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On the hybrid using of unicast-broadcast in wireless sensor networks☆

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ABSTRACT

A hybrid Unicast joint Broadcast Aggregation (UBA) schedule scheme is proposed for maximizing aggregation information and minimizing delay for wireless sensor networks (WSNs). UBA scheme adopts following regimes for maximizing aggregation information and minimizing delay. (a) The nodes in the far to sink region adopt broadcast manner, which can not only efficiently collect more sensing information within the same time slot but also reduce overall network delay. (b) The nodes in the near to sink region use unicast manner to collect sensing information, which can efficiently save energy consumption to extend network lifetime. This is UBA scheme with a great advantage that it can collect more sensing information and reduce delay without shortening network lifetime. Simulation and theoretical analytical results clearly indicate that the proposed scheme can significantly improve sensing information by 25% and reduce delay by 14% to 18% under the same network lifetime.

1. Introduction

The key function of wireless sensor networks (WSNs) is sensing and collecting surrounding information periodically through sensor nodes constituting the network and aggregating to sink node for further processing [1–5]. In those applications, all of the node samples are in each sample cycle. For each sample cycle, all sensor nodes do sampling once [2,5]. Data aggregation refers to the situation in which two data packets meet with each other at a node in the routing procedure and aggregated into one new data packet [1,6].

According to WSNs for real-time requirements, data aggregation can be divided into two categories. (1) Convergecast [7]. It is one of the most used non-real-time data aggregation patterns in WSNs. (2) Real-time data collection. In the real-time data aggregation network, sink node needs to gather as much sensing information as possible in a predetermined sample cycle [1]. For the node, if sensing information collected by node has no available time-slot to be sent in this sample cycle, it will cause data loss. The reason is that this node will generate a new piece of sensing information in the next sample cycle and it becomes meaningless to transmit the old sensing information [1]. After this happens, there is no doubt that sensing information aggregated by sink node will be reduced due to data loss. In general, sample cycle of real-time network is much less than non-real-time network. Real-time network time-slot schedule will not wait to receive all the sensing information from node's children before sending them in accordance with the method of aggregation convergecast.

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Data aggregation schedule scheme in design of real-time is more difficult than convergecast for the following four reasons. (a) More complicated scheduling. Node transmits only once in convergecast but many times in real-time, so it is wise to choose to transmit many times. But when to transmit is also a complex issue, which increases the difficulty in scheduling design [8–13]. (b) The combination between real-time data aggregation scheduling and network lifetime optimization leads to its scheduling design more difficult. Therefore, it is an important research issue on how to achieve trade-off optimization between lifetime of network and real-time in real-time data aggregation. (c) The number of sensing information. In convergecast, sensing information of each node can be aggregated by sink. However, when sample cycle is small, the sensing information generated by the node will be discarded if it fails to be sent out within this sample cycle. It means that the packet loss ratio will be higher. (d) Delay. Delay is defined as the time-slots from generating sensing information to be received by sink [11,14]. Obviously, in real time data aggregation, delay should be as small as possible, but smaller delay means that node's data needs to be sent to sink node as soon as possible, which consumes more energy and needs more time slots to transmit the data packet, it also increases the level of difficulty of scheduling.

Summarily, in the real-time data aggregation, the major concerns for WSNs are to maximize the sensing information and network lifetime, meanwhile, minimize the average data transmission delay. To make some improvements, we put forward a hybrid scheduling scheme that combines the unicast with broadcast strategy between sensors within predetermined sample cycle given by system. Different from previous studies, this article describes a simple but novel data aggregation schedule approach through which the performance of real-time data aggregation can be further improved.

The main contributions of this article can be summarized as follows:

(1) A hybrid Unicast joint Broadcast Aggregation (UBA) schedule scheme is proposed for WSNs. UBA scheme firstly proposes to use unicast joint broadcast scheduling method to transmit sensing information, which can improve multiple performances of scheduling algorithm.

