Pinwheel Broadcast Paradigm in Supporting Power-Conserving Mobile Stations

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Abstract*-Due to the limited bandwidth and restricted number of channels in the wireless access environment, the broadcast paradigm has become an important technique for accessing messages. Energy saving is an important issue in the mobile computing environment. In this paper, we propose a broadcast paradigm that constructs the broadcast channel according to the access frequency of each type of message in order to save energy in mobile devices. The pinwheel scheduling algorithm (PSA) presented in this paper is used to organize all types of messages in the broadcast channel in the most symmetrical distribution in order to reduce both the tuning and access time. Performance of the proposed mechanism is analyzed and the improvement is demonstrated with numerical results. The results show that the proposed mechanism is capable improving both tuning time and access time as the skew access characteristic exists among the disseminated messages.*

Keywords: mobile computing, broadcast system, power saving, access time, tuning time.

1. Introduction

Data broadcasting has emerged as an efficient means for the dissemination of information over asymmetry wireless networks [1]. Examples of data broadcasting applications are traffic information, weather information, and news distribution systems. In such applications, client needs for data items are usually overlapping. To avoid multiple retransmissions and to decrease the number of requests from mobile devices (MDs), frequently requested messages are periodically broadcasted on the downlink channels by a base station (BS), and MDs in its cell tune into these channels to extract the desired messages. Rarely requested messages are accessed by MDs by sending explicit requests over the uplink channels and then receiving messages on the downlink channels.

Energy saving is an important issue in the wireless environment [2, 3]. MDs equipped with small batteries with low energy storage are selectively switched between the active mode and doze mode for energy saving. Since much more energy is consumed in the active mode than in the doze mode, a MD in the active mode listens to the broadcast channels to obtain desired messages and then goes into the doze mode while waiting for the desired messages to be transmitted. The performance of broadcast systems is often characterized by two metrics: access time and tuning time [4, 5]. Access time refers to how fast the MD can access the requested data. It reflects the responsiveness of the system. Tuning time, on the other hand, refers to the duration for which the MD stays active. It measures the energy consumed by the MD in the active mode. A good broadcast system should achieve both low access time and low tuning time.

A lot of research effort [5- 9] has focused on broadcast schedules in order to improve access time and/or tuning time, especially in the context of a single item retrieval. Generally, the tuning time can be reduced by means of air indexing [6]. The basic idea is to interleave the index information with data in the broadcast schedule to assist the MD in locating data. Following the links in the index structure, the MD alternates between the active and doze modes until the requested data arrive. However, most existing air indexing schemes were designed for flat broadcast in which all data items are broadcast at the same frequency [6, 10, 11]. This sacrifices responsiveness when MD accesses are not uniformly distributed among data items. Chen et al. [12] proposed organizing the index tree in a broadcast channel, using either Huffman coding with fixed fanout or a greedy algorithm with variable fanout, in order to achieve a new optimal tuning time. However, the access time was not discussed.

To reduce average access time under nonuniform access distribution, popular messages should be broadcast more frequently than unpopular ones. This is known as nonflat data broadcast. However, most existing schemes of nonflat broadcast scheduling did not consider air indexing [9, 13]. Vaidya and Hameed [9] designed an algorithm for minimizing the access time for a given broadcast schedule. A system where different MDs listen to different broadcast channels was also considered. Hameed and Vaidya [14] subsequently presented a log-time algorithm for scheduling broadcasts derived from an existing fair-queuing algorithm. This algorithm significantly improves the time-complexity over previously proposed broadcast scheduling methods. Yu and Tan [15] presented a nonuniform strategy in which messages are broadcast for a number of times proportional to their access frequency in a broadcast cycle to optimize the mean data access time. However, none of the above studies addressed the issue of energy saving. Without indexing, the client has to stay continuously active and monitor the broadcast channel until the requested data arrive. This consumes significant amount of battery power and sacrifices energy efficiency.

This paper presents a new approach which organizes messages in the broadcast channel so that mobile stations can find the desired message quickly and at the same time consume small amount of power. The algorithm presented in this paper, named the pinwheel scheduling algorithm (PSA) [16], is used to organize disseminated messages into broadcast channels in a most symmetrical distribution. No channel is needed for indexing, a small amount of extra information to assist a mobile station to find its desired message is placed in front of each broadcast message then is disseminated together in a time slot. Mobile stations can then receive the desired messages quickly by extracting the extra information. The numerical results show that the presented mechanism achieves signification improvement in both the tuning time and access time.

