Power-Efficient Interface Selection Scheme using Paging of WWAN for WLAN in Heterogeneous Wireless Networks

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Abstract— **In heterogeneous wireless networks, there have been several efforts aimed at having mobile devices equipped with multiple interfaces connect optimally to the access network that minimizes their power consumption. However, a study of existing schemes notes that in the idle state, a device with both a WLAN and a WWAN interface need to keep both interfaces "on" in order to receive periodic beacon messages from the AP (WLAN) and downlink control information from the base station (WWAN), resulting in significant power consumption. Therefore, in this paper, we propose a Power-efficient Communication Protocol that includes turning off the WLAN interface after it enters the idle state and using the existing paging of WWAN in order to wake up the WLAN interface when there is incoming long-lived multimedia data.**

Further, we propose turning on the WLAN interface when the number of packets in the radio network controller's buffer reaches a certain threshold level in order to avoid repeatedly turning on and off WLAN interfaces, that consumes a significant amount of power. The tradeoffs between the power saving and the number of packets dropped at the buffer are investigated analytically. Simulation results for scenarios of interest are also provided.

I. INTRODUCTION

Most recently, a significant number of telecommunication carriers are migrating towards heterogeneous wireless networks where Wireless Local Area Networks (WLANs) based on IEEE 802.11 standards and third-generation Wireless Wide Area Networks (3G WWANs) such as CDMA2000 and UMTS are interconnected in order to offer Internet access to end users with better Quality of Service (QoS). These trends are set by the well-known fact that the two technologies have characteristics that complement each other perfectly. However, before a cost-effective and seamless integration of heterogeneous wireless networks is realized, a number of issues have to be resolved. There are several research and standards group activities including the recently formed IEEE 802.21 Working Group focused on this integration of networks.

In particular, since most mobile terminals are battery powered, it is a challenge to design new techniques that allow mobile terminals to maintain their active connection as they move across different types of wireless networks, that is known as "vertical handoff", while minimizing their power consumption [1]. There have been several efforts aimed at having mobile devices equipped with multiple interfaces, switch their connection to the access network that provides the best coverage. The authors of [1] introduced several performance metrics that can be used in the handoff decision. In [2], various network layer based inter-network handover techniques are evaluated for a realistic heterogeneous network testbed . As for a potential integration architecture for WLAN and 3G WWAN, the authors of [3] describe a loosely-coupled architecture in the form of an IEEE 802.11 gateway and a corresponding service access client software.

Here, it is worth mentioning that a large portion of the power consumption in a wireless interface corresponds to the power consumed while the interface is idle. In most existing vertical handoff management schemes [1]-[2], a mobile node must turn on both WLAN and WWAN interfaces even in the idle state in time to receive the periodic beacon signals from the AP and the signal through the downlink Paging Channel (PCH) from the Base Station (BS), resulting in significant power consumption.

Therefore, in this paper, we propose a Power-efficient Communication Protocol (PCP) for heterogeneous wireless networks. This scheme assumes that if a certain time expires just after the WLAN interface enters the idle state, the interface is turned off without any periodic wake-up. In the remainder of this paper, this state will be referred to as the "inactive state". In addition, we use the existing paging in cellular networks in order to turn on the WLAN interface due to incoming data from long-lived multimedia traffic. Our goal is to keep the WLAN interface, which consumes a significant amount of power in the idle mode, off for a longer period of time. Therefore, we propose using the relatively lower-power PCH for waking up the WLAN interface on an as-needed basis. If the WLAN interface spends considerable amount of time in the idle state, as in the case of Internet access and long multimedia downloads, there are obvious benefits for entering the inactive state and limiting the power consumption.

Further, our proposed scheme is designed to avoid repeatedly turning on and off WLAN interfaces, that consumes a significant amount of power. We propose turning on the WLAN interface when the number of packets in the Radio Network Controller (RNC)'s buffer reaches a certain threshold level.

