Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2008, Article ID 342141, 13 pages
doi:10.1155/2008/342141

Research Article

Power-Efficient Communication Protocol for Integrated WWAN and WLAN

SuKyoung Lee,[1] WonSik Chung,[1] KunHo Hong,[1] and Nada Golmie[2]

[1] *Department of Computer Science, Engineering College, Yonsei University, Seoul 120-749, South Korea*
[2] *National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*

Correspondence should be addressed to SuKyoung Lee, sklee@cs.yonsei.ac.kr

Received 27 February 2007; Revised 27 August 2007; Accepted 31 October 2007

Recommended by Kameswara Rao Namuduri

One of the most impending requirements to support a seamless communication environment in heterogeneous wireless networks comes from the limited power supply of small-size and low-cost mobile terminals as in stand-alone WLANs or cellular networks. Thus, it is a challenge to design new techniques so that mobile terminals are able to not only maintain their active connection as they move across different types of wireless networks, but also minimize their power consumption. 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 for WLAN notes that in the idle state, a device with both a WLAN and a WWAN interface needs to keep both interfaces *on* in order to receive periodic beacon messages from the access point (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 (PCP) that includes turning off the WLAN interface after it enters the idle state and using the paging channel of WWAN in order to wake up the WLAN interface when there is incoming long-lived multimedia data. This scheme is known to limit the power consumption, while at the same time, it makes use of the paging channel in cellular networks. 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 tradeoffs between the power saving and the number of packets dropped at the buffer are investigated analytically through the study of an on/off traffic model. Simulation results for scenarios of interest are also provided.

1. INTRODUCTION

The current trends towards achieving a ubiquitous computing environment require the integration of a variety of current and future wireless networking technologies to support seamless communication for multimedia applications. More specifically, 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 universal mobile telecommunications system (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 [1].

One of the most impending requirements to support seamless communication between heterogeneous wireless networks comes from the limited power supply of small-size and low-cost mobile terminals as in stand-alone WLANs or cellular networks. 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 handover*, while minimizing their power consumption [2]. There have been several efforts aiming at having mobile devices equipped with multiple (currently, dual-mode) interfaces, switching their connection to the access network that provides the best coverage. The authors of [2] introduced several performance metrics that can be used in the handover decision. In [3], the authors propose an end-to-end mobility management system that reduces unnecessary handover and ping-pong effects by obtaining and analyzing the conditions in different networks. In addition, various network layer-based inter-network handover techniques are evaluated for a realistic heterogeneous network testbed in [4]. As for a potential integration architecture for WLAN and 3G WWAN, the authors of [5] describe a loosely coupled architecture in the form of an IEEE 802.11 gateway and a corresponding service access client software. Most recently, a global-positioning-system- (GPS) based location-aware vertical handover scheme is introduced in [6], while in [7], an architecture of a vertical handover scheme based on the paging channel (PCH) of cellular networks is proposed.

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, denoted by idle power. In most existing vertical handover management schemes [2–4], a mobile node must turn on both WLAN and WWAN interfaces even in the idle state with the power save mode, in time to receive the periodic beacon signals from the AP and the signal through the downlink control channels (pilot, sync, or paging channel) 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, that is, an extension to the PCH-based vertical handover scheme proposed in [7]. This scheme assumes that if a certain time expires just after the WLAN interface enters the idle state, regardless of whether the power save mode is used, 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 PCH 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 in order to wake up the WLAN interface on an as-needed basis. Thus by utilizing the PCH to learn about the presence of incoming data, a mobile device can significantly reduce its power consumption since it does not have to continuously scan the beacon signals. 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 limiting the power consumption and entering the inactive state [8, 9]. In fact, it is reported in [9] that this scenario can result in up to 98% of battery power savings. In addition, we observe that this inactive state further reduces the power consumed by an AP since it is largely dependent on the power consumed by all the powered-on nodes that it is supporting.

Further, our proposed scheme is designed to avoid repeatedly turning on and off WLAN interfaces, which 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 2 discusses the proposed PCP protocol in greater detail. Section 3 provides an analysis of the power consumption during the non-communication state for a typical WLAN node, as well as the proposed PCP. Section 4 provides simulation results and a discussion of the results. Conclusions are offered in Section 5.

2. POWER-EFFICIENT COMMUNICATION PROTOCOL

In this section, we describe our power-efficient communication protocol (PCP) for heterogeneous wireless networking system. In the following, we first describe the system model assumed before presenting how the PCP works.

2.1. System model

Several interworking mechanisms have been proposed in [1–6, 10, 11] to combine WWANs and WLANs into integrated wireless data environments. Two main architectures have been proposed for interworking between WLAN and cellular systems: (1) tight coupling and (2) loose coupling. When the loose-coupling scheme is used, the WLAN is deployed as an access network complementary to the cellular network. In this approach, the WLAN bypasses the core cellular networks, and data traffic is routed more efficiently to and from the Internet without having to go over the cellular networks. However, this approach mandates the provisioning of special authentication, authorization, and accounting (AAA) servers on the cellular operator for interworking with WLANs' AAA services. On the other hand, when the tight-coupling scheme is used, the WLAN is connected to the cellular core network in the same manner as any other cellular radio access network (RAN) so that the mechanisms for mobility, QoS, and security of the cellular core network can be reused. As a result, a more seamless handover between cellular and WLAN networks can be expected in the tightly coupled case as compared to the same for the loosely coupled case. As shown in Figure 1, tight-coupling approach is employed in our system model and hence, a single operator or multiple operators may operate the WWAN and WLANs. In the latter case, the multiple operators are able to have an access to information useful for vertical handover decision such as power consumption and available bandwidth, with a proper roaming agreement. For instance, in [10], 3GPP (3rd generation partnership project) describes the interworking architecture, where a WLAN has a set of roaming agreements with different cellular networks, enabling mobile users to roam onto any of these networks with a single subscription. In [11], the serving GPRS support node (SGSN) emulation architecture allows an independent operator to deploy 802.11 WLAN and make business arrangements with UMTS operators. Under the roaming agreement, some information necessary for vertical handover can be shared among heterogeneous networks and the extent of the information to be shared depends on the roaming agreement among the network operators. Further, for 4G networks, 3GPP is currently developing more

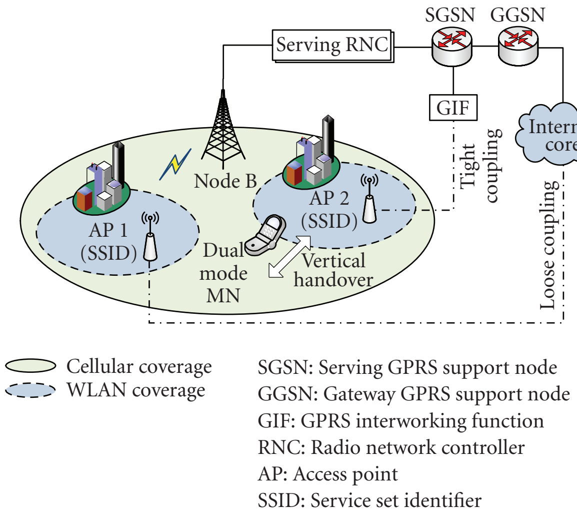


Figure 1: Architecture of an integrated heterogeneous network consisting of WWAN and WLAN.

Table 1: Typical power consumption for WLAN and WWAN interfaces.