The rest of this paper is organized as follows. Section 2 presents the construction of the broadcast channel. Section 3 shows the proposed mechanism with its mean tuning time and mean access time for different number of message types. Finally, section 4 concludes this study.

2. The construction of the broadcast channel

In a general broadcast paradigm of the wireless environment, disseminated messages are organized in the broadcast channel appropriately so that mobile stations can quickly find their interested messages and save their power (i.e. reduce tuning time or access time). Since various kinds of messages are with different popularity, with no partiality to treat each kind of message would receive an inefficient consequence.

The access time can be improved by organizing popular messages with higher disseminating frequency in broadcasting. For the economic of bandwidth usage, extra information combined with the message is placed into a time slot for quick access. The mobile station extracts such information at the beginning of each time slot to determine immediately if the message is desired. If it is, the mobile station continues receiving the rest of the time slot. If it is not, the mobile station goes to sleep. According to the extra information received, the mobile station awakes up then returns to active mode in an accurate time slot to proceed the next searching. This strategy gives very short access time and tuning time for mobile stations receiving popular messages.

Figure 1 shows the structure of the broadcast channel. The broadcasting message can be recognized quickly by mobile stations by extracting the key field. If the key is recognized to be desired, the message followed in the broadcasting slot is received, otherwise, refer to the next field of the extra information, the mobile station goes to doze mode knowing the exact time slots that it will wake up to proceed the next reception. Figure 2 illustrates how a mobile station gets the required message.

In this paper, the Pinwheel Scheduling Algorithm (PSA) is proposed to organize messages in the broadcast channel. As Figure 3 shows, imagine the broadcast channel as a slotted ring, messages with different popularity organized by the PSA form various regular polygons in this ring. A mobile station may acquire a desired message any time, therefore, the average waiting slots would be minimum if the broadcasted messages form a regular polygon in the ring.

To illustrate how a mobile station acquires the desired message, some notations are defined as follows.

K : the number of message types.

qi : the key of message i (i=0~K-1).

The broadcast messages are organized in the broadcast channel using the PSA in the sequence q0, q1, q2, …, qK-1. Assume the accessed frequencies of message qi (i=0~K-1) are sorted in ascending order, i.e., message q0 is accessed most frequently by mobile stations and qK-1 is accessed least. Therefore, regarding to the broadcast channel, K regular polygons are formed. An efficient way for a mobile station to find the desired message is to seek the key from q0 to qK-1. For this reason, the distance of qi to the nearest qi+1 is recorded in the forward field of the extra information of qi (i=0 ~ K-2). A NULL symbol in the forward field of qK-1 implies that the desired message has not been broadcasted.

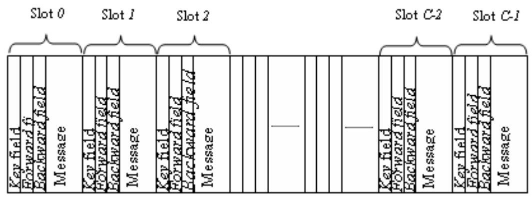

Figure 1. Structure of the broadcast channel

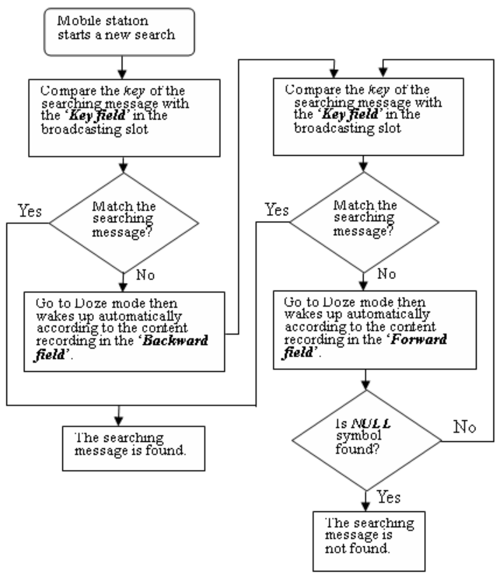

Figure 2. The flowchart that a mobile station receives a desired message.

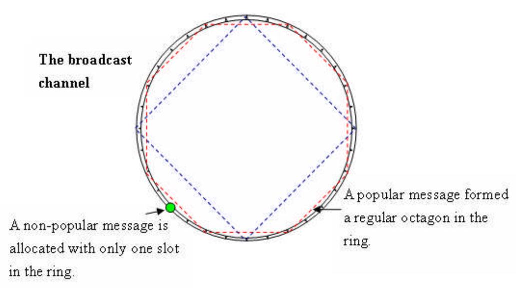

Figure 3. The concept of PSA.

