Optimal Network Discovery Period for Energy-Efficient WLAN Offloading

Dionysia Triantafyllopoulou, Tao Guo, and Klaus Moessner
Centre for Communication Systems Research
University of Surrey
Guildford, Surrey, GU2 7XH, United Kingdom
Email: {D.Triantafyllopoulou, T.Guo, K.Moessner}@surrey.ac.uk

Abstract— **In this paper we present an analytical framework that aims to improve the energy efficiency of traffic offloading via Wireless Local Area Networks, taking into account the energy consumption for both data transmission and network discovery operations. More specifically, the network scanning period is optimized in order to minimize the energy consumption in a vehicular scenario where a user moves along a road covered by a long range cellular network and a number of randomly deployed Wireless Local Area Networks. The performance of the system that performs periodic network scanning with the optimal period is compared against a sub-optimal system that does not take into consideration the user and network context information when determining the network scanning period. According to performance evaluation results, the use of the optimal network scanning period achieves significant improvement in terms of energy consumption and network detection delay.**

Keywords- ***context awareness, energy efficiency, network discovery, WLAN***

I. INTRODUCTION

Wireless Local Area Network (WLAN) [1] offloading has recently attracted increased attention of Mobile Network Operators as an efficient complementary technology for offloading the cellular network data [2]. WLAN offloading can also be used to reduce the users' transmission energy consumption, due to the short distance between a WLAN Access Point (AP) and the mobile users that are connected to it. In order to enable WLAN offloading, a user needs to scan the available access networks and perform vertical handovers between cellular networks and WLANs. However, the network discovery operations may consume considerable energy.

Traditionally, the procedure of network scanning is performed periodically. However, in the case of mobile users, a fixed pre-determined period that does not consider any information on the user and system conditions often results in inefficient performance in terms of energy consumption due to the fact that context information, such as the availability of neighboring networks and the user speed, are not taken into consideration. As a result, unnecessary energy-consuming network scanning may be performed in case the user is moving very slowly or not moving at all and the surrounding topology does not change. Moreover, in the case of high user speed, the network scanning may not be performed frequently enough, resulting in mis-detection of available networks.

The recent literature on energy efficient network discovery mainly focuses on adaptively determining the most appropriate time for a user to perform a network scan, aiming to accurately detect available neighboring networks without increasing the energy consumption [3]-[5]. More specifically, in [3], the authors consider information on the user mobility and the network density in order to determine the optimal WLAN scanning period. In [4], the authors propose an energy efficient idle scanning algorithm for local area networks, using information on the available networks and their operating channels, provided by the 3rd Generation Partnership Program (3GPP) core network, and user movement information provided by an accelerometer embedded in the mobile terminal. Finally, in [5], user location and WLAN AP availability information is considered in order to determine when a network scanning should be performed, and reduce energy consumption and network detection delay in an heterogeneous environment consisting of overlapping Long Term Evolution (LTE) [6] and WLAN networks.

To improve the energy efficiency of the network scanning procedure and enable energy-efficient WLAN offloading, in this paper we propose an analytical framework that exploits information on the user speed and on the availability of neighboring networks, in order to optimize the network scanning period. Its aim is to avoid unnecessary energy-consuming network scanning and mis-detection of available networks that can be used as targets of handover. The proposed framework is applied to a vehicular scenario where a user moves along a road covered by a long range cellular network, such as a LTE network, and a number of randomly deployed WLANs. The performance of the system that employs the proposed framework is compared against a system that performs network scanning with a fixed sub-optimal period, while the theoretical results are verified through simulations.

The rest of this paper is organized as follows. Section II introduces the proposed system model and assumptions. Section III describes the analytical framework for the determination of the optimal network scanning period in a vehicular scenario. Section IV evaluates the proposed algorithm's performance through simulations. Finally, Section V contains conclusions and plans for future work.