Interface	Power consumption (watt)		
	Idle	Uplink	Downlink
WWAN (CDMA: GTRAN)	0.082	2.8	0.495
WLAN	1.04 (PS on)	6.96	7.28
(Cisco Aironet 5 GHz)	1.59 (PS off)	—	—

detailed standards about how to establish a roaming agreement and transfer the information among multiple operators for seamless handover [12, 13].

Our system model is based on the generic architecture for integration of WWAN and WLAN defined in [4, 14]. In this architecture, the WLAN is connected to the SGSN via the GPRS interworking function (GIF), which provides a standardized interface to the GPRS core network and virtually hides the WLAN peculiarities. The primary function of the GIF is to make the SGSN consider the WLAN as a typical GPRS access system. In the system, the mobile node utilizes packet data protocol (PDP) to manage its ongoing sessions. When the mobile node is just turned on or enters the heterogeneous wireless networking system, a PDP address (usually an IP address) is allocated to the mobile node by a dynamic host configuration protocol (DHCP) server for IP connection. The PDP context can be maintained in the tightly coupled case as shown in Figure 1 when the mobile node changes an access technology. Thus when a vertical handover occurs, the packets destined to the mobile node can be rerouted at the SGSN by using the intra/inter SGSN routing area update (RAU) procedure defined in [14] without going through the reauthentication process.

2.2. The proposed PCP scheme

When connected to the WLAN, a WLAN interface card is usually in the idle mode for around 70% of the overall time including the time during which the interface is turned off [15]. Typically, as long as the WLAN interface is turned on (even in the idle state with power save mode), it will wake up periodically in time to receive beacon signals from the AP regarding any traffic activity on the link. Table 1 shows the power consumption for typical WWAN and WLAN interface cards [16–19]. It is noteworthy to point out that in the idle state, the power consumption level of a WLAN interface can be significant. Moreover, the power consumption level for a WLAN interface is about 13 and 19 times greater than a WWAN interface, with and without power saving (PS), respectively (shown in Table 1).

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 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., MMS: 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, which we call *inactive* state in this paper as shown in Figure 2. Herein, the PCP scheme modifies the WLAN interface state machine as follows:

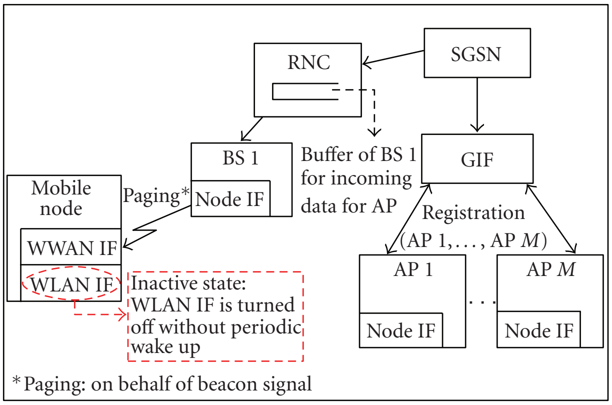
(i) Communication state: A WLAN interface sends or/ and receives data.

(ii) Non-communication state: A WLAN interface goes to this state when the data session is completed. (Typical WLAN: idle state; PCP: inactive state).

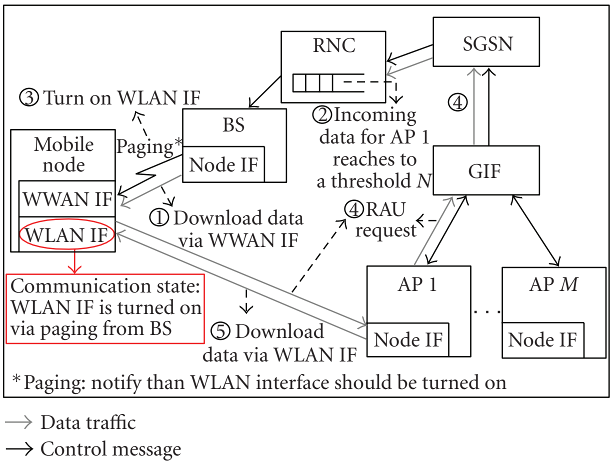
Figure 2 gives the detailed procedures that are executed by the WLAN interface in both states described above. Note that we only show the procedures that need to be implemented in support of PCP. These procedures are as follows.

(1) Registration of AP in WWAN

In the interworking architecture designed in [5], 48 bit medium access control (MAC) addresses are used to transfer the packets between the GIF and mobile nodes. To route the data packets from the GIF to mobile nodes, the GIF should know which APs it has to route the data. As in [5], the GIF in our PCP system, is able to obtain the MAC addresses and service set identifiers (SSIDs) of all the APs connected to itself. Either when the APs are initialized or installed, the SSID and the MAC address of each AP in an IEEE 802.11 access network should be registered with the connected GIF. The registration process is carried out using GIF/routing area identifier (RAI) discovery procedure proposed in [5]. While, originally, GIF/RAI discovery procedure is used for obtaining the MAC address for mobile nodes, the same procedure can also be utilized by the APs to discover the MAC address of the GIF and register with it. Through this registration process, the GIF can maintain the information of all the APs connected



(a) Inactive state of WLAN interface under PCP



(b) Communication state of WLAN interface under PCP

Figure 2: Overall architecture of PCP without periodic wake-up beacons (a) when the WLAN interface is in the inactive state, with the APs registered with the GIF, and (b) when the WLAN interface is in the communication state and is ready to receive incoming data from AP 1.

to itself and correctly route the data to the correct mobile nodes.

(2) Interface selection procedure for uplink traffic in inactive state

Once the transmission queue on the wireless link is filled with data packets, the WLAN interface enters the communication state and starts transmitting data. This procedure can be further divided into three substeps as follows.

Step 1. When the WLAN transmission queue contains a packet, the WLAN interface enters the communication state.

Step 2. The mobile node searches for all APs in its area. It associates with the AP that has the highest received signal strength (RSS). If no APs are found, data transmission is performed through the WWAN interface.

Step 3. The mobile node transmits the buffered data to the AP it is associated with during Step 2.

(3) Interface selection procedure for downlink traffic in inactive state

In a 3GPP system, the RNC is responsible for controlling user traffic between a user and the core network with buffers for different users. In other words, it is responsible for managing the resources of one or more radio base stations [20, 21]. 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 [20–23] 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 Figure 3 and include the following steps.

Step 1. For downlink transmission, data traffic comes into a per-user-buffer at the RNC when mobile node 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 its periodic paging message including PAGING_DT = true via its PCH.

Step 2. Upon receiving the notification, the WLAN interface is turned on and an available AP is found. If no APs are found, the data transmission is performed through the WWAN interface.

Step 3. Once the mobile node associates with the AP that has the highest RSS, it sends an RAU request message to the related GIF while receiving the incoming data through the WWAN interface.

Step 4. Upon receiving the RAU request message, the GIF forwards the RAU request message which contains the SSID and MAC address of the AP selected for the mobile node to the corresponding SGSN.

Step 5. Once the SGSN receives the RAU request message, it responds to the mobile node by sending an RAU accept message and switches the route for the data, destined to the mobile node, to the corresponding GIF. Then, the SGSN sends the incoming data to the GIF. However, the remaining packets in the RNC buffer are transmitted to the mobile node through the WWAN interface, if there still remain any.

Step 6. The GIF transmits the data received from the SGSN to the mobile node.

