Combining Paging with Dynamic Power Management

Carla F. Chiasserini, Ramesh R. Rao

Abstract—**In this paper we develop a novel approach to conserving energy in battery powered communication devices. There are two salient aspects to this approach. First, the battery powered devices move through multiple, progressively deeper, sleep states in a predictable manner. Nodes in deeper sleep states consume lower energy while asleep but incur a longer delay and higher energy cost to wake up. Second, the nodes are woken up on demand through a paging signal. To awaken nodes that are in deep sleep, the paging signal has to be decoded using very low power circuits such as those used in RF tags. To accommodate this need, in a manner that scales well with the number of nodes, the number of distinct paging signals has to be much less than the number of possible nodes. This is accomplished through a group based wake up scheme, that initially awakens the targeted node along with a number of other similarly disposed nodes that subsequently return to their original sleep state. Trade-offs among energy consumption, delay as well as overhead are presented; comparisons with other protocols show the potential for 16 to 50% improvement in energy consumption.**

Keywords—**Wireless Quality of Service, Protocol Design, Protocol Analysis.**

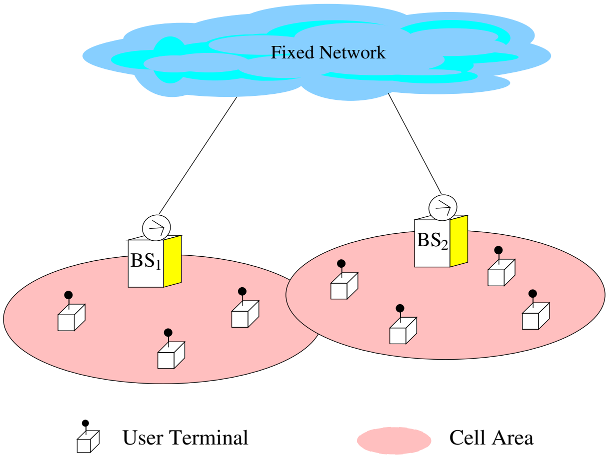

Fig. 1. Network scenario.

I. INTRODUCTION

MINIMIZING energy consumption in battery-powered devices is crucial to the design of wireless communication networks. One of the most common power conservation techniques is discontinuous reception whereby inactive users power down and turn on their receiver at some future time instant. In this paper we introduce a novel scheme that combines paging with a power management policy executed at the user devices. The goal is to maximize energy savings at battery-powered devices while satisfying their service requirements.

The paging protocol POCSAG [1] uses a coding format based on batches, with each batch consisting of eight frames. A user can be paged at only one of the eight frames, so that it may power down during the other seven and save energy. A similar approach is used in the FLEX [2] system where data intended for a particular pager is scheduled in a pre-defined time slot. In the MOBITEX data system [3] and in IEEE 802.11 [4] users in power saving mode wake up in time with a broadcast transmission from the base station that notifies which terminals have pending data. These schemes are called *synchronous* since the broadcast transmission from the base station and the users' waking-up time instants are synchronized.

An asynchronous in-band protocol is presented in [5]. The approach does not require system synchronization and each user is free to power on and off its receiver based on the battery status. When the terminal powers on, it keeps listening to the radio channel for a short time period. If a paging message is received, the terminal sends an acknowledgment to the base station, otherwise it switches off again. Paging and acknowledgment messages are transmitted in-band, i.e., within the user data flow. This method performs better than the synchronous technique in the presence of light traffic loads.

In HIPERLAN [6], the wireless LAN standard specified by ETSI, radio nodes that need to save power, so-called *p-savers*, communicate their own sleep-awake schedule to the so-called *p-supporter* node. The p-supporter queues all the packets destined to the p-savers and transmits these packets during the p-savers active time.

II. PAGING FOR DYNAMIC POWER MANAGEMENT

We focus on the packet data transfer between a base station, that is connected to the wired network, and mobile users. Other network scenarios, where a node is elected to be the master with respect to the other nodes in the vicinity, can be considered as well. Fig. 1 shows the reference network scenario where user terminals, either mobile or fixed, access the fixed network and communicate among each other through the base station (BS). The BS is responsible for collecting the uplink traffic generated by the users in the cell and for delivering the downlink data flow to the users. We focus on downlink traffic since it is envisioned that in 4th generation wireless systems traffic pattern will be highly asymmetrical, with 50/1 ratio or more favoring the downlink [7].

During the idle time periods, user terminals can switch off parts of the user device (e.g., display, radio frequency component, digital component, etc.) and enter a sleep state. Various sleep states are identified based on the associated power consumption and time to wake up; deeper the sleep state, less the power consumption and larger the delay overhead. The state of operation of the system components is typically controlled by a *dynamic power management* (DPM) policy [8], [9], [10],

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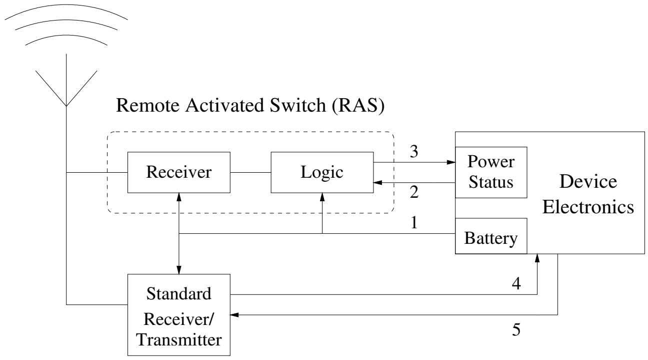

Fig. 2. Scheme of the user device circuit.

[11], [12]. Our objective is to develop a way to trade-off energy saving and traffic QoS degradation by exploiting the synergy between the power management policy that is executed at the user device and the scheduling of downlink traffic at the BS.

In the proposed scheme, users do not need to power on and see whether they have pending traffic at the BS, instead the BS wakes users up when necessary. To implement this we need a method to remotely activate a user terminal through a RF (Radio Frequency) signal, ideally at negligible energy cost. RF tags technology offers good examples of low power or totally passive devices that use RF power received from the base station to drive the logic and transmission parts of the circuit [13], [14], [15], [16]. RF tags have been used as transmitter/receiver devices (transponders) for remote localization and identification of animals, cars and other kinds of items [16], [17], [18].