II. SYSTEM MODEL AND ASSUMPTIONS

In this section we consider a vehicular scenario according to which a user moves with a constant speed along a road covered by a long range cellular network and a number of randomly deployed WLAN APs, as shown in Fig. 1 [7]. As the user moves along this road, he performs network scanning, depicted by vertical arrows in Fig. 1, periodically in order to detect the WLAN APs that show up and perform appropriate vertical handovers, taking advantage of their lower energy consumption requirements. It is assumed that WLAN network scanning is only performed when the user is connected to the long range cellular network. Using the parameters summarized in Table I, we formulate a constraint optimization problem for the determination of the optimal network scanning period, t_s, with the aim to minimize the total energy consumption.

TABLE I.
DEFINITIONS OF THE ANALYTICAL FORMULATION PARAMETERS

Parameter	Definition
ρ	Access Point density (APs/m^2)
u	User speed (m/s)
R	WLAN cell radius (m)
t_s	Network scanning period (s)
d_s	Network scanning distance
d_w	WLAN coverage distance
d_m	Distance travelled under the macro cell coverage
d_{w_p}	Distance travelled under the WLAN coverage
d_{det}	Distance travelled until the detection of a WLAN, while being under WLAN coverage
t_{det}	Network detection delay
N_{scan}	Number of channel scans
E_p	Total energy consumption
E_{scan}	Energy consumption per network scan
N_m	Number of macro cell coverage areas the user moves across
N_w	Number of WLAN coverage areas the user moves across
P_m	Transmission power under the macro cell coverage
P_w	Transmission power under the WLAN coverage
λ_s	Average arrival rate of new APs (APs/s)
λ_m	Average arrival rate of new APs (APs/m)

In this scenario, the distance between consecutive WLAN APs, y, is assumed to follow a negative exponential distribution with rate parameter λ_m, having a probability density function $f(y) = \lambda_m e^{-\lambda_m y}$, and a cumulative distribution function $F(y) = 1 - e^{-\lambda_m y}$ [7]. Therefore, since the user is assumed to move with a constant speed u, the arrival of WLAN APs follows a Poisson distribution with rate parameter λ_s, according to which the probability of n AP arrivals in time t is defined as $P(n,t) = \frac{(\lambda_s t)^n e^{-\lambda_s t}}{n!}$. The AP arrival rate parameter λ_s depends on the radius R of a WLAN cell, the user speed u and the AP density ρ as follows: $\lambda_s \cong 2Ru\rho$ APs/s [3]. Consequently, the average arrival rate of new APs in distance is $\lambda_m = \lambda_s / u$ APs/m.

III. THE PROPOSED ANALYTICAL FRAMEWORK

A. Analytical Formulation of the Energy Consumption

Following the assumptions introduced in section II, the distance travelled under the macro cell coverage, d_m, depends on the network scanning period t_s, and the consequent network scanning distance $d_s = ut_s$, as shown in (1).

Therefore, the average distance travelled under the macro cell coverage is defined as follows:

$$\begin{aligned} E[d_m] &= \textstyle\sum_{n=1}^{\infty} n\, d_s P(0,(n-1)t_s)\big(1 - P(0,t_s)\big) = \\ &= \textstyle\sum_{n=1}^{\infty} n\, d_s e^{-\lambda_s (n-1) t_s}\big(1 - e^{-\lambda_s t_s}\big) = \\ &= d_s\big(1 - e^{-\lambda_s t_s}\big) \textstyle\sum_{n=1}^{\infty} n\, e^{-\lambda_s (n-1) t_s}. \end{aligned} \tag{2}$$

If a WLAN shows up while the user is still connected to another AP, the user can perform a horizontal handover to the new AP before he loses connectivity with the existing one. Therefore, the average WLAN coverage is defined as $d_w = 2R + d_{yw}$, where d_{yw} is defined in (3) and shown in Fig. 1.

The average WLAN coverage is defined in (4), where $E[y \mid y < 2R] = \frac{\int_0^{2R} y f(y) dy}{P(y<2R)} = \frac{-2Re^{-2R\lambda_m} + \frac{1}{\lambda_m} - \frac{1}{\lambda_m} e^{-2R\lambda_m}}{1 - e^{-2R\lambda_m}}$ [7], while $P(y < 2R) = F(2R) = 1 - e^{-2R\lambda_m}$ and $P(y > 2R) = 1 - F(2R) = e^{-2R\lambda_m}$.