The user requests a QoS profile, and when the PDP context for the downlink traffic is activated, the QoS profile is set in the PDP context. As shown in Figure 4, the QoS profile requested by the user is stored in both the gateway GPRS support node (GGSN) and the mobile node, and hence the GGSN is able to set the threshold, n, according to the QoS profile. For example, in the case of long-lived multimedia Internet traffic or real-time multimedia services such as mobile

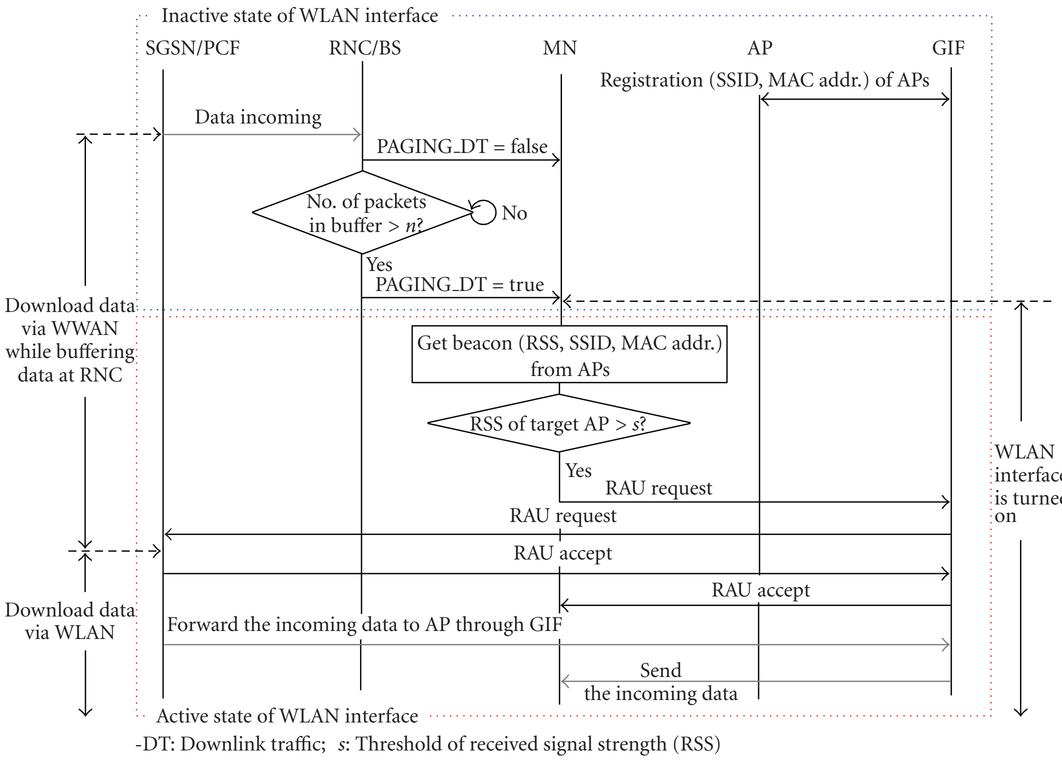


Figure 3: Signaling procedure when WLAN interface goes from the inactive to communication state to receive downlink traffic.

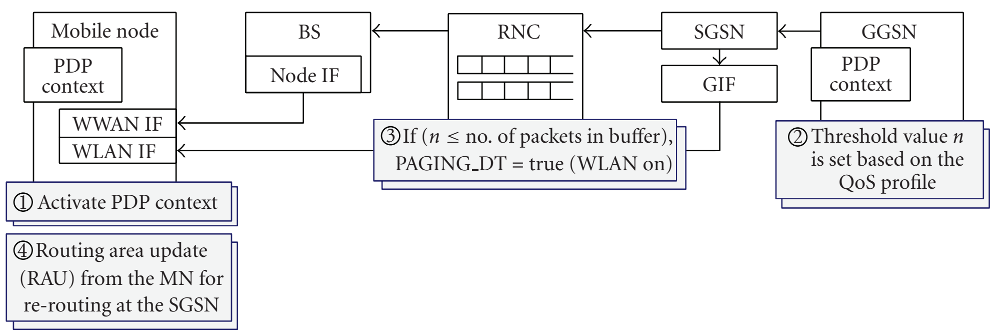


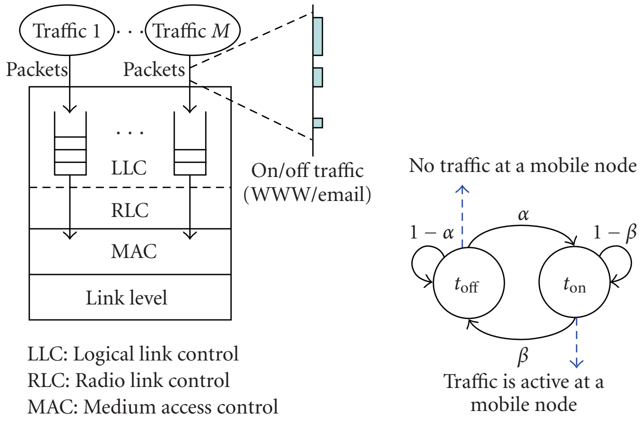
Figure 4: Schematic procedure of setting the threshold, n in our PCP system.

TV and interactive services, the occupancy of the buffer may reach n quickly while it may not for the best effort services like web browsing, e-mail, and MMS. Thus the threshold value should be set lower for the multimedia or real time services than for best effort and nonreal time services. Note that every network operator does not need to go by the same value for a certain application while its own traffic statistics should be considered. Then, the RNC is notified of the threshold value on which the RNC is able to decide whether or not the WLAN interface is turned on in the above Step 1.

In fact, UMTS has its own QoS classes which are specified in [22]. Table 2 shows the UMTS QoS classes and the representative application for each class. In particular, conversational and streaming classes are mainly used to carry real-time multimedia traffic flows such as voice over IP (VoIP) and video telephony, and there have been many studies for characterizing the real-time traffic flows [24–27]. In [25], the author proposes that audio activities can be modeled as alternating between two states: on and off period. The authors of [26, 27] empirically show that various prevailing multimedia

Table 2: UMTS Qos classes and representative applications [22, 24].

Traffic type	Application	Application level traffic model
Conversational	Voice	EXP On/Off
Streaming	Video streaming	EXP On/Off
Interactive	Web	Pareto On/Off
Background	FTP	Constant BitRate (CBR)



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

Figure 5: 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 an On/Off behavior.

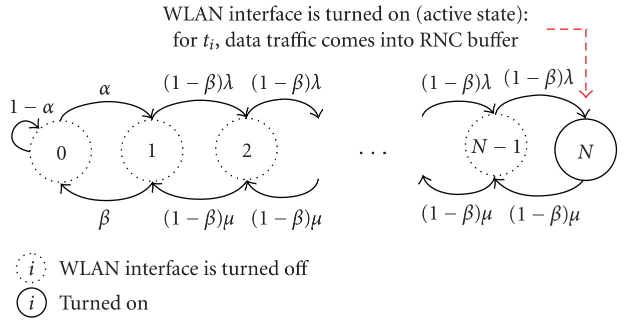


Figure 6: State transition diagram for PCP with $n = N$, where WLAN interface is turned on from inactive state once the number of packets becomes N in the buffer of RNC.

applications such as multimedia conferencing, multicast lectures, distant learning, and IP telephony can be modeled as an on-off traffic with the different probability distribution of the on and off period. As can be seen in Table 2, voice data and video streaming fit into an on/off traffic model as in [26, 27]. Besides, each QoS class (more specifically, each multimedia application) should be characterized by the length and the probability distribution of on and off periods. Thus we propose to set the value of threshold, n, depending on the QoS class requested by the application. As shown in Figure 4, GGSN is in charge of setting the value of the threshold, n, in the integrated WLAN and cellular networking system.