The schematic representation of a switch that can be used to remotely activate the device is shown in Fig. 2. Whenever the user terminal becomes idle, it enters a sleep state, i.e., the standard receiver/transmitter as well as parts of the device electronics is turned off. Paging signals are received and demodulated by the Remotely Activated Switch (RAS), then the signal information is passed to the logic circuit that detects the bits sequence. If the received sequence matches the user's paging sequence, the device turns on the standard receiver. Notice that the RAS receiver may be either totally passive (e.g., an amplitude demodulator) or supplied by the battery source through connection 1.

In the proposed protocol the base station tracks the power state of each user and exploits this information to adjust the transmission of downlink traffic to the user's energy constraints. If necessary, paging is delayed in order to let users stay in sleep state longer, and hence increase their energy saving, provided that the required QoS is still guaranteed.

The reminder of the paper is organized as follows. We introduce notations and outline some related work in Sect. III. The proposed scheme is introduced in Sect. IV, and its analysis and performance are presented in Sects. V and VI, respectively. Since the aim of the proposed protocol is to let the terminal devices be in sleep state as often as possible, the problem of how to track users position arises. A simple localization protocol that allows a user in sleep state to wake up as soon as it needs to update its position is discussed in Sect. VII. Conclusions and directions for further research are drawn in Sect. VIII.

III. PRELIMINARIES

We assume that a user device can be in L different states depending on the operational status of the system components. We consider that states $1, ..., L-1$ are sleep states, whereas L corresponds to the state in which the user device is fully working. Each state is characterized by a certain power consumption, denoted by P_l $(l = 1, ..., L)$, such that $P_1 < P_2 < \ldots < P_L$. Every transition from state l $(l = 1, \ldots, L)$ to state m $(m = 1, \ldots, L$ and $m \neq l)$ has a cost in terms of power consumption, denoted by $P^t_{l,m}$, and of delay overhead, denoted by $W_{l,m}$. The cost associated with transitions from state l to m with $l = 2, ..., L$ and $m < l$ is usually much lower than the cost associated with the reverse transition and for the sake of simplicity is neglected.

Let us define Z_l $(l = 1, ..., L-1)$ as the minimum time that has to be spent in state l to obtain a positive energy gain. We derive Z_l from the following formula,

$$Z_l \cdot (P_{l+1} - P_l) = W_{l,L} \cdot (P^t_{l,L} - P_{l+1}) - W_{l+1,L} \cdot (P^t_{l+1,L} - P_{l+1}) \quad (1)$$

where the left term is the energy gain obtained from being in state l rather than in state $l+1$ and the right term is the difference between the cost due to transition from l to L and the cost due to transition from $l+1$ to L. Thus we have,

$$Z_l = \max\left\{0, \frac{W_{l,L} \cdot (P^t_{l,L} - P_{l+1}) - W_{l+1,L} \cdot (P^t_{l+1,L} - P_{l+1})}{P_{l+1} - P_l}\right\} \quad (2)$$

DPM techniques are used in electronic systems, such as portable computers and radio communication devices, to automatically detect system components that are idle and switch them off [8], [9], [10], [11], [12]. DMP policies can be classified as predictive or stochastic.

Traditionally, predictive techniques have been applied only to the case $L = 2$, with $l = 1$ being the off state and $l = 2$ the on state. A widely-used predictive technique consists in turning off the system components if an idle time, T_{idle}, greater than or equal to a time-out value T_1 is detected. This approach is based on the assumption that if $T_{idle} \geq T_1$, the system is likely to remain idle for a time period longer than $T_1 + Z_1$ and therefore to obtain a positive energy gain. A more accurate method is proposed in [8] where the upcoming idle time is predicted by using an exponential-average approach. If the predicted idle time is longer than Z_1, the system component is switched off at once. However, predictive techniques have a few limitations: they assume only two states for the system (on and off), cannot provide an accurate trade-off between energy saving and performance degradation, and do not deal with a generic system architecture where service requests can be queued.

A stochastic policy has been proposed in [19] to overcome these limitations. The considered system can enter L states with $L \geq 2$, and it is composed of a *service provider*, a *service requester*, a *power manager*, and a *request queue*. The service provider and requester are represented as Markov processes, and the power manager determines the device state of operation by

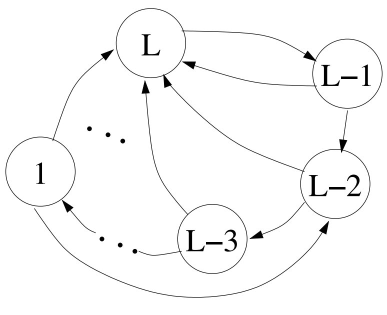

Fig. 3. Example of sleep pattern.

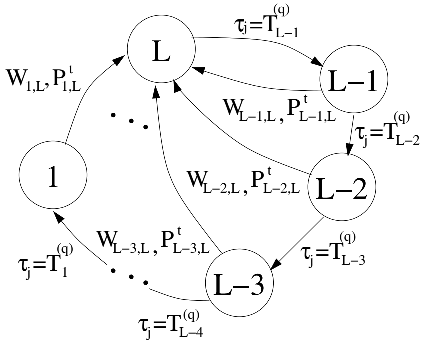

Fig. 4. Evolution of the sleep pattern of reference.

issuing commands to the service provider. In this case, the optimal policy strictly depends on how the system is modeled and on the abstractions that have been made. Moreover, the amount of energy that is consumed by the power manager remains to be accounted for.

IV. THE COMBINED SCHEME

The objective of all DMP policies is to allow users to always obtain a positive energy gain from entering a sleep state while still meeting the required QoS. Unlike the previous DMP policies, the proposed scheme achieves this goal by adjusting the users idle time through an appropriate scheduling of the downlink traffic. Idle times are extended by delaying the waking-up events as long as traffic delay constraints are still satisfied. The proposed scheme combines predictive power management technique executed at the user device with a paging protocol.

A. The Predictive Power Management Policy

The adopted DMP policy operates as follows.