The distance travelled until the detection of a WLAN, while being under WLAN coverage, d_{det}, depends on the WLAN cell radius, the network scanning distance and the inter-distance between consecutive APs, and is defined in (5).

Consequently, the average network detection distance is

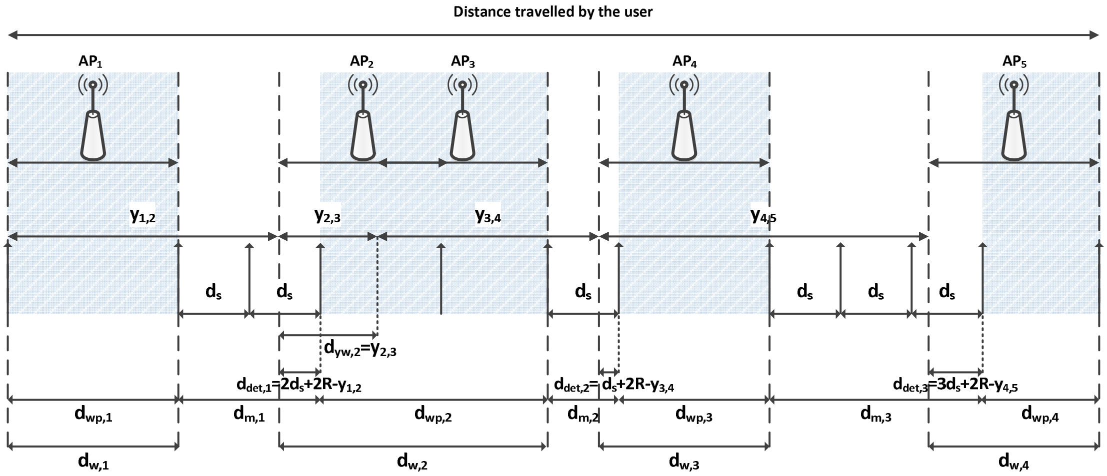

Figure 1. Periodic network scanning scenario. The shaded areas depict user connection to the closest WLAN AP

defined in (6), where $E[y > 2R] = \frac{\int_{2R}^{\infty} y f(y) dy}{P(y>2R)} = 2R + \frac{1}{\lambda_m}$ [7].

Therefore, based on (4) and (6), the average distance travelled under the WLAN coverage is

$$E\left[d_{w_p}\right] = E[d_w] - E[d_{det}]. \tag{7}$$

The average network detection delay t_{det}, i.e., the time during which the user is still connected to the macro cell although being in an area covered by a WLAN, is $E[t_{det}] = \frac{E[d_{det}]}{u}$.

The number of scans performed while the user is under the macro cell coverage depends on t_s, and is defined in (8).

Thus, the average number of scans is

$$\begin{aligned} E[N_{scan}] &= \textstyle\sum_{n=2}^{\infty} nP(0,(n-2)t_s)\big(1 - P(0,t_s)\big) = \\ &= \textstyle\sum_{n=2}^{\infty} n\, e^{-\lambda_s (n-2) t_s}\big(1 - e^{-\lambda_s t_s}\big) = \\ &= \big(1 - e^{-\lambda_s t_s}\big) \textstyle\sum_{n=2}^{\infty} n\, e^{-\lambda_s (n-2) t_s}. \end{aligned} \tag{9}$$

B. Network Scanning Period Optimization

Following the aforementioned definitions and equations (2), (7) and (9), the average energy consumption, both for data transmission and network scanning, is defined as follows:

$$E[E_p] = N_m P_m \frac{E[d_m]}{u} + N_w P_w \frac{E\left[d_{w_p}\right]}{u} + N_m E[N_{scan}] E_{scan} \tag{10}$$

Therefore, the problem of determining the optimal network scanning period with the aim to minimize the energy consumption can be formulated as follows:

$$\min_{t_s} E[E_p]$$

$$\text{subject to: } t_s \le \frac{2R}{u}$$

$$t_s \ge 0$$

The first constraint poses an upper bound on the network scanning period in order to guarantee that no WLAN AP opportunities are missed. Therefore, the maximum allowed network scanning period is equal to the time required to move across the coverage area of a single WLAN AP. The relaxation of this constraint, e.g., the energy consumption minimization subject to a guaranteed mis-detection probability, will be considered in our future work.