The remainder of this article is structured as follows. Section II discusses the proposed PCP in details. Section III provides an analysis of the power consumption during non-communication state for a typical WLAN node, as well as the proposed PCP. Section IV provides simulation results and a discussion of the results. Conclusions are offered in Section V.

II. POWER-EFFICIENT COMMUNICATION PROTOCOL

When connected to the WLAN, a WLAN interface card is usually in the idle mode for around 70% of the overall time excluding the time during which the interface is turned off [4]. Moreover, the power consumption level for a WLAN interface is greater (usually, more than 10 times greater) than a WWAN interface, with and without power saving.

Each cell in a WWAN may contain more than one WLAN hot spot because the service area of a BS is generally larger than that of a WLAN hot spot. Thus, in the idle state, the WWAN interface is assumed to listen continuously to the PCH to detect messages directed to all the APs in its cell in addition to the messages addressed to it. This assumption is valid since the WWAN interface has to support the operation of frequent traffic (e.g. Multimedia Messaging Service) compared with data traffic in WLAN.

Our proposed PCP scheme aims at limiting the WLAN power consumption, where the WLAN interface is made to consume power only when transmitting or receiving data. This is accomplished by turning off the WLAN interface without any periodic wake-up during the idle period. The proposed PCP scheme modifies the WLAN interface state machine as follows:

- Communication state: WLAN interface sends or/and receives data.
- Non-communication state: WLAN interface goes to this state when the data session is complete.

Note that this state corresponds to the idle state in a typical WLAN system and to an inactive state in the proposed PCP scheme.

We focus on downlink traffic since it is envisioned that fourth generation wireless system's traffic patterns will be highly asymmetrical.Next, we explain the procedures that are executed by the WLAN interface in both states described above for downlink traffic. Note, we only show the procedures that need to be implemented in support of PCP.

According to the PCP system, the PCH of a cellular network is utilized to provide information about all APs in its current cell. We assume that the Serving GPRS Support Node (SGSN) (or the Packet Control Function (PCF) in CDMA) can acquire the IP addresses and Service Set Identifiers (SSIDs) of all APs in its coverage area. In the PCP system, the IEEE 802.11 gateways serving the APs have a direct link to the SGSN either when the BSs are initialized or when APs are installed in the SGSN coverage area. Thus, the SSID and the MAC address of each AP in a 802.11 access network are registered with the corresponding SGSN during the initialization phase of the BS.

In a 3GPP system, the RNC is responsible for controlling user traffic between a user and the core network with buffers for different users [5]. Our PCP scheme uses a similar approach. Thus, for downlink transmission, the BS notifies the mobile node when the number of packets in a per-user-buffer at the RNC [5] reaches a certain threshold n (usually, less than the maximum buffer size) so that the mobile node does not consume its power due to frequent turn-on and off actions. The steps of our mechanism for signaling the presence of downlink data are illustrated in Fig. 1 and include the following:

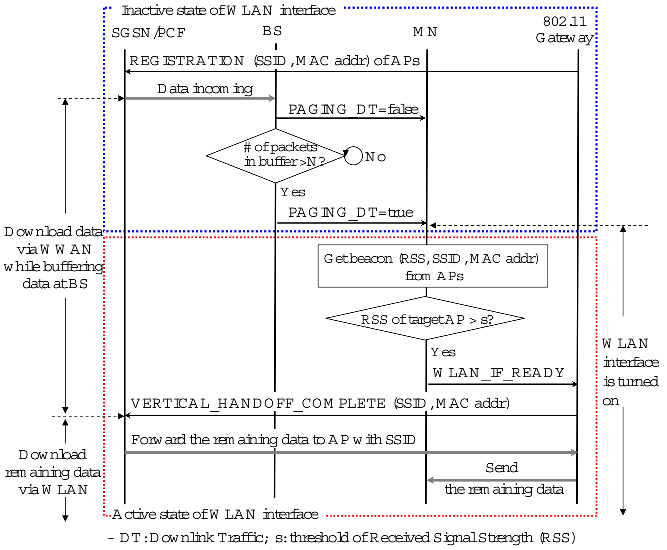


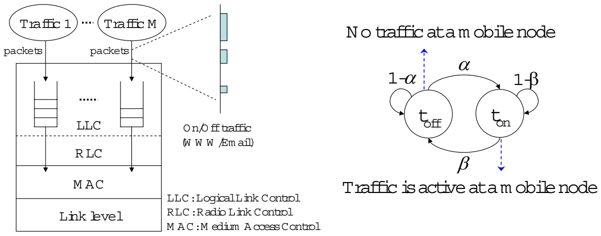
Fig. 1. Signaling procedure when the WLAN interface goes from the inactive state to the communication state to receive downlink traffic

- Step 1: For downlink transmissions, data traffic comes into a per-user-buffer at the RNC when the mobile node's WLAN interface is in the inactive state. Once the number of packets in the buffer reaches a threshold n, the BS notifies the mobile node about the existence of downlink data by sending a paging message (PAGING_DT=*true*) on the PCH.
- Step 2: Upon receiving the notification, the WLAN interface is turned on (i.e. it goes to the communication state) and an available AP is found. If no APs are found, the data transmission continues on the WWAN link.
- Step 3: The mobile node sends a WLAN_IF_READY message to the corresponding 802.11 gateway while receiving the incoming data through the WWAN.
- Step 4: Upon receiving the WLAN_IF_READY, the 802.11 gateway sends a VERTICAL_HANDOFF_COM PLETE message to the SGSN, which includes the SSID and MAC address of the AP selected for the mobile node.
- Step 5: Once the SGSN receives the VERTICAL_HANDOFF_COMPLETE, it starts to forward the remaining data to the 802.11 gateway instead of to the BS.
- Step 6: The 802.11 gateway transmits the remaining data received from the SGSN to the mobile node.

Note that in our PCP system, the RNC keeps forwarding data on the WWAN interface while the WLAN interface is being turned on.

III. AN ANALYTICAL MODEL OF THE PCP SCHEME AND NUMERICAL RESULTS

Typically, users' packets are separated into different buffers at the RNC [5] since the BS simultaneously serves a number of users. A scheduler implemented at the BS selects the optimal user to transmit to at every transmission opportunity [6], as illustrated in Fig. 2 (a). Even though one buffer memory can be shared for all users, different thresholds can be set for each buffer.



(a) Downlink traffic at BS (b) Downlink On/Off traffic

Fig. 2. (a) A simplified schematic view of RNC/BS where downlink traffics from different users are scheduled into the buffers which are located higher up in the RLC layer in the RNC (b) Application downlink traffic sessions have On/Off behavior

To investigate the performance of our proposed PCP system, we now develop an analytical model considering the per-user-buffer at the RNC as a queueing system while also considering the power on/off state of the WLAN interface.

As far as traffic patterns are concerned, the WLAN system can be characterized by an on/off behavior as can be seen in Fig 2 (b) [7]. For example, for a web page transfer, a mobile node alternates between on period, t_{on} during which a set of web pages is downloaded as part of an application session and, off period, t_{off} during which there is no traffic due to the thinking time. From Fig. 2, the probabilities of a mobile node being in t_{on} and of a mobile node being in t_{off} are given by $p_{t_{\text{on}}} = \frac{\alpha}{\alpha+\beta}$ and $p_{t_{\text{off}}} = \frac{\beta}{\alpha+\beta}$, respectively. Let both on and off periods have an exponential distribution with mean β^{-1} and α^{-1}, respectively. During the t_{on} period, we assume that traffic arrives with a Poisson distribution of mean λ and that each mobile user has only one TCP session active at a time using WWAN.