1. Users are grouped into Q different *service classes* depending on their battery status and required quality of service. Users belonging to different service classes are assigned different *sleep patterns*; an example of sleep pattern evolution is shown in Fig. 3. The sleep pattern considered in the following is presented in Fig. 4, which refers to a generic user j belonging to service class q. The sleep pattern is $T^{(q)} = \left[T_1^{(q)}\ T_2^{(q)}\ \ldots\ T_{L-1}^{(q)}\right]$ $(q = 1, \ldots, Q)$, where $T_l^{(q)}$ is the value of time-out after which a user device belonging to service class q enters sleep state l; $T_l^{(q)}$ is set equal to 0 if users never enter sleep state l. Arcs connecting the sleep states to state L represent the user that wakes up and are marked with the associated values of transition delay overhead and power consumption. The variable τ_j indicates the time elapsed since the last time instant j was awake.

2. Whenever a user in service class q enters sleep state l $(l = 1, \ldots, L-1)$, it must spend in l a time period at least equal to $Y_l^{(q)}$ before moving to state $l-1$, with $Y_l^{(q)}$ being a system parameter s.t. $Y_l^{(q)} \geq Z_l$. It follows that

$$\begin{array}{rcll} T_{l-1}^{(q)} & = & 0 & \text{if users in class } q \text{ never enter state } l-1 \\ T_{l-1}^{(q)} & > & T_l^{(q)} + Y_l^{(q)} & \text{otherwise}\,. \end{array} \qquad (3)$$

3. Time-out values $T_l^{(q)}$ $(l = 1, \ldots, L-1)$ are chosen in such a way that (3) holds, and the users' QoS requirements and energy needs are satisfied. For example, if a user has little battery capacity left, it will use a sleep pattern with little or zero time-out values to quickly enter deep sleep states. In this case, the user will save more energy, however the delay penalty to pay to get back to state L may be significant. Whereas, if a user is concerned mainly about traffic quality of service, it will use a sleep pattern with higher and higher values for $T_l^{(q)}$ as l decreases such that it will enter deep sleep states less rapidly.

4. The generic user j belonging to service class q and currently in sleep state l can wake up only if it has spent in l a time period at least equal to $Y_l^{(q)}$ $\left(Y_l^{(q)} \geq Z_l\right)$; i.e.,

$$\tau_j \geq T_l^{(q)} + Y_l^{(q)}\ . \qquad (4)$$

We note that the conditions expressed in (3) and (4) guarantee that a user always achieves a positive energy gain by entering a sleep state. We also highlight that the proposed policy requires the implementation of an extremely simple power manager entity; in fact, once the user device has selected a sleep pattern, it just follows a deterministic pattern through the sleep states.

B. The Paging Scheme

The objective of this scheme is to page users that are following their sleep pattern at proper time instants such that the trade-off between energy saving and delay overhead is optimized.

We assume that the BS knows the service class associated with each user and for each user in sleep state records the last time instant at which the user was awake. The BS is therefore able to compute for the generic user j belonging to service class q the value τ_j and predict the user's current state. The user's current state, denoted by l, is such that the time elapsed since the last time instant j was awake, is greater than or equal to $T_l^{(q)}$ but less than $T_{l-1}^{(q)}$. We also assume that the BS pages users in the same service class by using the same set of paging signals, denoted by $x_l^{(q)}$ $(l = 1, ..., L;\ q = 1, \ldots, Q)$. The reason for this assumption is that a device in sleep state can detect a paging signal through a passive RAS receiver only if the sequence is transmitted at low rate [14]. Thus, in order to keep the signaling overhead small, paging sequences must be short and their number may be not large enough to uniquely address all the users in the same area.

As a consequence, the generic user j belonging to service class q wakes up whenever it has spent in state l a time equal to or greater than $Y_l^{(q)}$ and either one of these two events takes