Our PCP system aims to prevent the WLAN interface from being turned on for transient traffic. Accordingly, the RNC keeps forwarding the data while the WLAN interface is being turned on. While a mobile node is turning on its WLAN interface, it can stay connected to the BS because it is not moving out of the coverage of the BS. Thus packets can still be read through the WWAN interface even after a handover to WLAN, ensuring that inflight packets in WWAN are not lost as described in Step 5 [4, 28].

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

Typically, users' packets are separated into buffers at the RNC [20–23] 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 [29, 30], as can be shown in Figure 5(a). Different buffering schemes can be used in the BS's. Even though one buffer memory can be shared for all users, different buffer thresholds can be set per user, for example, thresholds can be based on percentages of the buffer memory size for a scheduling purpose.

To investigate the performance of our proposed PCP system, we now develop an analytical model treating the per-user-buffer at the RNC as a queueing system while also considering the power on/off state of the WLAN interface. We focus on downlink traffic since it is envisioned that in the fourth generation, wireless system traffic patterns will be highly asymmetrical, with 50/1 ratio or more favoring the downlink.

As far as traffic patterns are concerned, the WLAN system can be characterized by an on/off behavior as can be seen in Figure 5(b) [30, 31]. 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 it takes user to investigate the downloaded web pages or doing other jobs (e.g., editing) on the mobile node. From Figure 5, the probabilities of a mobile node being in t_{on} and of a mobile node being in t_{off} are given by $p_{t_{on}} = \alpha/(\alpha+\beta)$ and $p_{t_{off}} = \beta/(\alpha+\beta)$, respectively. Let both on and off periods have an exponential distribution with means β^{-1} and α^{-1}, respectively. During the t_{on} period, we assume that traffic arrives with a Poisson distribution of mean λ. It is also assumed 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 rate 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 Figure 5(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 Figure 6. 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

$$\begin{aligned} p_0 &= p_{t_{\text{off}}}, \\ \alpha p_0 &= \beta p_1, \\ \alpha p_0 + (1-\beta)\mu p_2 &= (1-\beta)\lambda p_1 + \beta p_1, \\ \lambda p_{i-1} + \mu p_{i+1} &= (\lambda+\mu) p_i, \quad 2 \le i \le N-2. \end{aligned} \tag{1}$$

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 $p_0 = \beta/(\alpha+\beta)$, from (1), the rate at which the WLAN interface is turned on from the inactive state is given by

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

where

$$u(x) = \begin{cases} 1, & t_i - x > 0, \\ 0, & t_i - x \le 0, \end{cases} \tag{3}$$

and $\rho = \lambda/\mu$. 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 $p_{\text{on}}^{(k)} = (1-\beta)\lambda p_{k-1}(1-(1-\beta)\mu p_k)u(x) = \{\alpha(1-\beta)\lambda\rho^{k-2}/(\alpha+\beta)\}\{1-\alpha(1-\beta)\lambda\rho^{k-2}/(\alpha+\beta)\}u(x)$.

While the WLAN interface is being initialized, the SGSN sends data packets through the WWAN interface. As soon as the SGSN receives the message from the mobile node that the WLAN interface is ready, the data traffic is transferred to the WLAN interface from the SGSN. Although this is a form of soft handover, packet drop can still be when the RNC buffer becomes full. That depends on the data rate from SGSN and the size of the buffer at the RNC. When the buffer size is N, for PCP with $n = N$, the number of packets dropped

$$d^{(N)} = (1-\beta)\lambda p_N v(x) = \frac{\alpha(1-\beta)\lambda\rho^{N-1}}{\alpha+\beta}v(x), \tag{4}$$

where

$$v(x) = \begin{cases} x, & t_i - x > 0, \\ t_i, & t_i - x \le 0. \end{cases} \tag{5}$$

Here, we note that the RNC layer controls the data rate from SGSN, and the buffer size can be set to be greater than the TCP window size, [20, 23], in order to prevent data packets from being dropped at the RNC buffer. For PCP with $n = k$ $(k < N)$, once the buffer has k packets, a vertical handover to the WLAN is initiated so that it is less likely that a packet is dropped than when $n = N$.

For PCP with $n = 1$ (see Figure 7), where the WLAN interface is turned on from the inactive state upon the receipt of the first packet arriving at the RNC, the rate at which the

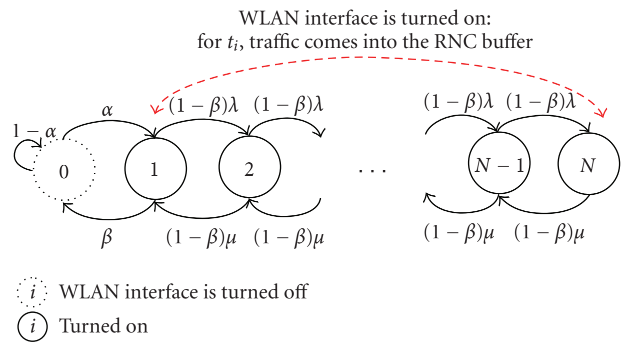


Figure 7: State transition diagram for PCP with $n = 1$ when WLAN interface is turned on from inactive state once the first packet comes.

WLAN interface is turned on from the inactive state is expressed as

$$p_{\text{on}}^{(1)} = \alpha p_0 = \frac{\alpha\beta}{\alpha+\beta}. \tag{6}$$

With regard to the packet drop probability, if the initialization of the WLAN interface is over before the buffer at the RNC has N packets, there will be no packets dropped at the RNC (in this study, the possibility for packet dropping due to the WLAN status after a vertical handover to the WLAN is not considered). That means $d^{(1)} = 0$ under the condition that $\rho \times t_i \ll N$.

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

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

which works for both cases of PCP with $n = N$ and $n = 1$. Suppose that there is a traffic flow with the characteristic of $E[i] \ll N$, that means the traffic is not heavy and the traffic lasts for a short period of time (e.g., MMS, voice-email, and etc.), then it is better to send it to the WWAN since the power will be consumed more due to the frequent turn-on and -off actions under PCP with $n = 1$ than under PCP with $n = N$. However, for the case that $E[i]$ is closer to N, PCP with $n = 1$ achieves better performance than PCP with $n = N$ in terms of reducing the number of packets dropped.

Actually, during the so-called *idle-with-power-saving* mode in commercial off-the-shelf WLAN cards, the WLAN interface card indicates its desire to enter the idle state to the AP via a status bit located in the header of each packet. In order to still receive data, the WLAN interface must wake up periodically to receive regular beacon transmissions coming from the AP, which identify whether the idle interface has data buffered at the AP and waiting for delivery. If the WLAN interface has data awaiting transmission, it will request them from the AP. After receiving the data, the WLAN interface can go back to sleep.