Having synchronized with the system clock, a mobile station extracts the key field of the broadcasting message qi. If key qi (i=1~K-1) is not the desired message, the mobile station reads the backward field which records the distance of qi to the nearest q0 (the most popular message should be looked for next), it then enters the doze mode and starts counting according to the content of the backward field and wakes up when q0 begins to be broadcasted. If key q0 is not the desired one, the mobile station returns to doze mode again then acquires the nearest q1, the next most popular message. Eventually, qi can be found if it is broadcasted by the base station.

2.1. The Pinwheel Scheduling Algorithm (PSA)

The concept of the PSA exploits an algorithm which organizes messages in the broadcast channel in a most symmetrical manner. Consider a broadcast channel possessing C time slots, in which one kind of message has to be broadcasted m times, by using PSA, the messages form a regular m polygon. To broadcast K kinds of messages, m0, m1, m2, … mK-1 in C time slots, using the PSA, m0, m1, m2, … and mK-1 polygons would be formed as regular as possible. If C is large enough, each polygon would be a regular polygon. Consequently, the messages placed in the time slots are disseminated cyclically by the base station. The major purpose that the base station organizes the messages quantitatively and symmetrically is to improve the access delay.

In a periodical broadcast channel with C empty slots numbered S0, S1, S2, … , SC-1, assume message qi must be disseminated mi times (mi≦C). The slots occupied by message qi are numbered U0, U1, U2,…and Umi-1, where U0<U1<U2<…<Umi-1. To make the distribution most symmetrical, the difference of a distance between any two adjacent slots of message must be less than or equal to 1. The condition can be written as follows,

$$\left|(U_l - U_{l-1}) - (U_j - U_{j-1})\right| \le 1,\ (l = 1 \sim m_i - 1,\ j = 1 \sim m_i - 1,\ l \ne j) \quad (1)$$

The positions of each occupied slot Ul (l = 0~ mi -1) can be represented as a series Su,

$$S_u = \lfloor lC / m_i \rfloor \quad (2)$$

When C >> mi, both the arranged messages and the remaining empty slots can be almost symmetrical.

After one message type has been arranged completely, the remaining empty slots are re-numbered and the same procedure is repeated for the next message type. In the proposed strategy, the most popular messages are arranged with the best symmetry to improve the access time. For non-popular messages, whether they are symmetrically arranged or not has little impact on the efficiency.

When all kinds of messages have been organized in the broadcast channel sequentially, the distance between qi and the nearest qi+1 (i=0~K-2) is recorded in the forward field of qi, and the distance between qi and the nearest q0 is written in the backward field of qi (i=1~K-1). Nothing is recorded in the backward field of q0 since it is never been referred. A NULL symbol is placed in the forward field of qK-1 to show the mobile station that the desired message is not found.

Since message q0 is disseminated m0 times, the distance between two adjacent slots is C/ m0, therefore, the average number of slots for which qi (i=1~K-1) waits for the nearest q0 is C/(2m0). Another attention, the average number of slots that qi (i=0~K-2) waits for the nearest qi+1, can be figured out by the following explanation.

Consider messages qi and qi+1 to be broadcasted n and m (n≧m) times in possessing the C time slots broadcast channel. Using the PSA, a regular n polygon and a regular m polygon on a circle are formed for messages qi and qi+1, respectively. The relationships between n and m can be written as follows,

$$n = \lceil n/m \rceil (n+m-\lceil n/m \rceil m) + (\lceil n/m \rceil - 1)(\lceil n/m \rceil m - n), \quad (3)$$

let

$\alpha = \lceil n/m \rceil$, $\beta = (n+m-\lceil n/m \rceil m)$, $\gamma = \lceil n/m \rceil - 1$ and $\delta = (\lceil n/m \rceil m - n)$.

The significance of α, β, γ, δ are that a regular m polygon among its m edges there are β edges maps to α vertices of a regular n polygon, and there are δ edges maps to γ vertices of a regular n polygon. Consequently, the average number of slots for which qi waits for the nearest qi+1 is

$$T(n,m,C) = \frac{\beta \sum_{i=0}^{\alpha-1} (iC/n + C/2n) + \delta \sum_{i=0}^{\gamma-1} (iC/n + C/2n)}{n}$$
$$= \frac{C}{n^2} [(n+m-\lceil n/m \rceil m) \sum_{i=0}^{\lceil n/m \rceil - 1} (i+1/2) + (\lceil n/m \rceil m - n) \sum_{i=0}^{\lceil n/m \rceil - 2} (i+1/2)] \quad (4)$$

2.2. The mean tuning time

To analyze the mean tuning time and the mean access time, more notations are defined as follows,

Ai : the number of accesses of message i (i=0~K-1) in a statistical duration.