The advantages of adopting hybrid unicast joint broadcast method are as follows: (a) Increasing sensing information collected by sink node. When adopting the broadcast method through which data packet is transmitted to one-hop neighbor nodes, as long as any one-hop neighbor node transmits the sensing information to sink node by multi-path routing, it is regarded as successful transmission. Therefore, the probability of collecting this sensing information is greatly improved. (b) Reducing delay. Using broadcast method can reduce delay in which sensing information of the node is transmitted to sink through multi-path routing, so the fastest route in multi-path routing is the delay of this node. Compared with unicast method, the delay is reduced. (c) Achieving above goals without shortening the network lifetime. The main disadvantage of broadcast method is more energy consumption, and therefore it is rarely applied to WSNs where energy is very valuable. After a further study of real-time data aggregation schedule scheme, we find that data sending forward times of nodes in the near sink region are higher than nodes in the far sink region, so their energy-consumption are higher. Therefore, in UBA schedule, different data transmission methods are adopted in different regions like using unicast in the near sink region and broadcast in the far sink region. In this way, we can take full advantage of residual energy of nodes in the far sink region to collect more sensing information and reduce data transmission delay without shortening the lifetime of network.

(2) Through the analysis and design of time slot scheduling algorithm, network delay will be reduced to minimum.

In UBA scheme, we try to assign time slot for child node of before that of parent node. Only in this way, can parent node receive child nodes sensing information within this sample cycle, rather than the next. If the time slot for child node is after parent node, sensing information received from child node will not be transmitted until the arrival of the next sample cycle because parent node has sent the fusion data packet. It will cause serious delay. So, under the interference free model, this paper proposes a Time-Slot Distribution Algorithm for Children (TSDAC) algorithm for minimizing data transmission delay in WSNs, and we theoretically prove that the proposed scheduling algorithm is feasible.

The rest of this paper is organized as follows: In Section 2, the related works are reviewed. The system model and problem are described in Section 3. In Section 4, a hybrid unicast joint broadcast aggregation (UBA) schedule scheme is proposed for WSNs. The experimental results of UBA are provided in Section 5. We draw the conclusions in Section 6.

2. Related work

Data collection is the key function for WSNs [15,16]. Processing the gathered information efficiently is a key issue for WSNs [13–15]. A great deal of work has been devoted to this field [13–16].

The convergecast problem is not the same with TDMA scheduling. In convergecast [7,17], each node generates only one data packet. Convergecast operation is divided into two steps: (a) Data receiving stage, where each node only receives data packet from its children nodes; (b) Data transmission stage, where the received data and its own data are aggregated into one data packet and then are sent to sink node via multi-hop.

Most research works on convergecast divide this problem into two parts. Firstly, a logical tree is constructed, which is followed by the scheduling of transmissions with the constructed tree. Secondly, the common objective of scheduling algorithms is to use the minimum number of time slots. Those studies can be seen in TAG [17], FILA [18], and EXTOK [19]. Liu et al. [20] proposed a centralized scheduling algorithm with the delay bound of $23R+\Delta+18$ time slots, where $R$is the network radius and $\Delta$is the maximum node degree.

Cluster-based data collection can be regarded as a data aggregation [21]. In the cluster based WSNs, the network is divided into many same structure called cluster, each cluster has a node called cluster head (CH) node, all other nodes called cluster member (CM). CM node transmits its own data to cluster head, and cluster head fuses the collected data and then sends it to sink through the multi-hop routing [21].

For the purpose of increasing sensing information aggregated by sink node and realizing fast network data collection to sink, Parvaneh Rezayat proposed a novel real-time Power-Aware Two-Hop (PATH) based routing protocol [22]. A two-hop neighborhood information-based routing protocol is proposed for real-time WSNs by Yanjun Li [23]. Bo Yu has proposed Distributed Aggregation Scheduling algorithm (DAS) [24]. DAS is to determine schedules for all the nodes of network to solve the distributed aggregation scheduling problem with a distributed manner.