Fig. 2 depicts the optimal network scanning period with respect to an increasing number of freely accessible APs/km^2, ranging from very low to increased AP density [8], and an increasing user speed that ranges from pedestrian to vehicular. The parameters used for this calculation are the following: the transmission power under the macro cell coverage, P_m, is 250mW [9], while the transmission power under the WLAN coverage, P_w, is 100mW [10]. The WLAN cell radius, R, is 50m, while the energy consumption per network scan, E_{scan}, is 13.7mJ, assuming that the power consumption of a WLAN mobile terminal for network scanning is 1.37W [11], with a duration of each active scan to be 10ms [12]. N_m and N_w, i.e., the number of macro cell and WLAN coverage areas the user moves across, respectively, are equal to 1, as the optimization

---

$$d_m = \left\{\begin{array}{ll} d_s, & \text{at least 1 AP show up in first } t_s \\ 2d_s, & \text{no AP show up in first } t_s\text{, at least 1 AP show up in next } t_s \\ \vdots & \qquad\vdots \\ nds, & \text{no AP show up in first } (n-1)t_s\text{, at least 1 AP show up in next } t_s \\ \vdots & \qquad\vdots \end{array}\right\} \tag{1}$$

$$d_{yw} = \left\{\begin{array}{ll} y, & \text{user moves across the coverage of 1 more AP before entering the macro cell coverage} \\ 2y, & \text{user moves across the coverage of 2 more APs before entering the macro cell coverage} \\ \vdots & \qquad\vdots \\ ny, & \text{user moves across the coverage of } n \text{ more APs before entering the macro cell coverage} \\ \vdots & \qquad\vdots \end{array}\right\} \tag{3}$$

$$E[d_w] = 2R + E\left[d_{yw}\right] = 2R + \textstyle\sum_{n=0}^{\infty} nE[y \mid y < 2R]\, P(y < 2R)^n P(y > 2R) \tag{4}$$

$$d_{det} = \left\{\begin{array}{ll} d_s + 2R - y, & y > 2R\text{, at least 1 AP show up in first } t_s \\ 2d_s + 2R - y, & y > 2R\text{, no AP show up in first } t_s\text{, at least 1 AP show up in next } t_s \\ \quad\vdots & \qquad\vdots \\ nds + 2R - y, & y > 2R\text{, no AP show up in first } (n-1)t_s\text{, at least 1 AP show up in next } t_s \\ \quad\vdots & \qquad\vdots \end{array}\right\} \tag{5}$$

$$\begin{aligned} E[d_{det}] &= \textstyle\sum_{n=1}^{\infty} E[nd_s + 2R - y|y > 2R]\, P(0,(n-1)t_s)\big(1 - P(0,t_s)\big) = \\ &= \textstyle\sum_{n=1}^{\infty} nd_s + 2R - E[y|y > 2R]\, P(0,(n-1)t_s)\big(1 - P(0,t_s)\big) \\ &= \textstyle\sum_{n=1}^{\infty} (nd_s + 2R - E[y|y > 2R])\, e^{-\lambda_s (n-1) t_s}\big(1 - e^{-\lambda_s t_s}\big) = \\ &= \textstyle\sum_{n=1}^{\infty} \left(nd_s - \frac{1}{\lambda_m}\right) e^{-\lambda_s (n-1) t_s}\big(1 - e^{-\lambda_s t_s}\big) = \\ &= \big(1 - e^{-\lambda_s t_s}\big) \textstyle\sum_{n=1}^{\infty} \left(nd_s - \frac{1}{\lambda_m}\right) e^{-\lambda_s (n-1) t_s} \end{aligned} \tag{6}$$

$$N_{scan} = \left\{\begin{array}{ll} 2, & \text{at least 1 AP show up in first } t_s \\ 3, & \text{no AP show up in first } t_s\text{, at least 1 AP show up in next } t_s \\ \vdots & \qquad\vdots \\ n, & \text{no AP show up in first } (n-2)t_s\text{, at least 1 AP show up in next } t_s \\ \vdots & \qquad\vdots \end{array}\right\} \tag{8}$$