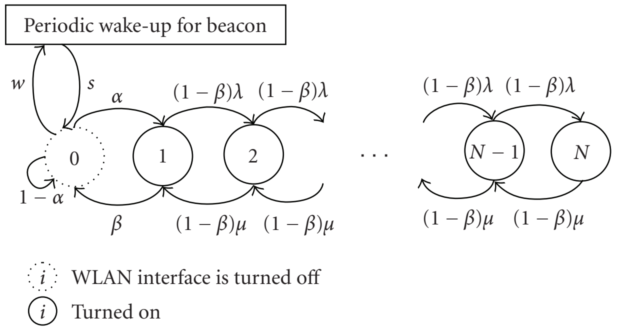


Figure 8: State transition diagram for WLAN interface and AP buffer when PCP is not applied.

Let w and s denote the wake-up rate during the idle state to receive a beacon signal from AP and the sleep rate during the idle state after receiving the beacon signals from the AP, respectively, both of which are fixed (see Figure 8). Then, for the *idle with power saving* mode, the rate, at which WLAN interface is turned on, can be characterized as follows:

$$p_{\text{on}}^{\text{w/oPCP}} = \left(\alpha + (1-\alpha)\frac{w}{w+s}\right)p_0 = \frac{(w+s\alpha)\beta}{(w+s)(\alpha+\beta)}, \quad (8)$$

where if the size of the AP buffer can be assumed to be the same as the RNC buffer, the amount of packets dropped is also the same as the case of PCP with $n = 1$.

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

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

where in general, C_{ia} is known to be greater than C_i so that C_i and C_{ia} are set to 0.68 W and 1 W, respectively, while C_d is assumed to have the value of 0.06 W. These values were taken from [19].

To obtain some simulation results (refer to Section 4) as well as numerical results, we have assumed 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 that is capable of coding schemes up to CS-4, and t_{on} is set to either 120 or 360 seconds. It is also assumed that the initialization time for the WLAN interface, t_i, is one second and the buffer size, L_b, is set to 20 KB.

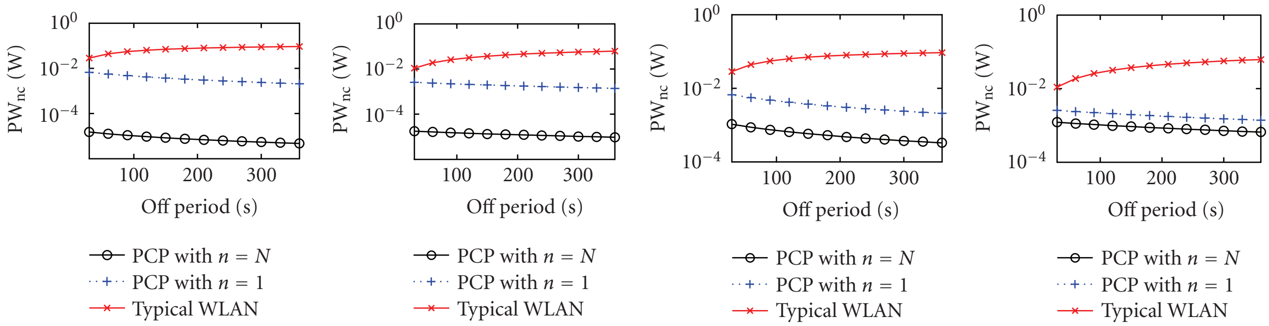
For a typical WLAN interface with power saving mode, beacons are only sent at fixed intervals and a typical value is in the order of 100 milliseconds (e.g., Lucent Orinoco 802.11b AP sends beacons at an interval of 102.4 milliseconds). Thus, the beacon period, s^{-1}, can be set to 100 milliseconds. 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 beacon signal, $1/w$, is expressed as L_{beacon}/B + processing time at interface, where B is the channel bit rate.

In Figures 9(a), 9(b), 9(c), and 9(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 seconds 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.

Comparing Figures 9(a) and 9(b) with Figures 9(c) and 9(d), the average power consumption for the non-communication state obtained with a typical WLAN system is higher than the proposed PCP system, where the power consumption for PCP with $n = N$ is lower than PCP with $n = 1$ over all the ranges of off period considered for $R = 40$ Kbps and 50 Kbps. The performance improvement brought by PCP with $n = N$ over PCP with $n = 1$ is around 16% and 46% greater when $R = 40$ Kbps than when $R = 50$ Kbps, for $t_{\text{on}} = 120$ and 360 s, respectively. Thus under the same active period, the higher the data rate gets, the higher the power consumed for a non-communication state of PCP with $n = N$ becomes because the data packets from the traffic with a higher data rate fill the buffer faster. From Figures 9(a) and 9(d), it is noted that in terms of power consumption, the above observed performance improvement is still valid, irrespective of the active period length (either 120 or 360 seconds). The graphs in Figure 9 also indicate that as the off period increases, the power consumed by the PCP system decreases.

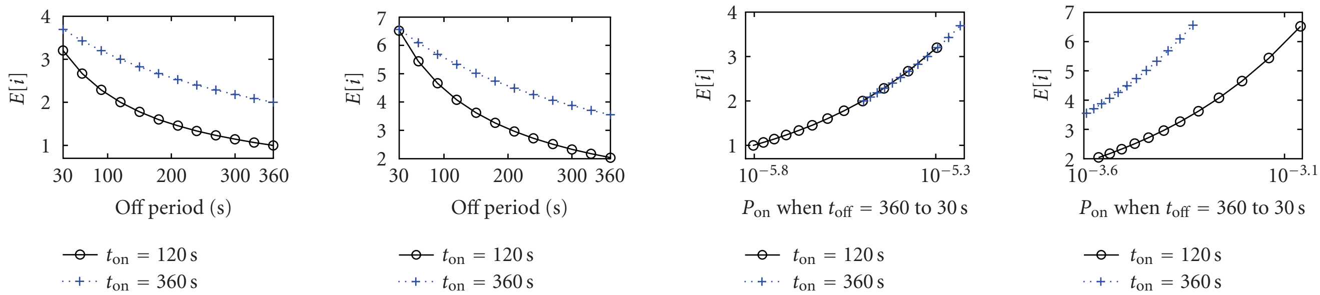
Figures 10(a), 10(b), 10(c), and 10(d) show the average number of packets in the RNC buffer during a vertical handover to WLAN. The numerical results in Figure 10 are obtained from (7). We observe from Figures 10(a) and 10(b) that as the off period increases, the average number of packets in the buffer decreases. For a smaller off period, the difference between the average number of packets in the buffer is also smaller for both cases of $t_{\text{on}} = 120$ and 360 seconds. The curves in Figures 10(c) and 10(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 with our PCP.