According to these studies above, we can know that a commonly used method is unicast. This paper is different from previous studies, which takes advantage of the characteristic of broadcast method, a hybrid of Unicast joint Broadcast Aggregation (UBA) schedule scheme is proposed in this paper. The performance of UBA scheme is better than the previous scheduling strategy.

3. The system model and problem statement

3.1. The network model

We consider a multi-hop WSNs $G=(V, E)$, where $V=\{v_1, v_2, ..., v_n\}$is a set of nodes which are deployed following a homogenous Poisson point process with a density ofρsensors per unit area in a two-dimensional region [15]. $v_1 \in V$ is the base station (or sink) at the center of network which collects the final aggregation result. All nodes once deployed are not movable and have the same initial energy and communication range$r$.$E$is a set of communication links. Following common practices [10–14,20], it is assumed that the sensor nodes are organized into a tree structure rooted at the base station for data collection.

Similar to other studies [20], clocks are assumed to be synchronized among sensor nodes [6,14]. Time is divided into slots and the duration of a time slot allows a sensor node to transmit one packet. To simplify presentation, we assume that the acquired data reported by each node at a sampling interval, if any, fit into one packet. Interference model of network uses literature [1,6,20]: each node has only one transmit frequency, sending and receiving data can not happen simultaneously. And for any node$N_i$andN_j,$i, j > 0$, when satisfying formula(1),$N_i$can transmit data to$N_j$successfully within the communication range r.

$$|N_i - N_j| \le r, |N_k - N_j| \ge (1+\varepsilon).r, \varepsilon > 0, k \notin i, k \notin j \tag{1}$$

To avoid collisions, only transmissions that do not conflict with each other are allowed to be scheduled in the same time slot.

3.2. Data aggregation model

We consider a cyclical data collection scenario in which each sensor node generates a data per sampling interval by sensing its physical environment and transmits it to a special node called sink, via multi-hop communications [7,17,18]. In the course of collecting information, data aggregation at intermediate forwarding nodes can substantially improve energy efficiency by reducing the number of transmissions [13–16]. On the other hand, it also increases the amount of the sensing information contained in a single packet.

We adopt Ref. [1] proposed Generalized Maximum (GM) data aggregation functions some examples including max or min, ranging (i.e., [min, max]), and n-largest (or smallest) values. With this data aggregation function, intermediate node collects information from other sensor nodes, processes and aggregates them into a unit of information, i.e. a packet [1]. Then the package is sent to sink node or to next hop [1]. Another important feature of GM functions is that it allows duplicate data, i.e. inserting another copy of data does not affect the function results, so this feature can be adopted to broadcast transmission.

3.3. Energy consumption model and related definitions

The energy-consumption model is based on the power consumption model in [1,7,8]. The notation is given in Table 1. According to the distance between transmitter and receiver, the energy consumption for transmitting l-bit packet over distance d, which is denoted as E_t, can be expressed by free space and multi-path fading channel models as Eq. (2). The energy consumed for receiving data is in Eq. (3).

$$\begin{cases} E_t = lE_{elec} + l\varepsilon_{fs}d^2 if d < d_0 \\ E_t = lE_{elec} + l\varepsilon_{amp}d^4 if d > d_0 \end{cases} \tag{2}$$

$$E_R(l) = lE_{elec} \tag{3}$$

E_{elec} in the formula means the energy consumption in transmitting circuit. If the transmitting distance is less than threshold d_0, the consumption of power amplification adopts the free space model. If more than threshold d_0, adopts the multi-path attenuation model. $\varepsilon_{fs}$and $\varepsilon_{amp}$are the energy required to amplify power respectively in the two models. l denotes the number of bits of data. In this paper, the parameter of specific configuration above refers Ref. [7,8], shown as Table 1.

Table 1.
Network parameters.