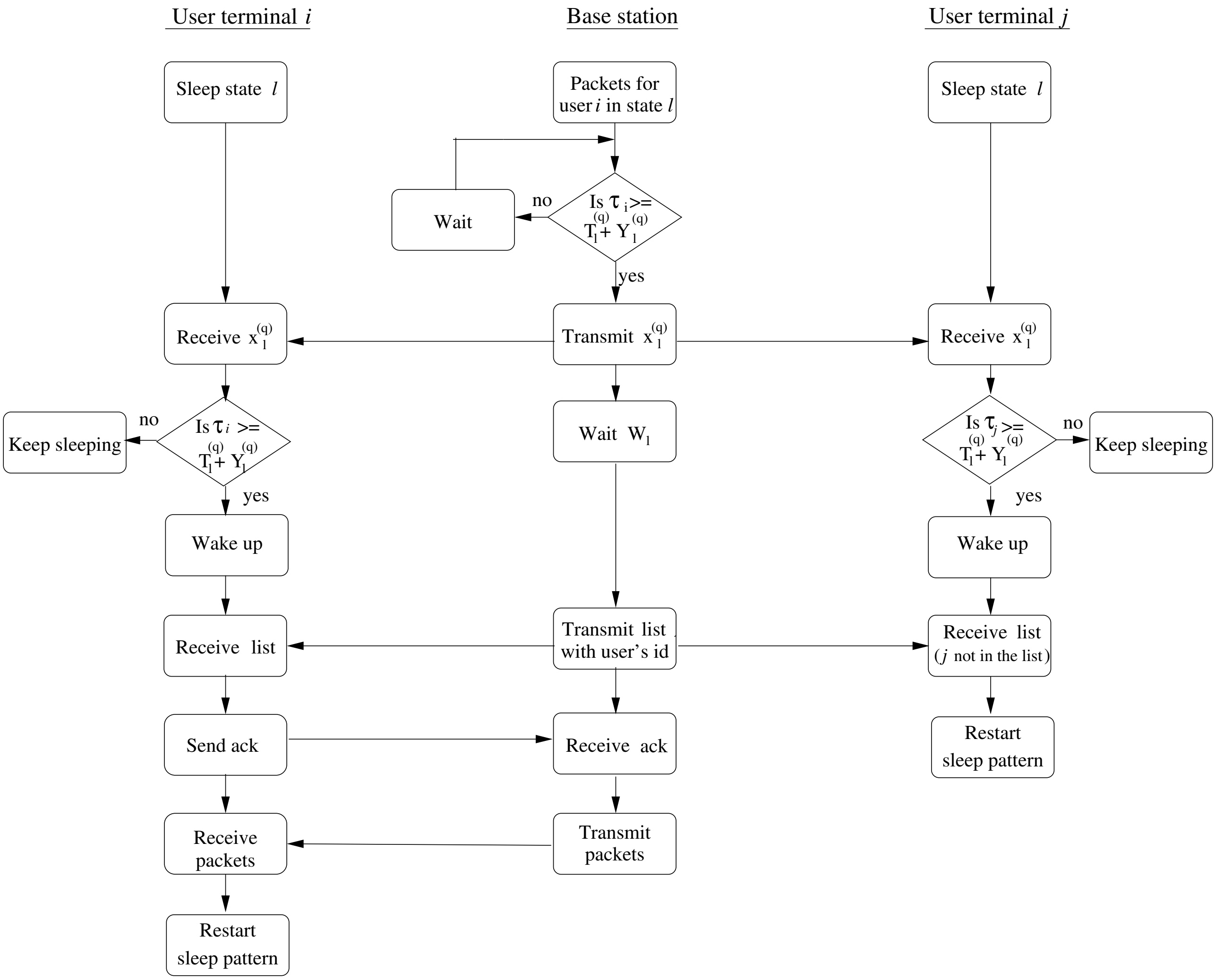

Fig. 5. Diagram of the paging scheme.

place: *i) j* is intentionally paged by the BS, *ii) j* detects a paging signal destined to another user which belongs to the same service class and is in the same sleep state. In order to reduce the probability that a user is awakened by mistake, the BS pages a user that has pending traffic and is currently in sleep state l only if the user has been in l for at least a time period equal to $Y_l^{(q)}$; otherwise the paging transmission is delayed.

As soon as a user becomes active, it listens to the broadcast transmission from the BS containing the list of users with pending traffic. Users that are in the list send an acknowledgment back to the BS and keep their receiver on until the downlink traffic is delivered. Users that are not in the broadcast list enter sleep state $L-1$.

A diagram of the waking up scheme is shown in Fig. 5, where users i and j are assumed to belong to the same service class q and both may be awakened by the same paging signal $x_l^{(q)}$. User j will receive data packets only if it gets active upon the paging signal arrival and sends back to the base station an acknowledgment.

Note that users in the same sleep state do not necessarily wake up all at the same time nor do they move as a group to the next sleep state although they follow the same sleep pattern. Also, a paging signal is transmitted by the BS only if the user to be paged will obtain a positive energy gain by waking up at that time instant.

V. PERFORMANCE ANALYSIS

Let us focus on one group of U users belonging to the same service class and which are assigned the same set of paging sequences and sleep pattern $T^{(q)}$. For the sake of simplicity, we refer to the sleep pattern shown in Fig. 4, however the analysis can be easily extended to the case that includes backward transitions from state l to m with $l = 1, \ldots, m$ and $m < L$. We assume that the time scale is discretized into time slots of unit duration and that the paging signal arrival at the BS is an i.i.d. process with the same distribution for all the users in the group. We denote by P_a the probability that a paging signal arrives at the BS for a certain user in a time slot; by $\tau_j(n)$, the time elapsed from the last time instant the generic user j was awake to time instant n, and by s the current power state of the generic user.

We define D_l as the delay from the time instant when a paging signal for the generic user j arrives at the BS to the time instant when the paging signal is transmitted to j, conditioned on j being in state l. D_l is greater than zero if at the time instant at which the paging signal for j arrives at the BS, τ_j is less than $T_l^{(q)} + Y_l^{(q)}$. We compute the average value of D_l as

$$\begin{aligned}\overline{D}_l &= \sum_{i=0}^{Y_l^{(q)}-1} i \cdot P\,\{\text{paging for } j \text{ arrives at BS when} \\ &\qquad \tau_j = T_l^{(q)} + Y_l^{(q)} - i \,|\, s = l\} \\ &= \sum_{i=0}^{Y_l^{(q)}-1} i \cdot P\,\{\text{paging for j arrives at BS when} \\ &\qquad \tau_j = T_l^{(q)} + Y_l^{(q)} - i \,|\, T_l^{(q)} \le \tau_j < T_{l-1}^{(q)}\} \\ &= \sum_{i=0}^{Y_l^{(q)}-1} i P_a (1-P_a)^{Y_l^{(q)}-1-i} \,. \end{aligned} \tag{5}$$

From (5) we find that

$$\overline{D}_l = Y_l^{(q)} + P_a^{-1}\left[(1-P_a)^{Y_l^{(q)}} - 1\right] \,. \tag{6}$$

By deconditioning on the sleep state assumed by the user and considering that the propagation time over the radio channel is negligible, the total average delay from the time instant when the paging signal has to be transmitted to the time instant when j is awake is

$$\overline{D}_t = \sum_{l=1}^{L-1} \left(\overline{D}_l + W_{l,L}\right) \cdot \frac{P\{s=l\}}{\sum_{k=1}^{L} P\{s=k\}} \,. \tag{7}$$

In order to compute probability $P\{s=l\}$, we first evaluate the average number of users in state l $(l = 1, ..., L)$. By defining $a^l(n)$ as the number of users in state l at time instant n, we have

$$\begin{aligned} a^l(n+1) &= a^l(n) + (\#\text{users in } s = l+1 \text{ moving to} \\ &\quad s = l \text{ at time } n) - (\#\text{users in } s = l \text{ moving to} \\ &\quad s = l-1 \text{ at time } n) - (\#\text{users in } s = l \text{ waking up} \\ &\quad \text{at time } n) \,. \end{aligned} \tag{8}$$

In order to further understand (8), note that: *i)* The term $(\#\text{users in } s = l+1 \text{ moving to } s = l \text{ at time } n)$ is equal to the number of users among the $a^{l+1}(n)$ users whose time spent in sleep state at time n is equal to $T_l^{(q)}$, provided that no user is paged in state $l+1$ at time n; otherwise it is equal to 0. Similarly for the term $(\#\text{users in } s = l \text{ moving to } s = l-1 \text{ at time } n)$; *ii)* The random variables τ_j $(j = 1, ..., U)$ have the same distribution $\forall j$ since the paging arrival process is i.i.d. and same for all the users; thus, we can suppress the subscript j; *iii)* The events that none is paged in state s at time n, and that $\tau(n)$ is equal to a given value, are independent.