Figure 11 plots the packet-drop rate, $d^{(N)}$, for PCP with $n = N$ versus off period. From Figure 11 as well as Figure 9, 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 packet drop rate compared with PCP with $n = 1$. However, what we also see is that for the PCP with $n = N$, the power consumption is about a couple of orders of magnitude lower than the case of PCP with $n = 1$. To see the decreased packet-drop rate in Figure 11(b) when $N = 25$, compared to



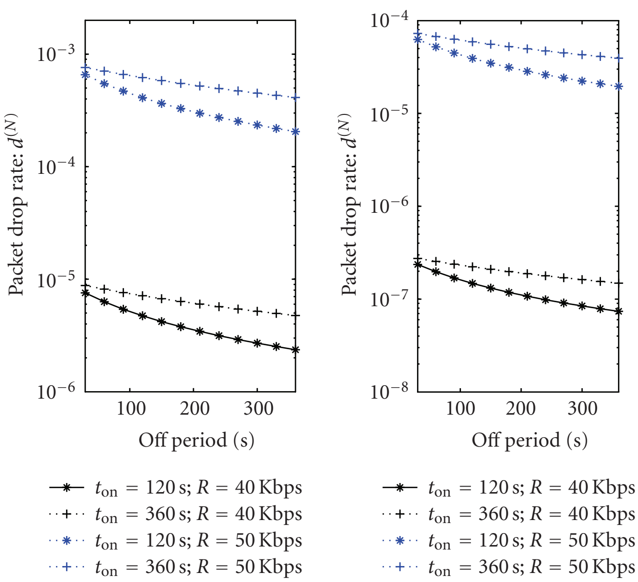
(a) $t_{on} = 120$ s and $R = 40$ Kbps (b) $t_{on} = 360$ s and $R = 40$ Kbps (c) $t_{on} = 120$ s and $R = 50$ Kbps (d) $t_{on} = 360$ s and $R = 50$ Kbps

FIGURE 9: Average power consumption for non-communication state versus varying off period.



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

FIGURE 10: The average number of packets in the buffer at RNC for varying off period and power-on rate when $t_{on} = 120$ and 360 seconds.



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

FIGURE 11: 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).

Figure 11(a), we know that the packet-drop rate of PCP with $n = N$ decreases as the buffer size is increased (if the buffer size is larger than TCP window size, no packet drop occurs). That means that setting the threshold n to $k < N$ makes the proposed PCP achieve lower packet-drop rate and higher power consumption than PCP with $n = N$. Thus the value of threshold, n ($1 \leq n \leq N$), will have an impact on the performance of both the power consumption for the non-communication state and the packet-drop rate.

4. 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 handover to WLAN. We also evaluate the performance of the proposed PCP by comparing with an existing method based on [32] in terms of power consumption and we call the method POD (power on data) in our study. The POD scheme is similar to our scheme in that it utilizes an out-of-band signaling to completely turn off the WLAN interface. However, while in the POD scheme, WLAN is turned on whenever the data arrives at the RNC, our PCP scheme makes the WLAN interface be turned on whenever the per-user-buffer exceeds a given threshold. For these comparisons, a realistic simulation environment is created using the original NS2 components [33], the UMTS terrestrial radio-access

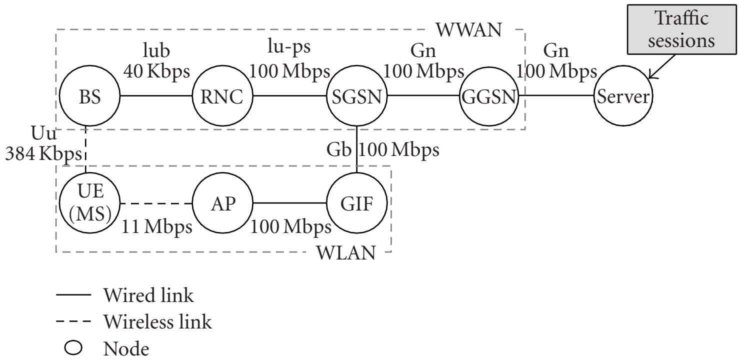
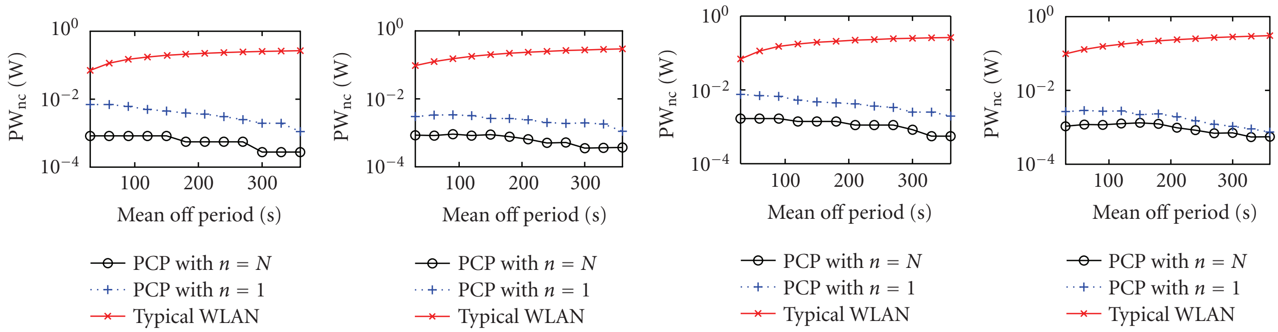


FIGURE 12: Network topology.



(a) $t_{on} = 120$ s and $R = 40$ Kbps (b) $t_{on} = 360$ s and $R = 40$ Kbps (c) $t_{on} = 120$ s and $R = 50$ Kbps (d) $t_{on} = 360$ s and $R = 50$ Kbps

FIGURE 13: Power consumption for non-communication state versus varying mean off period.

network (UTRAN) support modules [34] and the mobility package from [35].

Our simulation focuses on conversational and streaming classes in Table 2, and hence the downlink traffic source is simulated with the on-off model explained in Section 3. Noting that current multimedia applications use user decagram protocol (UDP) as the underlying transport protocol, UDP is used as the transport layer in our simulation.

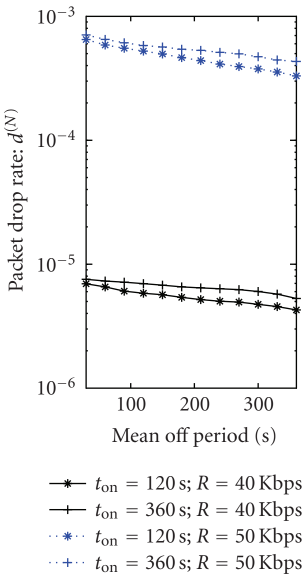
The system and traffic source parameter values for the simulation model are the same as those used in Section 3. According to the traffic model in Section 3, the channel stays in each on and off state according to an exponentially distributed duration and the traffic arriving at the per-user buffer follows a Poisson process. The tests were carried out using the network topology shown in Figure 12 where the transmission rate of each wireless link is indicated. We set the data rate between the mobile node and the AP to 11 Mbps assuming an IEEE 802.11b WLAN. The data rate per connection between the RNC and the BS is set to 40 Kbps, supposing that the maximum transmission rate of the UMTS system is 384 Kbps, but the scheduler in the RNC provides 40 Kbps data rate for a connection. Our simulation results are obtained with a 95% confidence interval. 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 using a simple network with a smaller capacity in order to keep the simulation time manageable.

In our simulation, we found that in the simulation tests, WLAN interface may not be turned on at the exact moment when the buffer at RNC reaches a threshold n. This can be caused by the link delay and a time difference between the moment when the buffer at RNC reaches a threshold n, and the moment when the paging signal to wake up the WLAN interface is sent to the mobile node. Discrete-event generation characteristics of the NS2 simulator also have an impact on the time difference. Thus the values of the simulation results do not exactly match with those of the numerical results, whereas the power consumption behavior observed in the simulation results is aligned with the numerical results.