of the network scanning period does not depend on N_m and N_w. The optimal scanning period in each case was calculated with the use of Matlab [13] that calculates the minimum of a single-variable function on a fixed interval using an algorithm based on Golden Section Search and Parabolic Interpolation. As it can be seen, the optimal network scanning period follows a declining course with the increase of the AP density and the increase of the user speed, as, in both cases, the new WLAN APs appear more frequently and the user has to perform network scanning more often in order to discover them and take advantage of the lower energy consumption opportunities they offer.

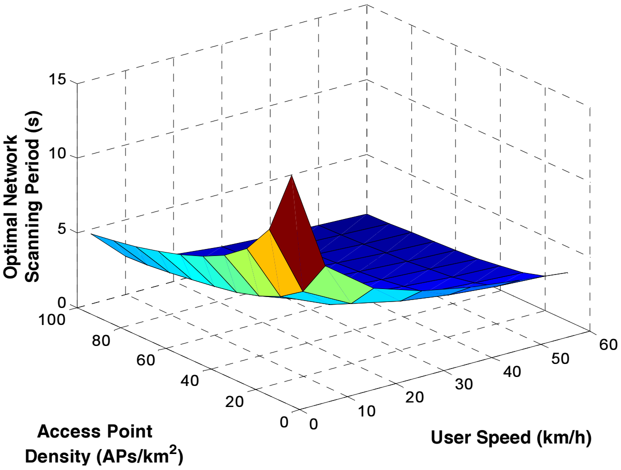

Figure 2. Optimal network scanning period versus the user speed and the AP density

IV. PERFORMANCE EVALUATION

To evaluate the performance of the proposed algorithm, the energy consumption for data transmission and network scanning, as well as the network detection delay with respect to the AP arrival rate, were calculated in five different cases, i.e., optimal network scanning period t_s, and constant, sub-optimal t_s equal to 1-4s, respectively. In all cases, the user is moving with a constant speed of 30km/h. The results derived from the analytical formulation are also verified through simulation.

The simulation model used for the verification of the theoretical results was constructed in C++, and implements the scenario of a user moving along a road covered by consecutive, non-overlapping, long range LTE networks, and a variable number of WLAN APs. Each LTE network has a radius R_{LTE} of 500m, while the inter-distance between WLAN APs follows a negative exponential distribution with a rate parameter λ_s that depends on the WLAN radius, the AP density and the user speed, as described in section II. The values of the transmission power under the macro cell coverage P_m, the transmission power under the WLAN coverage P_w, the WLAN cell radius R and the energy consumption per network scan E_{scan}, are the ones used for the evaluation of the analytical framework performance in section III.B. In each case, 4000 simulation runs were executed in order to achieve statistical accuracy. As a result, in all cases, the 95% Confidence Interval (CI) lies within less than 0.43% of the respective average values.

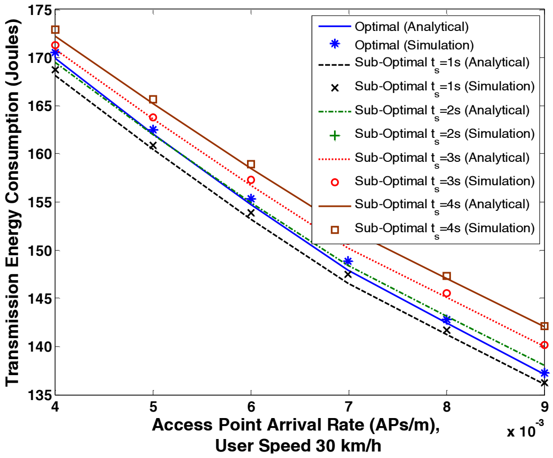

Figure 3. Energy consumption for data transmission versus the AP arrival rate

Fig. 3 depicts the transmission energy consumption versus an increasing average AP arrival rate, λ_m, which, in a two dimensional space, corresponds to AP densities ranging from 40 to 90 APs/km^2. The transmission energy consumption decreases with the increase of λ_m, as a result of the increased opportunities of a user to perform vertical handovers to the lower energy consuming WLANs that appear more often. The use of the optimal t_s results in lower transmission energy consumption compared to most of the sub-optimal systems, with the only exception of the 1s scanning period.