Parameter	Value
Threshold distance (d_0) (m)	87
Sensing range r_s (m)	15
E_{elec} (nJ/bit)	50
e_{fs} (pJ/bit/m^2)	10
e_{amp} (pJ/bit/m^4)	0.0013
Initial energy (J)	0.5

3.4. Problem statement

We assume that the time for one round of data collection is Ωtime slot, where variable $X^t_{(i,j)} \in \{0, 1\}$denotes whether a transmission has taken place from node i to node j in time-slot $t|t \in \{1..\Omega\}$. The purpose of UBA schedule scheme is how to select$X^t_{(i,j)}|t \in \{1..\Omega\}$,$i, j \in \{1..n\}$, in the case of satisfying Eq. 1 to make the following objectives optimization.

(1) The maximization of sensing information collected by sink

ϑ_i is the packet owned by node i, $\varsigma_i$denotes sensing information of node i. Each node of network generates sensing information at the beginning of a sample cycle. At this time, node i has the packet $\vartheta_i$including the sensing information ς_i. With the data aggregation, node i combines multiple packets received from other nodes into one packet $\vartheta_i$which includes multi-path routing sensing information, such as$\{\varsigma_i, \varsigma_j, \varsigma_k, ...\varsigma_l\}$. Denoting the number of node$i$sensing information included in packet$\vartheta_i$as ω_i=$|\vartheta_i|$=$|\varsigma_i, \varsigma_j, \varsigma_k, ...\varsigma_l|$. In a sample cycle, sensing information number $\omega_s$collected by sink node is the sensing information number of the entire network. The number of sensing information $\omega_s$aggregated by sink node is that the entire network. Thus, the first target of UBA schedule scheme is to maximize the sensing information of sink aggregated within a sample cycleΩ, i.e.$Max(\omega_s)$.

(2) Delivery delay (denoted as d_i). Delay d_i of Sensing information ς_i refers to the time-slots from node i generating sensing information ς_i to sink receiving it. And D denotes average delay of sink receiving the sensing information, i.e. $D=\sum_{i=1}^{n} d_i/n$, where n denotes the number of nodes in the network. Thus, the second goal of UBA schedule scheme is to minimize the D, i.e.min (D).

(3) Lifetime (denoted as ℓ): Like Refs. [8,17], lifetime is defined as the death time of the first node in the network. The third goal of UBA schedule scheme is to maximize ℓ, it also means minimizing node energy consumption which is the biggest in WSNs. $E_i$denotes node $i's$energy consumption, E_{ini}denotes node $i's$ the initial energy, i.e. $\max(\ell) = \max(E_{ini}/E_i)$.

Obviously, the goal of UBA schedule scheme can be calculated as follows:

$$\begin{cases} max(\omega_s), \min(D), \max(\ell) = \max(E_{ini}/E_i) \\ s.t. X^t_{(i,j)} \in \{0, 1\}|t \in \{1..\Omega\}, i, j \in \{1..n\} \\ |N_i - N_j| \le r, |N_k - N_j| \ge (1+\varepsilon).r|\varepsilon > 0, k \notin i, k \notin j \end{cases} \tag{4}$$

4. A hybrid unicast joint broadcast aggregation (UBA) schedule scheme design

4.1. The motive of UBA scheme

UBA scheme is an ingenious schedule strategy which can collect more sensing information, minimize network delay, and be able to significantly improve network performance by using unicast joint broadcast method at an appropriate level. Research motivation of unicast joint broadcast scheme(UBA) schedule scheme are analyzed from the following aspects: (1) In real-time data aggregation schedule, the times of nodes in the near sink region sending and receiving data packets are more than that of in the far sink region, so that adopting broadcast consuming more residual energy in the far sink region does not shorten the network lifetime. The reason is that a large amount of energy is residual in non-hotspots region. In this paper's network topology (Figs. 1, 4 and 5), the arrow line represents data transmission and the dashed line indicates transmission interference. In each sample cycle, every node samples and generates its origin data packet. So if we assume that the packet size is 5*10,000 bits, then the amount of information contained in an origin data packet can be assumed to 1 unit.