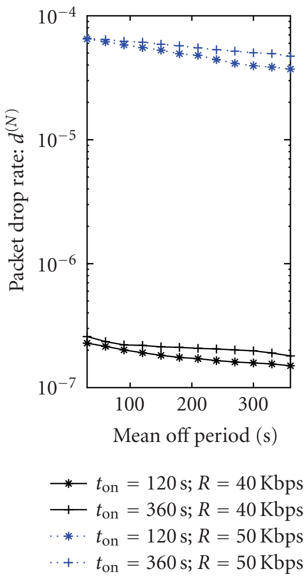
Figure 13 plots the power consumed by the WLAN interface for a non-communication state versus the off period ranging from 30 to 360 seconds for different values of R (40 and 50 Kbps) when t_{on} is 120 and 360 seconds. As we noted for the numerical results in the previous section, our proposed PCP achieves better performance than a typical WLAN in terms of the power consumption for a non-communication state. The power consumption behavior patterns shown in Figure 13 are aligned along with the numerical results in Figure 9. From the graphs in Figure 13, when the data rate is lower (i.e., 40 Kbps) in the active state, the power consumption improvement in PCP with $n = N$ over

Table 3: Performance improvement (%) of PCP over POD in terms of power consumption.

	R		Performance improvement of PCP over POD		
		t_{off}	$n = 1$	$n = 10$	$n = N(= 20)$
$t_{on} = 12$ s	40 Kbps	10 s	62.86%	91.20%	91.20%
		20 s	39.76%	83.22%	83.22%
		30 s	73.15%	79.97%	79.97%
	50 Kbps	10 s	33.35%	58.69%	71.82%
		20 s	10.36%	45.24%	68.00%
		30 s	8.27%	42.11%	74.80%
$t_{on} = 36$ s	40 Kbps	10 s	41.77%	89.15%	89.15%
		20 s	46.32%	87.87%	87.87%
		30 s	33.03%	83.78%	83.78%
	50 Kbps	10 s	4.39%	19.31%	33.01%
		20 s	5.55%	22.13%	38.39%
		30 s	4.52%	21.19%	37.19%



(a) Case of PCP with $n = N$ ($N = 20$)



(b) Case of PCP with $n = N$ ($N = 25$)

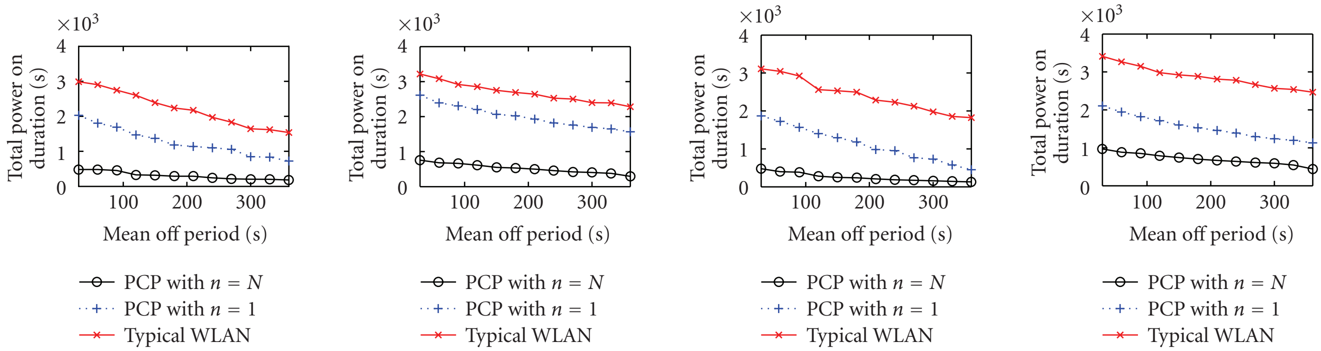
Figure 14: Average packet-drop rate at the RNC buffer for varying mean off period.

PCP with $n = 1$ is 12% and 38% greater than when the data rate is 50 Kbps, for $t_{on} = 120$ and 360 seconds, respectively. The same phenomenon is observed for a smaller active period, $t_{on} = 120$ seconds (about the same, and 26% greater for 40 and 50 Kbps, resp.) compared with $t_{on} = 360$ seconds. Hence it can be known from these results that PCP with $n = N$ works better with regard to the power consumed for a non-communication state, compared to PCP with $n = 1$ 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 low data rate and/or small active period, it is desirable to make the threshold n less than the maximum buffer size. This is clearly indicated from the packet-loss rate shown in Figure 14 as well as Figure 9.

Figure 14 shows the packet-drop rate during the vertical handover to WLAN for PCP with $n = N$. On the other hand, there was no packet dropping for PCP with $n = 1$. From Figure 14 as well as Figure 11 in the numerical results section, we observe that there is a tradeoff between the power consumption and the data loss in the proposed PCP system with a larger threshold, n. That is, the PCP system with 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 the network manager places more importance on the data-loss performance.

Figure 15 plots the total power-on duration during the overall simulation time as a function of the off period in the simulation network. In Figure 15, PCP achieves a better performance than a typical WLAN in terms of the total power-on duration. Accordingly, we know that the reduction of power consumption as seen in Figure 13 results from the reduction of the total power-on duration because the mobile node is able to stay in a non-communication state without a periodic waking up under our PCP.

The performance of our scheme and that of POD scheme are compared in Table 3. This table compares the two schemes for $R = 40$ and 50 Kbps for different values of the threshold, $n = 1$, 10, and N, which is set to 20, showing the improvement percentage in total power consumption during the entire simulation time for our PCP scheme over POD scheme. The two schemes are simulated for different idle time periods 10, 20, and 30 seconds. To capture the behavior of multimedia applications in this test, on and off periods are decreased compared to the previous simulation tests based on the on and off periods investigated in [24, 26]. It is evident from Table 3 that our PCP scheme performs better than POD for all the three threshold values. This is due to the fact that in POD scheme, the WLAN interface is turned on more frequently than our PCP scheme since the proposed PCP scheme does not turn on the WLAN interface until the



(a) t_{on} = 120 s and R = 40 Kbps (b) t_{on} = 360 s and R = 40 Kbps (c) t_{on} = 120 s and R = 50 Kbps (d) t_{on} = 360 s and R = 50 Kbps

Figure 15: Total power-on duration of WLAN interface for varying mean off period.

per-user buffer reaches the given threshold. This trend, with respect to the threshold, is the same for both on periods and both data rates.

From these results in Table 3, it can also be observed that though the absolute performance of PCP is better than that of POD as a whole, its margin of performance improvement is less for R = 50 Kbps than for R = 40 Kbps. We ascribe this observation to the fact that the occupancy of the buffer reaches n more quickly for higher data rate. Thus for long-lived/real-time multimedia traffic, the threshold should be set lower than that for short/best-effort traffic.

5. CONCLUSION

In this paper, we propose a power-efficient communication protocol (PCP) for heterogeneous wireless networks, that utilizes the paging channel of cellular networks in order to turn off the WLAN interface completely during the 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/-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 due to RNC buffer overflow during a vertical handover to WLAN. 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 because for the idle time, the power consumption resulting from the periodic wake-up is eliminated, whereas the PCP system with a larger threshold n will incur a lower power consumption at a cost of greater data loss.

Finally, we expect to expand on this work in the future by developing a loose-coupling-architecture-based signaling system which will be able to wake up the WLAN interface, in the place of the WWAN paging and further investigate the impact of the developed signaling on the PCP system.

ACKNOWLEDGMENT

This work was supported by Grant no. R01-2006-000-10614-0 from the Basic Research Program of the Korean Science and Engineering Foundation.