Now, we investigate the buffer size along with the power consumption of the WLAN interface. Let N be the maximum number of packets allowed in a per-user-buffer at the RNC (i.e. buffer size). If we set the threshold n to the burst size, N, in Fig. 2 (b), the arrival process to each buffer at the RNC can be modeled as an Interrupted Bernoulli Process (IBP). First, to analyze the buffer under our proposed PCP with $n = N$, we note that during t_{off} period, the buffer contents must be zero. When the state of the buffer at the RNC first makes a transition to the t_{on} state, for each subsequent transition to the same t_{on} state, a packet arrives in the buffer with mean λ. At the same time, the contents of the buffer are transmitted to the mobile node through the WWAN interface with mean rate μ until the BS wakes up the corresponding WLAN interface.

Therefore, we are able to construct a Markov chain model for the per-user-buffer at the RNC as shown in Fig 3. If we denote by p_i the steady-state probability that the buffer contains i packets, then it is easy to show that the steady-state probabilities are given by

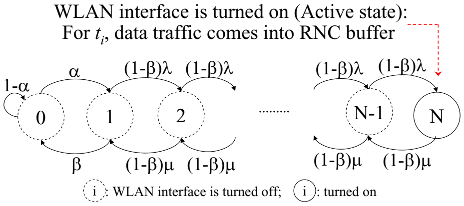


Fig. 3. State transition diagram for PCP with $n = N$ where WLAN interface is turned on from inactive state once the number of packets becomes N in the buffer of RNC

$$p_0 = p_{t_{\text{off}}} \tag{1}$$

$$\alpha p_0 = \beta p_1 \tag{2}$$

$$\alpha p_0 + (1-\beta)\mu p_2 = (1-\beta)\lambda p_1 + \beta p_1 \tag{3}$$

$$\lambda p_{i-1} + \mu p_{i+1} = (\lambda + \mu) p_i \qquad 2 \le i \le N-2 \tag{4}$$

Let x and t_i denote the time elapsed from the moment when the WLAN interface is turned on and the time taken to initialize the WLAN, respectively. Since $p_0 = \frac{\beta}{\alpha+\beta}$, from Eqs. 2-4, the rate at which the WLAN interface is turned on from the inactive state is given by

$$\begin{aligned} p_{on}^{(N)} &= (1-\beta)\lambda p_{N-1}(1-(1-\beta)\mu p_N)u(x) \\ &= \frac{\alpha(1-\beta)\lambda\rho^{N-2}}{\alpha+\beta}\left(1 - \frac{\alpha(1-\beta)\lambda\rho^{N-2}}{\alpha+\beta}\right)u(x) \end{aligned} \tag{5}$$

where $u(x) = \begin{cases} 1 & t_i - x > 0 \\ 0 & t_i - x \le 0 \end{cases}$ and $\rho = \frac{\lambda}{\mu}$. Thus, it can be easily known from the case of $n = N$ that the rate at which the WLAN interface is turned on with $n = k$ becomes $p_{on}^{(k)} = (1-\beta)\lambda p_{k-1}(1-(1-\beta)\mu p_k)u(x) = \frac{\alpha(1-\beta)\lambda\rho^{k-2}}{\alpha+\beta}(1 - \frac{\alpha(1-\beta)\lambda\rho^{k-2}}{\alpha+\beta})u(x)$.

While the WLAN interface is being initialized, the SGSN sends data packets through the WWAN interface. Although this is a form of soft handoff, packets can still be dropped when the RNC buffer becomes full. This depends on the SGSN data rate and the size of the buffer at the RNC. When the buffer size is N, i.e. PCP with $n = N$, the number of packets dropped is

$$\begin{aligned} d^{(N)} =& (1-\beta)\lambda p_N v(x) \\ =& \frac{\alpha(1-\beta)\lambda\rho^{N-1}}{\alpha+\beta} v(x). \end{aligned} \tag{6}$$

where $v(x) = \begin{cases} x & t_i - x > 0 \\ t_i & t_i - x \le 0 \end{cases}$. Here, we note that the RNC layer may control the SGSN data rate and the buffer size may be set to be greater than the TCP window size [5] in order to prevent data packets from being dropped For PCP with $n = k$ ($k < N$), once the buffer has k packets, a vertical handoff to the WLAN is initiated, so that it is less likely that a packet is dropped than with $n = N$.