Fig. 4 depicts the energy consumption for network scanning, versus the AP arrival rate for all the systems under consideration. As it can be seen, the network scanning energy consumption of the system that uses the optimal t_s is slightly higher compared to most of the sub-optimal systems. However, this is the price to pay in order to detect the available neighboring networks in time and achieve the reduction of the total energy consumption. It can also be seen that the system that performs network scanning every 1s results in considerably increased network discovery energy consumption.

The total energy consumption versus the AP arrival rate is

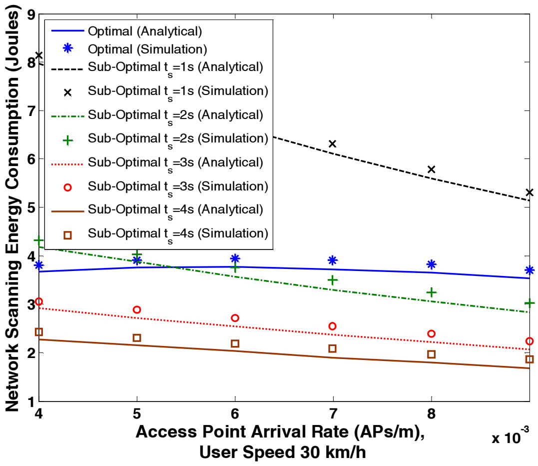

Figure 4. Energy consumption for network scanning versus the AP arrival rate

shown in Fig. 5. In both cases, the proposed system results in the lowest total energy consumption compared to all the sub-optimal systems. It should be noted that although the system that performs network scanning with 1s period has the lowest transmission energy consumption, due to the earlier detection of available WLANs, it results in increased total energy consumption, especially in cases of low λ_m due to the increased network discovery energy consumption. Similarly, the system that employs the 4s network scanning period also results in increased total energy consumption, especially in cases of increased λ_m, when APs appear more often and the 4s network scanning period is not enough to detect them early.

The average network detection delay versus the AP arrival rate for all systems under consideration is shown in Fig. 6. $E[d_{det}]$ increases with the increase of t_s all sub-optimal systems. The use of the optimal t_s achieves considerable reduction of the network detection delay compared to the 2-4s period sub-optimal systems for increased AP arrival rates. As expected, the 1s network scanning period results in the lowest network detection delay. However, as seen in Fig. 5, this also results in increased total energy consumption.

V. CONCLUSION

In this paper, we introduced an analytical framework for the improvement of the energy efficiency of the network discovery procedure and WLAN offloading in a vehicular scenario, through the optimization of the network scanning period. The performance of the system employing the optimal network discovery period was compared against a system that performs periodic network scanning in a sub-optimal manner. According to performance evaluation results, the network scanning period optimization allows a user to reduce its energy consumption and the network detection delay. Our plans for future work include self-optimization (SON) mechanisms to optimize the scanning period in an online manner without requiring prior knowledge of the AP density information.

ACKNOWLEDGMENT

This paper has been supported by the ICT-ACROPOLIS Network of Excellence, FP7 project number 257626. The views expressed are those of the authors and not necessarily reflective of the views of the ACROPOLIS consortium. The authors would like to thank all members of the ACROPOLIS consortium for their work, some of which is reflected in this paper.