REFERENCES

[1] IEEE Standard 802.21 Working Group, "Draft IEEE standard for local and metropolitan area networks: media independent handover services," March 2006.

[2] J. McNair and F. Zhu, "Vertical handoffs in fourth-generation multinetwork environments," *IEEE Wireless Communications*, vol. 11, no. 3, pp. 8–15, 2004.

[3] C. Guo, Z. Guo, Q. Zhang, and W. Zhu, "A seamless and proactive end-to-end mobility solution for roaming across heterogeneous wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 5, pp. 834–848, 2004.

[4] R. Chakravorty, P. Vidales, K. Subramanian, I. Pratt, and J. Crowcroft, "Performance issues with vertical handovers—experiences from GPRS cellular and WLAN hot-spots integration," in *Proceedings of the 2nd IEEE Annual Conference on Pervasive Computing and Communications (PerCom '04)*, pp. 155–164, Orlando, Fla, USA, March 2004.

[5] A. K. Salkintzis, C. Fors, and R. Pazhyannur, "WlAN-GPRS integration for next-generation mobile data networks," *IEEE Wireless Communications*, vol. 9, no. 5, pp. 112–124, 2002.

[6] M. Ylianttila, J. Mäkelä, and K. Pahlavan, "Analysis of handoff in a location-aware vertical multi-access network," *Computer Networks*, vol. 47, no. 2, pp. 185–201, 2005.

[7] S. K. Lee, S. H. Seo, and N. Golmie, "An efficient power-saving mechanism for integration of WLAN and cellular networks," *IEEE Communications Letters*, vol. 9, no. 12, pp. 1052–1054, 2005.

[8] T. Rappaport, "Convergence of cellular and wireless LAN: hotspot traffic statistics and user trends," http://users.ece.utexas.edu/~wireless/Montage%20Meeting%20Minutes/CTIATalk_March04.pdf.

[9] G. Anastasi, M. Conti, and W. Lapenna, "A power-saving network architecture for accessing the internet from mobile computers: design, implementation and measurements," *Computer Journal*, vol. 46, no. 1, pp. 3–15, 2003.

[10] 3GPP, "3GPP system to wireless local area network (WLAN) interworking; system description (Release 7)," Technical Specification TS 23.234, v8.1.0, 3GPP, March 2007.

[11] V. K. Varma, S. Ramesh, K. D. Wong, M. Barton, G. Hayward, and J. A. Friedhoffer, "Mobility management in integrated UMTS/WLAN networks," in *Proceedings of the IEEE International Conference on Communications (ICC '03)*, vol. 2, no. 1, pp. 1048–1053, Anchorage, Alaska, USA, May 2003.

[12] 3GPP, "Architecture enhancements for non-3GPP accesses (Release 8)," Technical Specification TS 23.402, v1.3.0, 3GPP, September 2007.

[13] 3GPP, "Feasibility study of mobility between 3GPP-WLAN interworking and 3GPP systems (Release 8)," Tech. Rep. TR 23.827, v0.4.0, 3GPP, September 2007.

[14] 3GPP, "General packet radio service(GPRS); service description stage 2 (Release 7)," Technical Specification TS 23.060 v7.4.0, 3GPP, March 2007.

[15] R. Chary, et al., "Power management technologies for WLAN enabled handheld devices," Intel Developer Forum, 2003.

[16] M. Nam, N. Choi, Y. Seok, and Y. Choi, "WISE: energy-efficient interface selection on vertical handoff between 3G networks and WLANs," in *Proceedings of the 15th IEEE International Symposium on PIMRC '04*, vol. 1, pp. 692–698, Barcelona, Spain, September 2004.

[17] Option Wireless Technology, "Specifications of globetrotter," http://www.option.be/products/2_1_1_specifications.shtml.

[18] Atheros Communications, "Power consumption and energy efficiency comparisons of WLAN products," http://www.atheros.com/pt/whitepapers/atheros_power_whitepaper.pdf, 2003.

[19] K. Mahmud, M. Inoue, H. Murakami, M. Hasegawa, and H. Morikawa, "Energy consumption measurement of wireless interfaces in multi-service user terminals for heterogeneous wireless networks," *IEICE Transactions on Communications*, vol. E88-B, no. 3, pp. 1097–1109, 2005.

[20] 3GPP, "UTRAN overall description," Technical Specification TS 25.401, v6.5, 3GPP, December 2004.

[21] 3GPP, "Radio link control (RLC) protocol specification," Technical Specification TS 25.322, v6.2, 3GPP, December 2004.

[22] 3GPP, "Quality of service (QoS) concept and architecture (Release 7)," Technical Specification TS 23.107, v7.0.0, 3GPP, June 2007.

[23] M. C. Chan and R. Ramjee, "Improving TCP/IP performance over third generation wireless networks," in *Proceedings of the 23rd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '04)*, vol. 3, pp. 1893–1904, Hong Kong, March 2004.

[24] H. Wang, D. Prasad, O. Teyeb, and H. Schwefel, "Peformance enhancements of UMTS networks using end-to-end QoS provisioning," in *Proceedings of the 8th International Symposium on Wireless Personal Multimedia Communications (WPMC '05)*, Aalborg, Denmark, September 2005.

[25] P. T. Brady, "A model for generating on-off speech patterns in two-way conversation," *Bell System Technical Journal*, vol. 48, pp. 2445–2472, 1969.

[26] C.-N. Chuah and R. H. Katz, "Characterizing packet audio streams from Internet multimedia applications," in *Proceedings of the IEEE International Conference on Communications (ICC '02)*, vol. 2, pp. 1199–1203, New York, NY, USA, April-May 2002.

[27] R. B. Ali, S. Pierre, and Y. Lemieux, "UMTS-to-IP QoS mapping for voice and video telephony services," *IEEE Network*, vol. 19, no. 2, pp. 26–32, 2005.

[28] M. Stemm and R. H. Katz, "Vertical handoffs in wireless overlay networks," *Mobile Networks and Applications*, vol. 3, no. 4, pp. 335–350, 1998.

[29] R. G. Mukhtar, S. V. Hanly, and L. H. Andrew, "Efficient internet traffic delivery over wireless networks," *IEEE Communications Magazine*, vol. 41, no. 12, pp. 46–53, 2003.

[30] A. Gurtov, "Efficient data transport in wireless overlay networks," Academic dissertation, University of Helsinki, Faculty of Science, Department of Computer Science and International Computer Science Institute, Helsinki, Finland, April 2004.

[31] V. D. Park and M. S. Corson, "User data models for an IP-based cellular network," http://www.ieee802.org/20/Contribs/C802.20-03-13r1.pdf, 2003.

[32] E. Shih, P. Bahl, and M. J. Sinclair, "Wake on wireless: an event driven energy saving strategy for battery operated devices," in *Proceedings of the Annual International Conference on Mobile Computing and Networking (MobiCom '02)*, pp. 160–171, Atlanta, Ga, USA, September 2002.

[33] "UCB/LBNL/VINT Network Simulator ns-2," http://www.isi.edu/nsnam/ns/.

[34] "Enhanced UMTS radio access network extensions for ns-2 (EURANE)," http://www.ti-wmc.nl/eurane/.

[35] "NIST Seamless and Secure Mobility Project," http://www.antd.nist.gov/seamlessandsecure.shtml#project.