For PCP with $n = 1$, the rate at which the WLAN interface is turned on from the inactive state can be expressed as $p_{on}^{(1)} = \alpha p_0 = \frac{\alpha\beta}{\alpha+\beta}$.

As for the packet drop probability, if the initialization of the WLAN interface is over before the buffer at the RNC has N packets, we assume that there are no packets dropped at the RNC (the case where a packet is dropped after a vertical handoff to the WLAN has occurred is not considered). This signifies that $d^{(1)} = 0$ under the condition that $\rho \times t_i \ll N$.

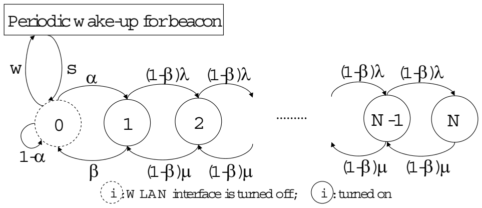


Fig. 4. State transition diagram for WLAN interface and AP buffer when PCP is not applied

Here, we compute the expected number of packets at the RNC buffer as

$$
\begin{aligned}
E[i] &= \sum_{i=0}^{N} i p_i \\
&= \frac{\alpha}{\alpha+\beta}\left\{\frac{1-\rho^N}{(1-\rho)^2} - \frac{N\rho^N}{(1-\rho)}\right\}
\end{aligned}
\tag{7}
$$

which is independent of the value of n. Consider a traffic flow such that $E[i] \ll N$, or in other words the traffic is light and lasts for a short period of time (e.g. Multimedia Messaging Service, voice-email and etc), then it is better to use the WWAN since more power is consumed when frequently turning on and off the WLAN interface under PCP with $n = 1$. However, for the case where $E[i]$ is closer to N, PCP with $n = 1$ achieves better results than PCP with $n = N$ in terms of reducing the number of packets dropped.

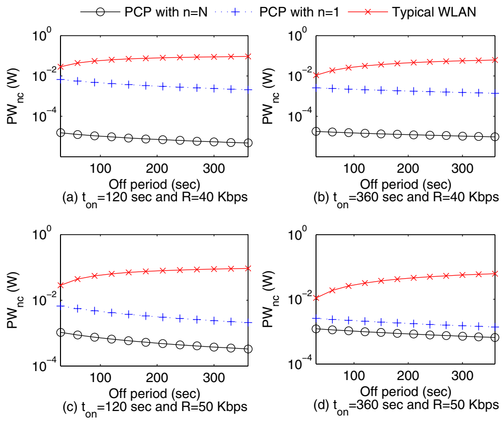
In the so-called "*idle with power saving*" mode in commercial off-the-shelf WLAN cards, the WLAN interface must wake up periodically to receive regular beacons coming from the AP. Let w and s denote the wake-up rate during the idle state and the sleep rate during the idle state after receiving the beacon signals from the AP, respectively. Both w and s are fixed as illustrated in Fig. 4. Then, for the *idle with power saving* mode, the rate at which WLAN interface is turned on, can be characterized as follows:

$$
\begin{aligned}
p_{on}^{\text{w/o PCP}} &= (\alpha + (1-\alpha)\frac{w}{w+s})p_0 \\
&= \frac{(w+s\alpha)\beta}{(w+s)(\alpha+\beta)}
\end{aligned}
\tag{8}
$$

where if the size of the AP buffer is equal to the same as the RNC buffer, the number of packets dropped is also the same as for PCP with $n = 1$.