Therefore, we write

$$\begin{aligned} a^l(n+1) &= a^l(n) + a^{l+1}(n) P\{\text{none paged in state } s \\ &\quad \text{at time } n \,|\, s = l+1\} P\{\tau(n) = T_l^{(q)} \,|\, s = l+1\} - \\ &\quad a^l(n) P\{\text{none paged in state } s \text{ at time } n \,|\, s = l\} \cdot \\ &\quad P\{\tau(n) = T_{l-1}^{(q)} \,|\, s = l\} - (\#\text{users in } s = l \text{ waking} \\ &\quad \text{up at time } n) \qquad 1 < l < L \,. \end{aligned} \tag{9}$$

Equation (9) can be computed by considering that for $1 < l < L$

$$\begin{aligned} &P\{\text{none paged in state } s \text{ at time } n \,|\, s = l\} = \\ &\qquad \left(1 - P_p^l(n)\right)^{a^l(n)} \,. \end{aligned} \tag{10}$$

where $P_p^l(n) = P\{\text{user paged at time } n \,|\, s = l\}$ (see the Appendix for the derivation of $P_p^l(n)$), and

$$\begin{aligned} P\{\tau(n) = T_{l-1}^{(q)} \,|\, s = l\} &= \\ &= P\left\{\tau(n) = T_{l-1}^{(q)} \,|\, T_l^{(q)} \le \tau(n) < T_{l-1}^{(q)}\right\} \\ &= (1-P_a)^{T_{l-1}^{(q)} - T_l^{(q)} - 1} \,. \end{aligned} \tag{11}$$

The number of users in sleep state l that wake up at time n are the m users among the $a^l(n)$ users that are intentionally paged by the BS $\left(m = 1, ..., a^l(n)\right)$, plus u among the remaining users $\left(u = 0, .., a^l(n) - m\right)$ that have been in state l for a time period equal to or longer than $T_l^{(q)} + Y_l^{(q)}$. By defining $r_l^{(q)} = P\left\{\tau(n) \ge T_l^{(q)} + Y_l^{(q)} \,|\, s = l\right\}$ (see the Appendix for the derivation of $r_l^{(q)}$), we have

$$\begin{aligned} &(\#\text{users in } s = l \text{ waking up at time } n) = \sum_{m=1}^{a^l(n)} \sum_{u=0}^{a^l(n)-m} \\ &\quad (m+u) \begin{pmatrix} a^l(n) \\ m \end{pmatrix} \left(P_p^l(n)\right)^m \left(1 - P_p^l(n)\right)^{a^l(n)-m} \\ &\quad \begin{pmatrix} a^l(n) - m \\ u \end{pmatrix} \left(r_l^{(q)}\right)^u \left(1 - r_l^{(q)}\right)^{a^l(n)-m-u} \\ &= a^l(n) P_p^l + \sum_{m=1}^{a^l(n)} \begin{pmatrix} a^l(n) \\ m \end{pmatrix} \left(P_p^l\right)^m \left(1 - P_p^l\right)^{a^l(n)-m} \\ &\quad r_l^{(q)} \left(a^l(n) - m\right) \\ &= a^l(n) P_p^l + a^l(n) r_l^{(q)} \left[1 - \left(1 - P_p^l\right)^{a^l(n)}\right] - \\ &\quad a^l(n) r_l^{(q)} P_p^l \,. \end{aligned} \tag{12}$$

Then, by writing

$$w^l(n) = P_p^l + r_l^{(q)} \left[1 - \left(1 - P_p^l\right)^{a^l(n)} - P_p^l\right] \tag{13}$$

we get

$$(\#\text{users in } s = l \text{ waking up at time } n) = a^l(n) w^l(n) \tag{14}$$

where $w^l(n)$ represents the probability $P\{\text{user wakes up at time } n \,|\, s = l\}$.

Finally, by using (11)-(14) in (9) we obtain

$$\begin{aligned} a^l(n+1) &= a^l(n) + a^{l+1}(n) \left(1 - P_p^{l+1}\right)^{a^{l+1}(n)} \cdot \\ &\quad (1-P_a)^{T_l^{(q)} - T_{l+1}^{(q)} - 1} - a^l(n) \left(1 - P_p^l\right)^{a^l(n)} \\ &\quad (1-P_a)^{T_{l-1}^{(q)} - T_l^{(q)} - 1} - a^l(n) w^l(n) \,. \end{aligned} \tag{15}$$

Similarly, for $l = 1$ and $l = L$ we have

$$\begin{aligned} a^1(n+1) &= a^1(n) + a^2(n)\left(1 - P_p^2\right)^{a^2(n)} \cdot \\ &= (1 - P_a)^{T_1^{(q)} - T_2^{(q)} - 1} - a^1(n)w^1(n) \qquad (16) \\ a^L(n+1) &= a^L(n) - a^L(n)(1 - P_a) + \\ &= \sum_{l=1}^{L-1} a^l(n - W_{l,L})\, w^l(n - W_{l,L}) \ . \qquad (17) \end{aligned}$$

Notice that the total number of users that are in the transition periods $W_{l,L}$ ($l = 1, ..., L-1$) is equal to $U - \sum_{l=1}^{L} a^l(n)$.

From (15)-(17) we can derive the average number of users in state l ($l = 1, ..., L$) as

$$\overline{a^l} = \frac{1}{N}\sum_{n=0}^{N} a^l(n) \qquad (18)$$

where N is a sufficiently large integer number. The probability that a user is in state l is

$$P\{s = l\} = \frac{\overline{a^l}}{U} \ . \qquad (19)$$

By knowing the expression of P_p^l and $P\{s = l\}$, we derive the channel occupation due to the transmission of paging signals as

$$c_o = \sum_{l=1}^{L} P_p^l \cdot U \cdot e \cdot P\{s = l\} \qquad (20)$$

where e is the paging signal duration.