A: the total number of accesses in a statistical duration, $A = \sum_{i=0}^{K-1} A_i$.

T0: the average number of slots for which message qi waits for the nearest q0 (i=1~K-1).

Ti: the average number of slots for which message qi waits for the nearest qi+1 (i=0~K-2).

Ci: the number of slots allocated to message qi, where

$$C_i = C \lfloor A_i / A \rfloor, \; C_0 = (1 - \sum_{i=1}^{k-1} \lfloor A_i / A \rfloor)$$

The mean tuning time is the mean number of slots in which mobile station stays in active mode multiplies the time spent to acquire the extra information plus a time for receiving the message. Denote TMean_Tuning_Slot as the mean number of slot in which mobile station stay in active mode, then

$$T_{Mean\_Tuning\_Slot} = \frac{A_0}{A}[\frac{A_0}{A} + 2(1 - \frac{A_0}{A})] + \frac{A_1}{A}[\frac{A_1}{A} + 3(1 - \frac{A_1}{A})] + \frac{A_2}{A}[\frac{A_2}{A} + 4(1 - \frac{A_2}{A})]$$
$$+ \ldots + \frac{A_{K-1}}{A}[\frac{A_{K-1}}{A} + (K+1)(1 - \frac{A_{K-1}}{A})]$$
$$= 1 + \frac{\sum_{i=0}^{K-1}(i+1)A_i}{A} - \frac{\sum_{i=0}^{K-1}(i+1)A_i^2}{A^2} \quad (5)$$

where Ai/A is the probability of message qi accessed by a mobile station. When a new search starts, the mobile station has to wait for a nearest q0 if the acquiring key is not desired, then goes to sleep to wait for a nearest q1 if q0 is not the required one. Similarly, the mobile station holds probability Ai/A to consume one tuning slot power to find the desired message and holds probability (1-Ai/A) to consume (i+1) tuning slot power. Therefore, the mean number of tuning slots to access message qi is $[A_i/A + (i+1)(1 - A_i/A)]$.

2.3. The mean access time

The mean access time is the mean number of slots for which mobile station spends to complete a message accessing multiplies the slot time. Let TMean_Access_Slot represent the mean number of slots that a mobile station spends to complete a message accessing, then

$$T_{Mean\_Access\_Slot} = \frac{A_0}{A}[\frac{A_0}{A} + T_0(1 - \frac{A_0}{A})] + \frac{A_1}{A}[\frac{A_1}{A} + (T_0 + T_1)(1 - \frac{A_1}{A})]$$
$$+ \frac{A_2}{A}[\frac{A_2}{A} + (T_0 + T_1 + T_2)(1 - \frac{A_2}{A})] + \ldots$$
$$+ \frac{A_{k-1}}{A}[\frac{A_{k-1}}{A} + (T_0 + T_1 + T_2 + \ldots + T_{k-1})(1 - \frac{A_{k-1}}{A})]$$
$$= \frac{1}{A} \sum_{i=0}^{k-1} A_i [\frac{A_i}{A} + \sum_{j=0}^{i} T_j (1 - \frac{A_i}{A})] \quad (6)$$

where

$$T_0 = \frac{C}{2C(1 - \sum_{i=1}^{k-1} \lfloor A_i / A \rfloor)} = \frac{1}{2(1 - \sum_{i=1}^{k-1} \lfloor A_i / A \rfloor)}$$

$$T_1 = T(C_0, C_1, C), T_2 = T\,(C_1, C_2, C), T_3 = T\,(C_2, C_3, C), \ldots, T_{k-1} = T(C_{k-2}, C_{k-1}, C)$$

The mobile station holds probability Ai/A to spend one slot time to get the desired message and holds probability (1-Ai/A) to spend T0 + T1 + T2 +…+ Ti slots (can be solved by using Eq. 4). Therefore, the mean number of slots to access message qi is

$$A_i/A+(T_0+T_1+T_2+...+T_{i-1})(1-A_i/A).$$

3. Numerical results

Assume that the knowledge of the key of each kind of message is disseminated to mobile stations by a specific broadcast channel when there is message either being inserted into or removed from the broadcast cycle. The key is essentially related with the mobile stations to access the desired messages. Chen, Yu and Wu [12] presented a good solution to minimize the tuning time. Based on the access frequency, they proposed methods to build index trees and proved that the index tree with fixed fanout has minimal tuning time. However, the access time was not discussed, and the method of indexing mobile stations to acquire desired messages was not explained either. To estimate the efficiency of the proposed PSA mechanism, we compare the tuning time and access time of PSA to the index tree with 2 fixed fanouts (TId=2) [12] since the broadcast overhead (the information assisting mobile stations to access desired messages) of both mechanisms is the same.