Now we can compute the average power consumed for a non-communication state during a unit time t. Let C_i and C_d be the power consumed for receiving beacon/data and the baseline power consumption in the idle state, respectively. Let C_{ia} be the power consumption due to waking up from the inactive state to receive incoming data which is vertically handed off from the WWAN. For PCP, there is no baseline power consumption since the mobile node goes to the inactive state when not transmitting data. Then, in the non-communication state, the average power-consumption during time t is

$$
PW_{nc} = \begin{cases} (C_i P_{on}^{\text{w/o PCP}} + C_d p_0)t & \text{for typical WLAN} \\ C_{ia} P_{on}^{(k)} t & \text{for PCP with } n = k \end{cases}
\tag{9}
$$



(a) t_{on}=120 sec and R=40 Kbps

(b) t_{on}=360 sec and R=40 Kbps

(c) t_{on}=120 sec and R=50 Kbps

(d) t_{on}=360 sec and R=50 Kbps

Fig. 5. Average power consumption for non-communication state for varying off periods

where, in general, C_{ia} is known to be greater than C_i, so that C_i and C_{ia} are set to 0.68W and 1W, respectively while C_d is assumed to be equal to 0.06W.

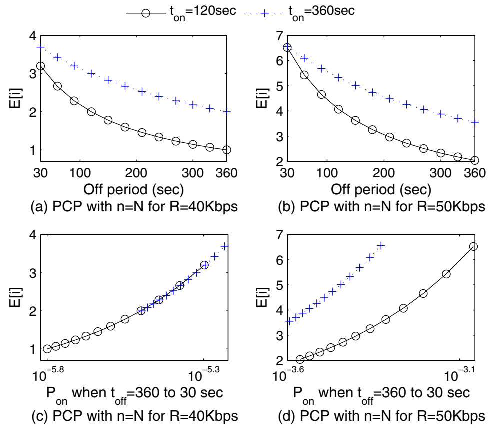
To obtain some simulation (refer to section IV) as well as numerical results, we assume that during the on period, the downlink transmission rate to the mobile node is 80 Kbps which is an upper bound on the rate achievable by a 4-downlink slot GPRS mobile node, and t_{on} is set to either 120 or 360 s. We also assume that the initialization time for the WLAN interface, t_i is 1s and the buffer size, L_b, is set to 20 Kbytes.

For a typical WLAN interface with power saving mode, beacons are only sent at fixed intervals and typical values are in the order of 100 ms Thus, the beacon period, s^{-1} is set to 100 ms. We assume that the WLAN interface does not have to stay awake after the beacon reception. Let L_{BEACON} be the length of the beacon management frame assumed to be about fifty bytes long. Then, the processing time for a beacon message, $1/w$ is expressed as $\frac{L_{\text{beacon}}}{B} + \textit{processing\_time\_at\_interface}$ where B is the channel bit rate.

In Figs. 5 (a) and (b), and Figs. 5 (c) and (d), the average power consumed by the WLAN interface for the non-communication state, PW_{nc}, is plotted as a function of the off period ranging from 30 to 360 s for $R = 40$ and 50 Kbps, where R denotes the data rate to the BS during t_{on} with a packet size equal to 1000 bytes.

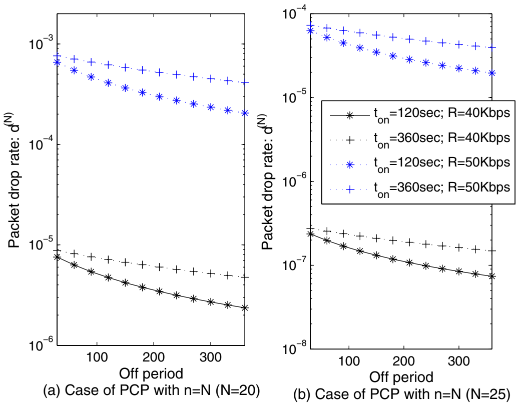
From the graphs in Fig. 5, we observe that the average power consumption for the non-communication state obtained with a typical WLAN system is higher than the proposed PCP system, and the power consumption for PCP with $n = N$ is lower than PCP with $n = 1$ over all ranges of off period considered for $R = 40$ Kbps and 50 Kbps. More specifically, when $t_{\text{on}} = 120$ s, the power consumption is reduced by 99.8% and 84.2% for $R = 40$ and 50 Kbps respectively. Similarly when $t_{\text{on}} = 360$ s, the power consumption is reduced by 99.3% and 52.5% for $R = 40$ and 50 Kbps, respectively.