By considering the generic period of time t we derive the average power saving per user as

$$\begin{aligned} PS \ = \ & \frac{1}{t}\sum_{l=1}^{L-1}\Big\{(\text{power saved in } l) \cdot (\text{time spent in } l) - \\ & [(\text{power cost of transition from } l \text{ to } L) - \\ & (\text{power consumed in } L)] \cdot W_{l,L} \cdot \\ & (\#\text{times user wakes up while being in } l)\Big\} \ . \qquad (21) \end{aligned}$$

We write

$$\begin{aligned} (\#\text{times user wakes up while being in } l) \ &= \\ & \sum_{n=0}^{t} \frac{a^l(n)}{U} w^l(n) \qquad (22) \end{aligned}$$

therefore,

$$\begin{aligned} PS \ = \ & \frac{1}{t}\sum_{l=1}^{L-1}\Big\{ (P_L - P_l) \cdot t \cdot P\{s = l\} - \\ & \left(P_{l,L}^t - P_L\right) \cdot W_{l,L} \cdot \sum_{n=0}^{t} \frac{a^l(n)}{U} w^l(n)\Big\} \ . \qquad (23) \end{aligned}$$

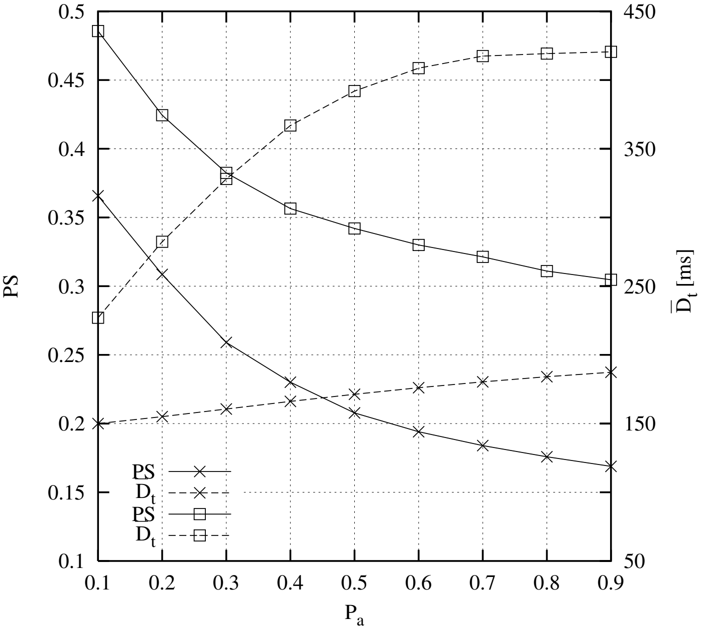

Fig. 6. Power gain and paging delay versus paging signal arrival rate for two different sleep patterns.

VI. RESULTS

Through the analysis carried out in Sect. V we derive the performance of the proposed combined scheme in terms of power gain PS, average delay of the paging signals $\overline{D}_t$, and channel occupation due to paging.

We assume that the number of users is equal to 10 and L is equal to 4, and we compute the system parameters values based on the data reported in [9]. We consider that the power consumed at the user terminal in a sleep state is normalized with respect to the power consumed while the user is in receiving mode; thus, we have: $P_4 = 1$, $P_3 = 0.63$, $P_2 = 0.31$, $P_1 = 0.057$, and $P_{l,4}^t = 1.2 \cdot P_l$ for $l = 1, ..., 3$. The time to wake up from every sleep state is assumed to be constant and equal to: $W_{3,4} = 10$ ms, $W_{2,4} = 100$ ms, and $W_{1,4} = 150$ ms. Results were obtained also for uniformly distributed delay overheads with average equal to the above constant values; in this case Z_l was derived from (2) by using the average delay overheads. However, no significant difference was observed between the two sets of results.

Fig. 6 presents the behavior of PS and $\overline{D}_t$ as the arrival rate of paging signals varies. The plot shows that power saving decreases as paging arrival rate increases since terminals characterized by a lower paging rate enter deep sleep states with higher probability. However, Fig. 6 shows that significant power gains can be achieved even for a high downlink traffic load (i.e., high values of P_a) if a delay in the user's reaction is allowed. On the other hand, if the user has tight delay constraints, a significant power gain can be obtained only in the case of low downlink traffic load. The plot can be used to evaluate the trade-off between the average delay and the power saving experienced by the users as downlink traffic load varies.

The remaining results are derived for four different sleep patterns $T^{(q)}$ with $q = 1, \ldots, 4$, whose time-out values are

TABLE I

TIME-OUT VALUES OF THE CONSIDERED SLEEP PATTERNS (EXPRESSED IN MS).

	$q=1$	$q=2$	$q=3$	$q=4$
$T_3^{(q)}$	1	1	1	1
$T_2^{(q)}$	10^3	50	50	80
$T_1^{(q)}$	10^4	200	200	300
$Y_l^{(q)}$	Z_l	Z_l	$Z_l+20(L-l)$	$Z_l+60(L-l)$

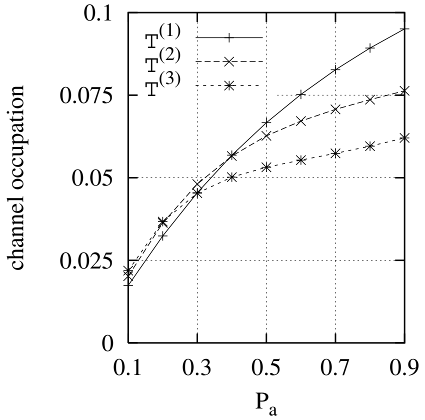

Fig. 7. Channel occupation due to paging signals.

shown in Table I. We note that sleep pattern $T^{(1)}$ lets users remain awake with high probability, while patterns $T^{(q)}$ with $q = 2, \ldots, 4$ allow users to enter sleep states more quickly. Also, as the sleep patterns varies from $T^{(2)}$ to $T^{(4)}$, $Y_l^{(q)}$ $(l = 1, \ldots, L-1)$ increases and the time spent by the users in deep sleep states is longer. The values shown in Table I were chosen as examples of different operational conditions; the derivation of optimal sleep patterns depending on the required QoS and hardware constraints will be subject of further research.

Channel utilization due to paging signals transmitted by the BS is presented in Fig. 7. The paging signal duration, e, is assumed to be ten times less than the packet transmission time. As we vary the sleep pattern from $T^{(1)}$ to $T^{(3)}$, we get higher values for $Y_l^{(q)}$ $(l = 1, ..., 3)$ and users are forced to stay longer in the sleep states. In this case the downlink traffic transmitted by the BS becomes more bursty and therefore channel occupation due to paging decreases. Similarly, fixed the sleep pattern, the delivered traffic is more bursty as the traffic load increases; thus, the number of paging signals sent by the base station and of acknowledgments sent by the paged users decrease.