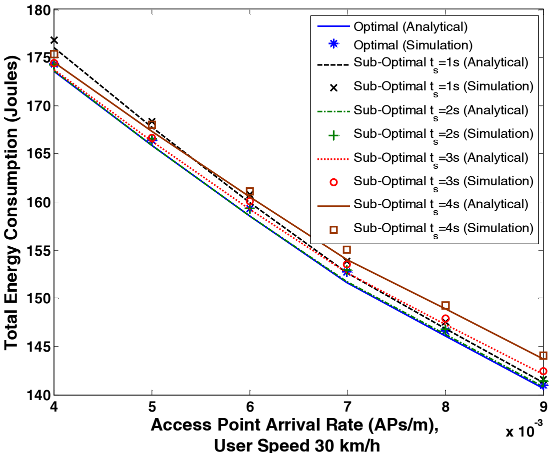

Figure 5. Total energy consumption versus the AP arrival rate

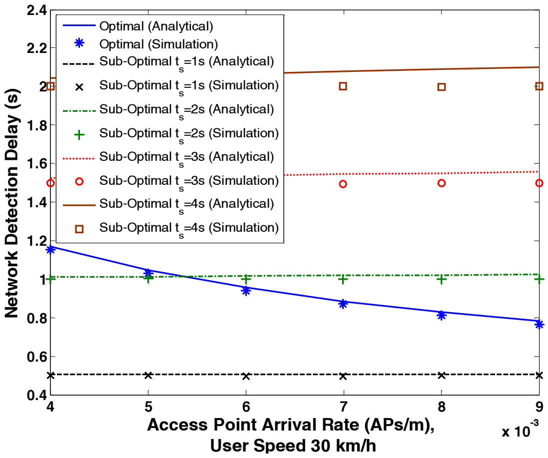

Figure 6. Network detection delay versus the AP arrival rate

REFERENCES

[1] *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*, IEEE Std. 802.11-2012, March 2012.

[2] S. Dimatteo, P. Hui, B. Han, V.O.K. Li, “Cellular Traffic Offloading through WiFi Networks”, in *IEEE 8th Int. Conf. on Mobile Adhoc and Sensor Systems (MASS)*, Valencia, 2011, pp.192-201.

[3] K.H. Kim, A.W. Min, D. Gupta, P. Mohapatra, J.P. Singh, “Improving energy efficiency of Wi-Fi sensing on smartphones”, in *IEEE Int. Conf. on Computer Communications (INFOCOM)*, Shanghai, 2011, pp.2930-2938.

[4] K. Doppler, C.B. Ribeiro, J. Kneckt, “On efficient discovery of next generation local area networks”, in *IEEE Wireless Communications and Networking Conf. (WCNC)*, Cancun, Quintana-Roo, 2011, pp.269-274.

[5] D. Triantafyllopoulou, T. Guo, K. Moessner, “Energy Efficient ANDSF-assisted Network Discovery for non-3GPP Access Networks”, in *IEEE Int. Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD)*, Barcelona, 2012, pp.297-301.

[6] 3GPP TS 36.912, V11.0.0 (2012-09): Feasibility study for Further Advancements for E-UTRA (LTE-Advanced); (Release 11).

[7] K. Shafiee, A. Attar, V.C.M. Leung, “Optimal Distributed Vertical Handoff Strategies in Vehicular Heterogeneous Networks”, *IEEE Journal on Selected Areas in Communications*, vol.29, no.3, pp.534-544, March 2011.

[8] R. Schwartz, M. Johansson, “Carrier WiFi Offload, Building a Business Case for Carrier WiFi Offload”, Wireless 20/20, March 2012.

[9] F.D. Calabrese, C. Rosa, M. Anas, P.H. Michaelsen, K.I. Pedersen, P.E. Mogensen, “Adaptive Transmission Bandwidth Based Packet Scheduling for LTE Uplink”, in *IEEE 68th Vehicular Technology Conf. (VTC-Fall)*, Calgary, 2008, pp.1-5.

[10] J. Wang, S. Filin, T. Baykas, M.A. Rahman, C. Song, H. Harada, “A feasible neighbor discovery algorithm for coexistence control system over TVWS”, in *IEEE Wireless Communications and Networking Conf. (WCNC)*, Paris, 2012, pp.3244-3248.

[11] M.B. Kjasrgaard, “Location-based services on mobile phones: minimizing power consumption”, *IEEE Pervasive Computing*, vol.11, no.1, pp.67-73, Jan.-Mar. 2012.

[12] “Voice over Wireless LAN 4.1 Design Guide”, Cisco Validated Design I, Jan. 2010.

[13] Mathworks Matlab, http://www.mathworks.co.uk/products/matlab/.