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 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.

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Optimal Network Discovery Period for Energy-Efficient WLAN Offloading

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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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>Access Point density (APs/m$^2$)</td>
</tr>
<tr>
<td>$u$</td>
<td>User speed (m/s)</td>
</tr>
<tr>
<td>$R$</td>
<td>WLAN cell radius (m)</td>
</tr>
<tr>
<td>$t_s$</td>
<td>Network scanning period (s)</td>
</tr>
<tr>
<td>$d_s$</td>
<td>Network scanning distance</td>
</tr>
<tr>
<td>$d_w$</td>
<td>WLAN coverage distance</td>
</tr>
<tr>
<td>$d_m$</td>
<td>Distance travelled under the macro cell coverage</td>
</tr>
<tr>
<td>$d_{det}$</td>
<td>Distance travelled until the detection of a WLAN, while being under WLAN coverage</td>
</tr>
<tr>
<td>$E_{en}$</td>
<td>Total energy consumption</td>
</tr>
<tr>
<td>$E_{scm}$</td>
<td>Energy consumption per network scan</td>
</tr>
<tr>
<td>$N_m$</td>
<td>Number of macro cell coverage areas the user moves across</td>
</tr>
<tr>
<td>$N_w$</td>
<td>Number of WLAN coverage areas the user moves across</td>
</tr>
<tr>
<td>$P_{sc}$</td>
<td>Transmission power under the macro cell coverage</td>
</tr>
<tr>
<td>$P_w$</td>
<td>Transmission power under the WLAN coverage</td>
</tr>
<tr>
<td>$\lambda_m$</td>
<td>Average arrival rate of new APs (APs/s)</td>
</tr>
<tr>
<td>$\lambda_w$</td>
<td>Average arrival rate of new APs (APs/m)</td>
</tr>
</tbody>
</table>

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

$$E[d_m] = \sum_{n=1}^{\infty} n d_s P(0,(n-1)t_s)(1 - P(0,t_s)) = \sum_{n=1}^{\infty} n d_s e^{-\lambda_w(n-1)t_s}(1 - e^{-\lambda_w t_s}) = d_s(1 - e^{-\lambda_w t_s}) \sum_{n=1}^{\infty} n e^{-\lambda_w(n-1)t_s}$$  \hspace{1cm} (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

$$E[y | y < 2R] = \int_{0}^{2R} y f(y) dy / P(y < 2R) = \frac{-2R e^{-2R\lambda_m} + \frac{1}{\lambda_m} e^{-2R\lambda_m}}{1 - e^{-2R\lambda_m}}$$  \hspace{1cm} (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...
defined in (6), where \( E[y > 2R] = \int_{2R}^{\infty} y f(y) dy / P(y > 2R) = 2R + \frac{1}{\lambda_m} \) [7].

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

\[
E[d_{w}] = E[d_{w}^{\prime}] - E[d_{det}].
\]

(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

\[
E[N_{\text{scan}}] = \sum_{n=2}^{\infty} n P(0, (n - 2)t_{s})(1 - P(0, t_{s})) = \sum_{n=2}^{\infty} n e^{-\lambda_{s}(n-2)t_{s}} (1 - e^{-\lambda_{s}t_{s}}) = (1 - e^{-\lambda_{s}t_{s}}) \sum_{n=2}^{\infty} n e^{-\lambda_{s}(n-2)t_{s}}.
\]

(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:

\[
E[E_{p}] = N_{m} P_{m} \frac{E[d_{w}]}{u} + N_{w} P_{w} \frac{E[d_{w}^{\prime}]}{u} + N_{m} E[N_{\text{scan}}] E_{\text{scan}}
\]

(10)

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

\[
\min \bar{E}[E_{p}]
\]

subject to: \( t_{s} \leq \frac{2R}{u} \)

\( t_{s} \geq 0 \)

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/km², 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, \( E_{\text{scan}} \), 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...
of the network scanning period does not depend on $N_m$ and $N_p$. 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](image)

**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 $\lambda_2$ 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 $P_s$, 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](image)

Fig. 3 depicts the transmission energy consumption versus an increasing average AP arrival rate, $\lambda_m$, 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 $\lambda_m$, 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.

![Figure 4. Energy consumption for network scanning versus the AP arrival rate](image)

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
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 $\lambda_m$ 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 $\lambda_m$, 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.

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REFERENCES


Figure 5. Total energy consumption versus the AP arrival rate for all systems under consideration

Figure 6. Network detection delay versus the AP arrival rate