Figs. 8, 9 and 10 present results obtained through simulation by assuming the same scenario as presented in [5] for comparison purposes. In [5] the downlink packet traffic is assumed to arrive at the BS according to a Poisson distribution. The length of each packet is geometrically distributed and the time unit duration is chosen equal to the mean packet transmission time (we set the mean packet transmission time equal to 10 ms). The BS queues the downlink traffic in a infinite buffer and exhaustively serves the user that sent an acknowledgment. If more than one

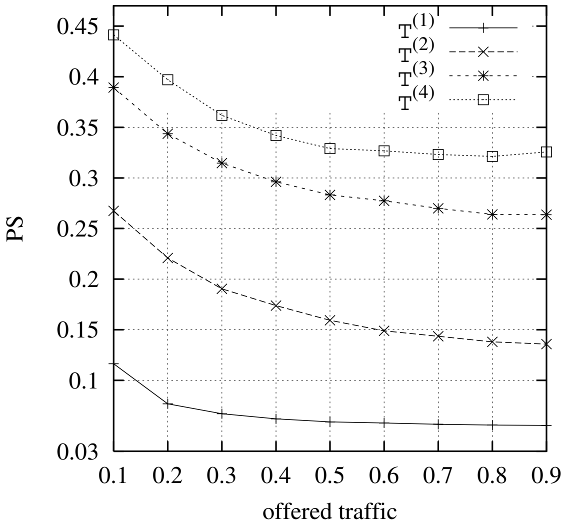

Fig. 8. Power gain obtained through the proposed combined scheme.

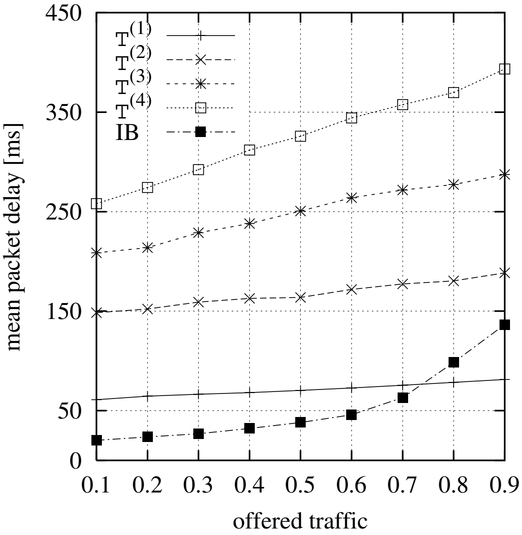

Fig. 9. Mean packet delay due to the proposed combined scheme compared to the mean packet delay obtained through the in-band (IB) protocol.

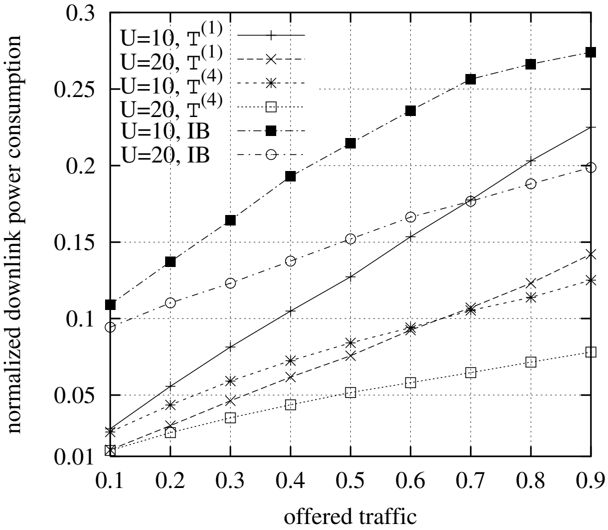

Fig. 10. Normalized downlink power consumption due to the proposed protocol compared to the power consumption due to the in-band (IB) paging scheme.

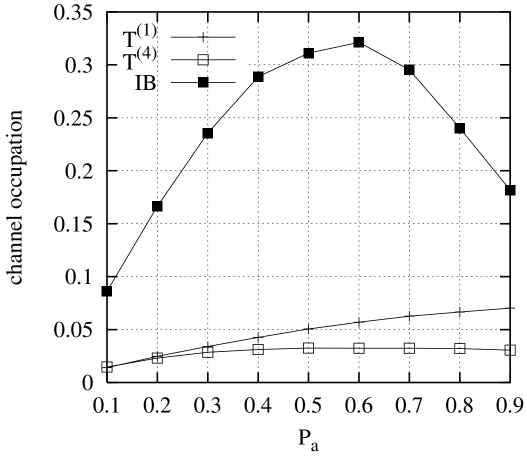

Fig. 11. Channel occupation due to paging signals. The proposed combined scheme and the in-band (IB) protocol are compared.

user sent an acknowledgment at the same time, they are served in a random order. (Please, refer to [5] for further details on the simulation scenario.)

Figs. 8 and 9 show the power gain and the mean packet delay, respectively, as the downlink traffic load varies. Packet delay is measured from the time instant when a packet arrives at the BS to the time instant when the packet is delivered to the user. The in-band protocol presented in [5] gives a lower packet delay than the proposed solution, but it is less efficient from the power consumption viewpoint. For the proposed approach, we consider different sleep patterns corresponding to increasing values of $Y_l^{(q)}$ $(l = 1, ..., 3)$; and, we obtain greater power gain and higher packet delay as we pass from $T^{(1)}$ to $T^{(4)}$. For a low value of PS (i.e., when pattern $T^{(1)}$ is used) we achieve a mean packet delay comparable to the results obtained for the in-band (IB) paging scheme; patterns $T^{(2)}$, $T^{(3)}$, and $T^{(4)}$ imply larger delay but also high power gain.

Fig. 10 shows the average downlink power consumed by a user while being awake, i.e., the average power spent to receive downlink traffic and transmit acknowledgments back to the BS. As in [5], the transmission power is set equal to 100, the paging signal duration, e, is assumed to be ten times less than the mean packet transmission time, and the acknowledgment duration is set equal to $0.02 \cdot e$. Curves are obtained for a number of users equal to 10 and 20. As the traffic load increases, the number of received packets increases, as well as the number of transmitted acknowledgments; thus, the power consumption grows. When the number of users varies from 10 to 20 while the offered traffic is held constant, performance improves since the downlink traffic load per user decreases. A comparison with the in-band scheme shows that the proposed protocol gives better performance for any of the considered sleep patterns. For U=10 and an offered traffic equal to 0.9 the obtained improvement is roughly equal to 16% in the case of $T^{(1)}$ and to 53% in the case of $T^{(4)}$. An even greater improvement is achieved for U=20.