Large degree of skewness (DS) implies that variation of access frequency between message types is large. In the numerical analysis, DS is defined from 1 to 3 to respectively represent the access frequency among disseminated messages to be the same (i.e. A0, A1, A2…are the same.), linear (e.g., A0, A1, A2, A3… are 1, 2, 3, 4, …) and exponential (e.g., A0, A1, A2, A3… are 1, 2, 4, 8,…). It is assumed that each broadcast channel is divided into 500 time slots so that each disseminated message can form either a regular polygon or near-regular polygon on the broadcast channel using the PSA.

Figure 4 shows the comparisons of the mean tuning slots between the PSA mechanism and the index tree with 2 fixed fanouts (TId=2) versus different DS. As Figure 4 shows, the mean tuning slots the PSA mechanism spent is sensitive to the DS but that of the TId=2 mechanism is insensitive to the DS. When DS = 1, the PSA mechanism acts as a linear search, therefore, the mean tuning slots is approximately half of the message types. The efficiency is improved obviously as the DS increases. The PSA mechanism receives a better efficiency than the TId=2 mechanism when DS = 3. On the other hand, the mean tuning slots of the TId=2 mechanism is stationary on different DS and increases slowly with increasing number of message types.

The comparisons of the mean access slots are shown in Figure 5. As explained in Figure 4, the mean access slots of the PSA mechanism is susceptible to the DS but the T_{Id}=2 mechanism is not. When DS = 1, the mean access slots of the PSA mechanism increases rapidly as the number of message type increases. The mean access slots of the PSA mechanism is improved when DS = 2. The mean access slots of the PSA mechanism is better than when DS = 3. In addition, the mean access slots of the T_{Id}=2 is approximately twice of the message types since the number of broadcasting messages constructed by the T_{Id}=2 is twice of the message types.

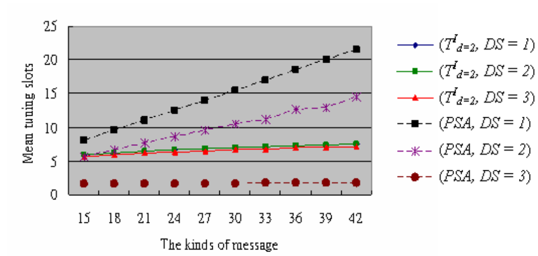

Figure 4. Comparisons of mean tuning slots between PSA and Index tree with 2 fixed fanouts (T_{Id}=2).

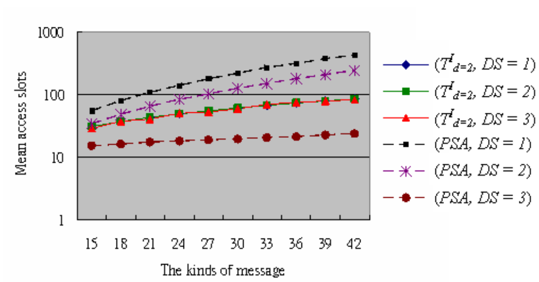

Figure 5. Comparisons of mean access slots between PSA and T_{Id}=2.

4. Conclusion

A new broadcast mechanism supporting mobile stations to achieve power conserving is presented in this paper. The number of slots assigned to a kind of disseminated messages is dependent on the access frequency by mobile stations. Using the PSA, all kinds of messages can be organized in the broadcast channel in a most symmetrical manner. Using the message searching algorithm presented in this paper, mobile stations can receive their desired messages with a low tuning time and access delay. The numerical results show the mean tuning time and mean access time can be significantly improved when a larger skewed access frequency exists among the kinds of message. The suggestion made in this paper is: when the larger skewed access characteristic exists among different type of messages, to achieve power conserving, the system may use the PSA to organize the disseminating messages, and mobile stations can use the proposed message searching algorithm to receive desired messages, otherwise, the index tree mechanism proposed by [12] provides a good solution.

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