For the network shown in Fig. 1, UBA algorithm allocates schedule time-slot for each node in WSNs as shown in Table 2. The schedule of node i is defined as node i(T, C). T denotes node $i's$ first transmission time-slot and C denotes sample cycle.

The scheduling result is denoted by the first transmitting time-slot and sample cycle. For example, the first time-slot to transmit for node 2 is the third time-slot of sample cycle and sample cycle is set to 4 time-slots. In Table 3, time-slot is fixed to 19, comparing the node load when using UBA schedule scheme and Estimate Aggregation Scheduling with Delay Constraints (EASDC) [25]. EASDC scheme is a collision-free schedule for the dynamic traffic patterns in which each node aggregates a packet to transmit to sink. EASDC is an aggregation scheduling algorithm for optimally estimating a process state and satisfying delay constraints under the protocol interference model. From Table. 3, when adopting UBA and EASDC

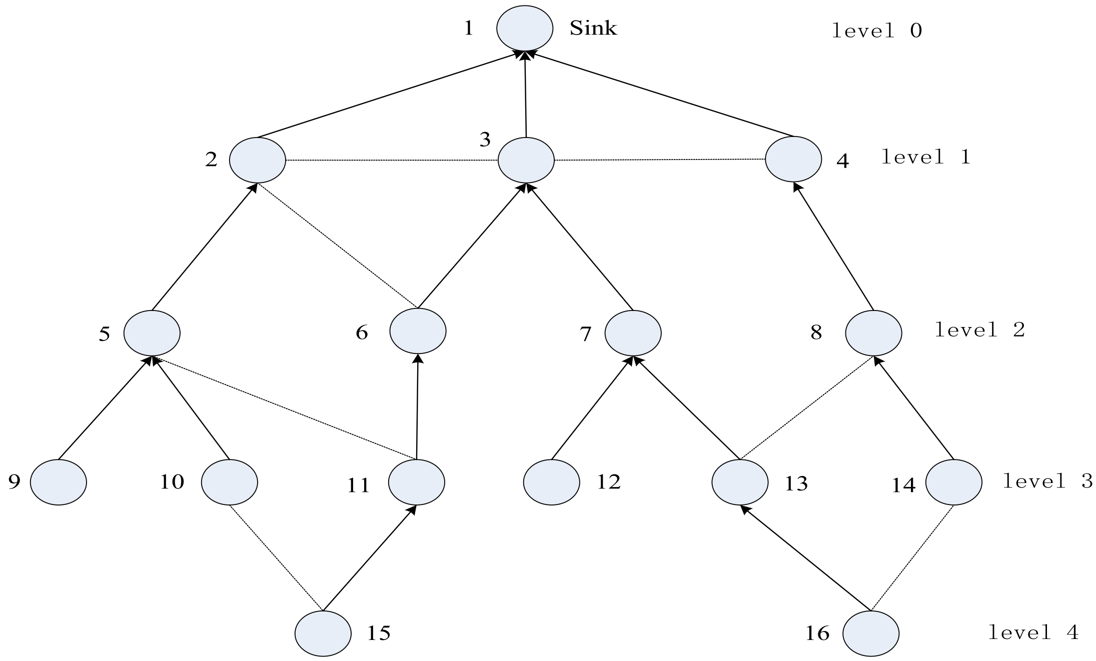

Fig. 1. A randomly generated aggregation tree with 16 nodes.

Table 2.
Node's schedule time slot.

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
C = 4	×	3,4	4,4	2,4	2,4	1,8	5,8	1,4	1,4	3,4	4,4	2,4	3,4	2,4	1,4	1,4
C = 5	×	4,5	5,5	3,5	3,5	1,5	2,5	2,5	1,5	2,5	4,5	1,5	3,5	1,5	1,5	2,5
C = 6	×	5,6	6,6	4,6	4,6	3,6	2,6	3,6	1,6	2,6	5,6	1,6	4,6	1,6	1,6	3,6

Table 3.
Node receiving data packets of EASDC vs UBA.

