the number of connected users on the number of connection errors for different user mobility models.

TLF can be explained by the fact that the ARMA predictor exploits the same information as the LF mobility model. The significant improvement in the number of prediction errors for the SLAW model is achieved for the cost of the higher number of connection errors (see Figure 6), because in the SLAW model users tend to move in groups, which results in multiple requests for the same resources while leaving other resources unused.

FINAL REMARKS

The general problem formulated in this article concerns a situation when the users are moving through an area covered by many wireless networks. Every user uses the network but can be connected to any particular wireless station that is within the range. We have formulated the general problem of assignment of users to the networks and then simplified it in order to show that prediction of future user locations causes fewer handovers and allows for efficient utilization of wireless network resources. Moreover, we point out that sophisticated methods of prediction will not improve the performance of the wireless system. In the future we plan to discard the simplifications introduced in this article and propose an efficient heuristic algorithm for the general problem formulated in the Problem Formulation section. In particular, our results suggest that we may expect a high number of prediction errors for the growing number of users, though this trend stops after a certain number of users populating the area is exceeded. At the same time, when the population is greater than some critical value, we may experience a growing number of connection errors, which can be seen by comparing Figures 3–6. Therefore, the proper heuristic approaches should consider the influence of the user population density, which clearly impacts the results. Currently, we plan an application of efficient methods stemming from these conclusions in a service-oriented (Grzech and Świątek 2009) sensor data acquisition system.

REFERENCES

"Air Interface for Fixed Broadband Wireless Access Systems Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands." 2005. IEEE Standard 802.16e. Available at: http://standards.ieee.org

Brockmann, D., Hufnagel, L., and Geisel, T. "The Scaling Laws of Human Travel." *Nature* 439 (2006): 462–5.

Brzostowski, K., Drapała, J., and Świątek, J. "System Analysis Techniques in eHealth Systems: A Case Study LNCS." *LNAI* 7196 (2012): 74–85.

Castelliccia, C. "HMIPv6: A Hierarchical Mobile IPv6 Proposal." *ACM SIGMOBILE—Mobile Computing and Communications Review* 4, no. 1 (2000): 48–59.

Dutta, A., Famolari, D., Das, S., Ohba, Y., Fajardo, V., Taniucho, K., Lopez, R., and Schulzrinne, H. "Media-Independent Pre-authentication Supporting Secure Interdomain Handover Optimization." *IEEE Wireless Communications Magazine* 15, no. 2 (2008): 55–64.

El Malki, K. "Low-Latency Handoffs in Mobile IPv4." 2007. IETF RFC 4881. Available at: http://tools.ietf.org/html/rfc4881 (accessed April 25, 2012).

Grzech, A., Rygielski, P., and Świątek, P. "Translations of Service Level Agreement in Systems Based on Service-oriented Architectures." *Cybernetics and Systems* 41, no. 8 (2010): 610–27.

Grzech, A. and Świątek, P. "Modeling and Optimization of Complex Services in Service-Based Systems." *Cybernetics and Systems* 40, no. 8 (2009): 706–23.

Grzech, A. and Świątek, P. "The Influence of Load Prediction Methods on the Quality of Service of Connections in the Multiprocessor Environment." *Systems Science* 35, no. 3 (2009): 7–14.

"IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Fast Basic Service Set (BSS)." 2008. IEEE Standard 802.11r-2008. Available at http://standards.ieee.org

Johnson, D. B., Perkins, C. E., and Arkko, J. "Mobility Support in IPv6." 2004. IETF RFC 3775. Available at: http://tools.ietf.org/html/rfc3775 (accessed April 25, 2012).

Koodli, R. et al. "Fast Handovers for Mobile IPv6." 2005. IETF RFC 4068. Available at: http://tools.ietf.org/html/rfc4068 (accessed April 25, 2012).

Lee, K., Hong, S., Kim, S. J., Rhee, I., and Chong, S. "SLAW: A Mobility Model for HumanWalks." In *Proceedings of the 28th IEEE Conference on Computer Communications (INFOCOM)*, 855–863, April 19–25 2009, Rio de Janeiro, Brazil.

Martello, S. and Toth, P. "Heuristic Algorithms for the Multiple Knapsack Problem." *Computing* 27, no. 2 (1981): 93–112.

Munkres, J. "Algorithms for the Assignment and Transportation Problems." *Journal of the Society for Industrial and Applied Mathematics* 5, no. 1 (1957): 32–8.

Rhee, I., Shin, M., Hong, S., Lee, K., and Chong, S. "On the Levy-Walk Nature of Human Mobility." In *IEEE INFOCOM 2008 - IEEE Conference on Computer Communications*, edited by IEEE, 924–932. Phoenix, AZ: IEEE, 2008.

Rygielski, P., Juszczyszyn, K., Grzech, A., and Świątek, P. "Prediction Based Handovers for Wireless Networks Resources Management." *Lecture Notes in Computer Science* 6882 (2011): 687–96.

Song, C., Qu, Z., Blumm, N., and Barabasi, A. L. "Limits of Predictability in Human Mobility." *Science* 327 (2010): 1018–21.

Świątek, P., Juszczyszyn, K., Brzostowski, K., Drapała, J., and Grzech, A. "Supporting Content, Context and User Awareness in Future Internet Applications." *Lecture Notes in Computer Science* 7281 (2012): 154–65.

Tomczak, J. M. "On-line Change Detection for Resource Allocation in Service-oriented Systems." *IFIP Advances in Information and Communication Technology* 372 (2012): 51–8.