During the same active period, the higher the data rate gets, the higher the power consumed for a non-communication state of PCP with $n = N$ since the buffer is filled at a higher rate.



(a) PCP with n=N for R=40Kbps (b) PCP with n=N for R=50Kbps (c) PCP with n=N for R=40Kbps (d) PCP with n=N for R=50Kbps

Fig. 6. The average number of packets in the buffer at RNC for varying off period and power-on rate when $t_{\mathrm{on}} = 120$ and 360 s



(a) Case of PCP with n=N (N=20) (b) Case of PCP with n=N (N=25)

Fig. 7. Packet drop rate at the RNC buffer for varying off period when threshold $n = N$ (i.e. the worst case of packet dropping for PCP)

In Figs. 5 (a)-(d), we note that in terms of power consumption, the above observed performance improvements are still valid, independent of the active period length (120 and 360 s).

Fig. 6(a) and (b) show the average number of packets in the RNC buffer during a vertical handoff to WLAN. We observe that as the off period increases, the average number of packets in the buffer decreases. Thus for a smaller off period, the difference between the average number of packets in the buffer is also smaller for both active period intervals ($t_{\mathrm{on}} = 120$ and 360 s). The curves in Figs. 6 (c) and (d) indicate that as the number of packets in the buffer increases, the power-on rate of WLAN interface increases as well. It is expected that the increasing number of packets in the buffer means that a predefined value of the threshold n is reached faster according to the proposed PCP scheme. In Fig. 7 and Fig. 5, we observe that PCP with $n = N$ achieves a better performance in terms of power consumed for a non-communication state at the cost of a higher packet drop rate compared with PCP with $n = 1$. However, note that for PCP with $n = N$, the power consumption is about couple of orders of magnitude lower than for PCP with $n = 1$.

Setting the threshold n to $k < N$ makes the proposed PCP achieve a lower packet drop rate and the cost of a higher power consumption than PCP with $n = N$ (Fig. 7(b)). Thus, the value of the threshold, n $(1 \leq n \leq N)$ has a significant impact on the power consumption and the packet drop rate.

IV. PERFORMANCE EVALUATION THROUGH SIMULATION

We compare the performance of the proposed PCP with a typical WLAN system with periodic wake-up in the idle state, in terms of power consumption for the non-communication state and the amount of data lost due to RNC buffer overflow during a vertical handoff to WLAN. For this comparison, a simulation environment is created using the original ns2 [8] components and the UMTS Terrestrial Radio Access Network (UTRAN) support modules found in [9].

The downlink traffic source is simulated with the on-off model explained in section III. The system and traffic source parameter values for the simulation model is the same as those used in section III. The tests were carried out using the network topology shown in Fig. 8 where the transmission rate of each wireless link is indicated. The simulations can be extended to a system with more APs but we wanted to capture the key performance comparisons between our PCP and a typical WLAN system to keep the simulation time manageable.

Fig 9 plots the power consumed by the WLAN interface for a non-communication state versus the off period ranging from 30 to 360 s for different values of R (40 and 50 Kbps) when t_{on} is 120 and 360 s. As we noted for the numerical results in the previous section, our proposed PCP achieves better performance than a typical WLAN in terms of the power consumption for a non-communication state. The power consumption behavior patterns shown in Fig. 9 compare well with the numerical results in Fig. 5.