ID		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
C = 4	EASDC	14	5	5	5	12	2	4	7	0	3	3	0	3	3	0	0
	UBA	14	5	5	5	12	4	10	10	0	5	5	0	5	5	0	0
C = 5	EASDC	11	4	8	4	12	4	7	7	0	4	4	0	4	4	0	0
	UBA	11	4	8	4	12	4	8	8	0	4	4	0	4	4	0	0

schedule scheme, we can see that the load of nodes in the first two levels is no change in the case of unicast schedule scheme. While network lifetime depends on the lifetime of node in the near sink region whose energy-consumption is the highest energy. And the nodes in the far sink region use residual energy to implement broadcast method, although this method increases energy consumption, network lifetime will not be shortened as long as the energy consumption of these nodes is not higher than the maximal energy consumption of node in the near sink region. This shows that UBA scheme will not shorten the network lifetime.

(2) The adoption of broadcast method in the far sink region and of unicast method in the near sink region can increase sensing information collected by sink. Table. 2 shows node's time-slot, when using EASDC scheme and the sample cycle is fixed to 4, node 6 time-slot allocation is (1, 8), child node 11 of node 6 time-slot allocation is (4, 4). Because parent node 6 can not send forwarding the first round collecting sensing information from child node 11, it must await time-slot 9 at the second round. But node 11 has generated the second round sensing information before time-slot 9. Therefore, the first round generated sensing information has lost real-time, which is discarded. It means that sink decreases collecting sensing information. If UBA scheme is adopted, the sensing information generated by node 11 at the first round is transmitted to the one-hop neighbor node 5, and node 5 can transmit the sensing information of node 11 to node 2 in time, then it is transmitted to the sink. It means that UBA scheme can not only avoid the loss of sensing information, but also gather more sensing information by sink node, so that the performance of network data packet loss ratio is lower.

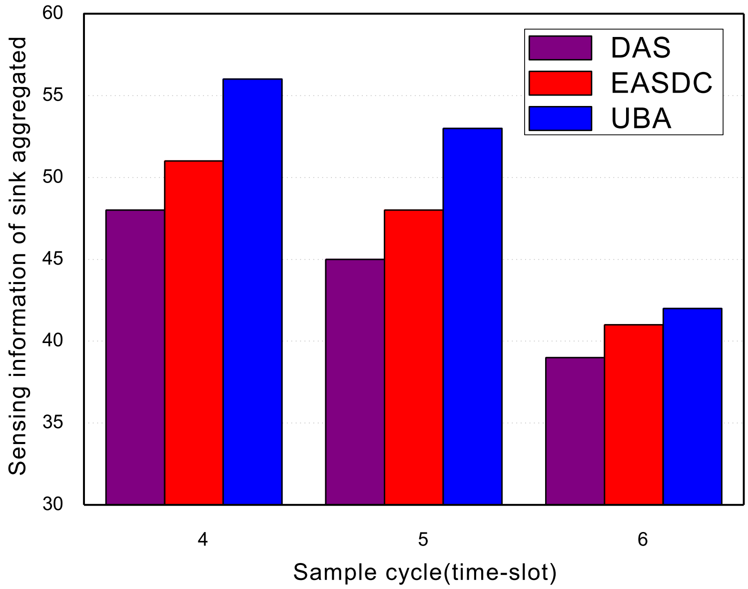

Fig. 2. Sensing information of sink aggregated.