Finally, Fig. 11 compares the channel occupancy due to the proposed paging protocol with the performance of the in-band scheme. The improvement reached with the combined scheme with respect to the in-band scheme is almost equal to one order of magnitude.

VII. THE LOCALIZATION PROTOCOL

We consider the following scenario. The geographic area served by the network is divided into various location areas each of them corresponding to a cluster of C cells. Like in GSM [20], a location database is responsible for a group of location areas and stores the data of those users that are currently in its area of responsibility; location databases are then connected to a home location database. The BSs regularly broadcast the ID of the location area (LAI) they belong to. Thus, a user that is not transmitting/receiving packets can determine its current location by periodically listening to the LAI. If the LAI heard by the user changes, the user notices this change and requests to update its location in the location databases. Whenever a new connection has to be established or there are pending packets to be delivered to a user terminal, a paging signal is broadcast by all the BSs in the location area where the intended user is currently present.

In the proposed paging protocol, users that are in sleep state and enter a new location area will not update their position in the location databases. This would likely cause an unacceptable increase of signaling traffic and packet delay; in order to avoid such inefficiencies, a simple solution is proposed.

We assume that each base station transmits an additional signal (namely, a pilot tone at a given frequency or a short bits sequence) to identify the location area to which the base station belongs. The purpose is to notify the user whether its location area has changed, not to notify the actual LAI; thus, all location areas in the network can be *locally* identified through a small number of different signals by adopting a reuse scheme. If frequency pilot tones are used, the user has to be able to tune its antenna to different frequencies and to detect when the strength of the current pilot tone drops below a given threshold. On the other hand, if bits sequences are used, the RAS has to be enhanced with a memory to store the sequence of the current location area, so that the logic circuit can compare the stored sequence with the newly received value.

Like the paging protocol, the proposed localization technique requires the user to power on only when necessary. The drawback is that the BSs need to broadcast an additional signal to identify the location area besides the actual LAI.

We point out that fast users will not significantly benefit from the presented approach since they have to either wake up often, and therefore they can never reach a deep sleep state, or seldom update their position, hence suffering of the inefficiencies described above. It is our opinion that the fact that fast users will consume more energy than slow users should be seen as a price to pay for accessing the network services at a higher mobility rate.

VIII. CONCLUSIONS AND FUTURE WORK

In this paper we proposed a new paging scheme that allows users to wake up only when necessary. The paging protocol is combined with a power management policy that maximizes the user power saving while still meeting the desired QoS. Results showing the trade-off between power gain and traffic delay were obtained through both analysis and simulation. Compared to the in-band protocol, the presented scheme performs better in terms of both power consumption and paging channel occupation.

With wireless devices supporting a variety of traffic, we aim at developing a system that dynamically adapts to the applications. Future work will deal with the definition of optimal timeout values for the sleep patterns associated with different service classes. We will also extend the proposed scheme by introducing a probability of error in the base station estimation of the users' operational state. This will allow us to study the performance of the proposed scheme in the presence of sleep patterns with probabilistic transitions. Finally, the problem of optimal trade-off between power saving and QoS in a multicast environment will be addressed. In this case, traffic requirements and energy constraints of all users in a multicast group will be taken into account.

APPENDIX

Recall that the arrival of paging signals at the BS is assumed to be an i.i.d. process with the same distribution for all the users in the group. For $l = 2, \ldots, L-1$ we have

$$\begin{aligned} r_l^{(q)} &= P\left\{\tau(n) \geq T_l^{(q)} + Y_l^{(q)} \mid s = l\right\} \\ &= P\left\{\tau(n) \geq T_l^{(q)} + Y_l^{(q)} \mid T_l^{(q)} \leq \tau(n) < T_{l-1}^{(q)}\right\} \\ &= \sum_{i=Y_l^{(q)}-1}^{T_{l-1}^{(q)}-T_l^{(q)}-1} P_a\left(1-P_a\right)^i \\ &= \left(1-P_a\right)^{Y_l^{(q)}-1} - \left(1-P_a\right)^{T_{l-1}^{(q)}-T_l^{(q)}} \qquad (24) \end{aligned}$$

and

$$\begin{aligned} P_p^l(n) &= \\ &= P\{\text{user paged at time } n \mid s = l\} \\ &= P\left\{\text{user paged at time } n \mid \tau(n) < T_l^{(q)} + Y_l^{(q)},\right. \\ &\quad \left. s = l\right\} \cdot P\left\{\tau(n) < T_l^{(q)} + Y_l^{(q)} \mid s = l\right\} + \\ &\quad P\left\{\text{user paged at time } n \mid \tau(n) = T_l^{(q)} + Y_l^{(q)},\right. \\ &\quad \left. s = l\right\} \cdot P\left\{\tau(n) = T_l^{(q)} + Y_l^{(q)} \mid s = l\right\} + \\ &\quad P\left\{\text{user paged at time n} \mid \tau(n) > T_l^{(q)} + Y_l^{(q)},\right. \\ &\quad \left. s = l\right\} \cdot P\left\{\tau(n) > T_l^{(q)} + Y_l^{(q)} \mid s = l\right\} \\ &= 0 + \sum_{i=1}^{Y_l^{(q)}} \begin{pmatrix} Y_l^{(q)} \\ i \end{pmatrix} P_a^i \left(1-P_a\right)^{Y_l^{(q)}-i} \cdot \\ &\quad P\left\{\tau(n) = T_l^{(q)} + Y_l^{(q)} \mid T_l^{(q)} \leq \tau(n) < T_{l-1}^{(q)}\right\} + \\ &\quad P_a \cdot P\left\{\tau(n) > T_l^{(q)} + Y_l^{(q)} \mid T_l^{(q)} \leq \tau(n) < T_{l-1}^{(q)}\right\} \\ &= \left[1 - \left(1-P_a\right)^{Y_l^{(q)}}\right] \frac{1}{T_{l-1}^{(q)} - T_l^{(q)}} + \\ &\quad P_a \frac{T_{l-1}^{(q)} - \left(T_l^{(q)} + Y_l^{(q)} + 1\right)}{T_{l-1}^{(q)} - T_l^{(q)}}\ . \qquad (25) \end{aligned}$$

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