From the graphs in Fig. 9, we also observe that when $t_{\mathrm{on}} = 120$ s, the power consumption of PCP with $n = N$ is lower than with $n = 1$. The power consumption is reduced by 83.6% and 72.2% for $R = 40$ and 50 Kbps, respectively. Similarly when $t_{\mathrm{on}} = 360$ s, the power consumption is reduced by 83.6% and 46.1% for $R = 40$ and 50 Kbps, respectively. These results further confirm that PCP with $n = N$ works better than PCP with $n = 1$ in terms of reducing the power consumed for a non-communication state when the data rate is lower and/or the active period is smaller. However, considering that mobile users do not always download the traffic with a lower data rate and/or smaller active period, it may be desirable to make the threshold n less than the maximum buffer size. This is clearly indicated from the packet loss rate shown in Fig. 10 as well

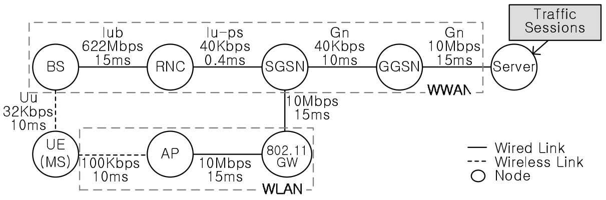


Fig. 8. Network topology

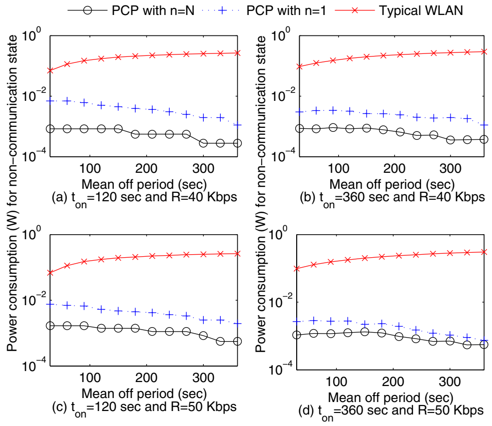


Fig. 9. Power consumption for non-communication state vs. varying mean off period

as Fig. 7.

Fig. 10 shows the packet drop rate during the vertical handoff to WLAN for PCP with $n = N$. Observe that there was no packet dropping for PCP with $n = 1$. From Fig. 10 and Fig. 7 in the numerical results section, we observe that there is a trade-off between the power consumption and the data loss in the proposed PCP system with a larger threshold, n. That is, the PCP system with a larger threshold n will incur a lower power consumption at the cost of a greater data loss, so that the threshold n should be set to a value smaller than the RNC buffer size (e.g. 1) if data loss is not tolerated.

V. CONCLUSION

In this paper, we propose a Power-efficient Communication Protocol (PCP) for heterogeneous wireless networks, that utilizes the paging of cellular networks in order to turn off the WLAN interface completely during idle time. In other words, we aim to save the power consumption resulting from periodic wake-ups during the idle time. The detailed signaling for the PCP system is presented. Further, our proposed PCP is designed to avoid repetitive turn-on and off actions which consume a great amount of power by turning on the WLAN interface when the number of packets in the buffer at RNC reaches a certain threshold n.

Performance results for the proposed PCP system are derived from an analytical model as well as simulations in terms of power consumption and data loss. The numerical and simulation results show that the power consumed in a non-communication state for our PCP system is lower than a typical WLAN system, whereas the PCP system with a larger threshold n will incur a lower power consumption at a cost of greater data loss.

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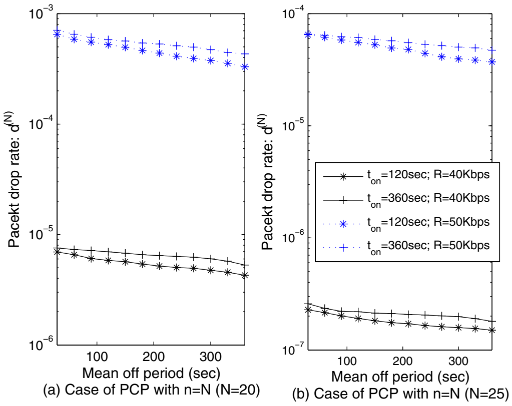

Fig. 10. Average packet drop rate at the RNC buffer for varying mean off period

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