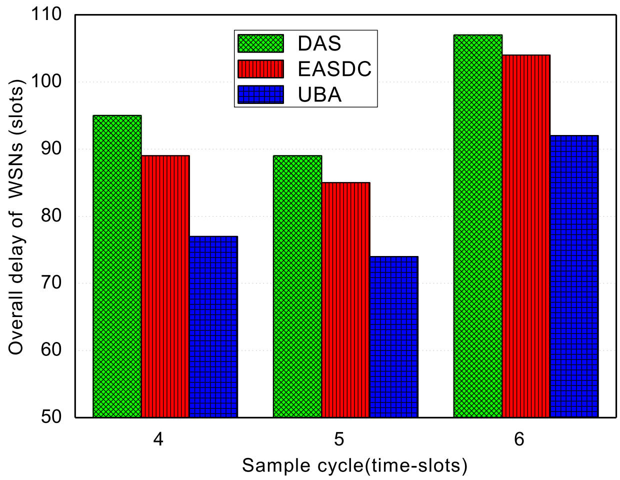

Fig. 3. Overall delay of the wireless sensor networks.

In Fig. 2, the time-slot is fixed to 19, comparing the sensing information aggregated by sink when using UBA schedule scheme, EASDC and Distributed Aggregation Scheduling algorithm (DAS) [24]. It indicates that UBA scheme can significantly increase sensing information of sink received.

(3) Reduce delay. Fig. 3 shows the comparison of delay with different scheduling strategies. In Table 2, the sample cycle is fixed to 4. For node 15, when the EASDC scheme is adopted, sensing information generated to sink need to be routed through node 11, 6, and 3 in the first round and its delay is 12 time-slots. If using broadcast method UBA scheme, sensing information need to be routed through node 10, 5, and 2 reaching at sink and its delay is 7 time-slots. Therefore, UBA scheme can reduce the delay, which means that the sensing information is faster aggregated to sink and meanwhile the real-time of WSNs is also improved.

4.2. Unicast joint broadcast schedule algorithm

To enable readers to understand this article more easily, Table 4 summarizes the notations used in this paper.

In this paper, an effective UBA scheme is proposed to increase collected sensing information and reduce data transmission delay of WSNs. UBA is different from the previous scheduling strategies as following the two aspects:

Table 4.
Notations.

Symbols	Definitions
N_i^c	The number of node *i's* child nodes
C_i^t	Node *i's* child nodes set
F_i^t	Node *i's* first transmission time-slot
N_i^p	Node *i's* transmission sample cycle
N_i^s	Node *i's* one-hop neighbor node (except for parent node)
C_i^n	The child nodes of node *i's* one-hop neighbor node
C_i^s	N_i^s U C_i^n
C	Sample cycle
A[]	Available time-slot array$A$[], if time-slot t is available,$A[t]$is TRUE, else$A[t]$is FALSE
L_i	The level of node *i*
P_i	Node *i'*sparent

(1) The previous strategies only adopt unicast method. However, UBA scheme adopts broadcast method from the third level to the lowest level of this aggregation tree to transmit sensing information that is adopting a mixture of unicast joint broadcast scheduling scheme.

(2) In the previous strategies, in order to improve the lifetime of network, scheduling strategy is that node's time-slot is assigned to as far as possible in the latter part of sample cycle, so every intermediate node has more time-slots to wait for the arrival of data packet from child nodes. Then the nodes put forward these sensing information after data fusion and this will make the sending data packet contain more sensing information, which can increase sensing information and save more energy [25]. But this method will increase the network delay. Meanwhile, we find that the non-hotspots regional (the areas far to sink) nodes have residual energy. So hotspots regional (the areas near sink) nodes try to follow the scheduling strategy, but it is not necessary for non-hotspots regional nodes. As long as the parent node has available time-slot that is the nearest one to its first transmission time-slot before its own scheduling time-slot, it will be assigned to its child node, which can reduce network delay without shortening lifetime of network. This is another advantage of UBA scheme comparing with previous scheduling scheme.

In summary, the UBA scheme is divided into two parts: (1) Firstly, each internal node in WSNs is assigned a time-slot to transmit data packet by using unicast scheduling scheme. (2) From third level to the lowest level, nodes adopt broadcast method to transmit data packet.

The first part of UBA algorithm is how to allocate each node scheduling time-slot, which means how to arrange $F_i^t$and $N_i^p$of node *i*. The main function of UBA algorithm is to allocate time-slot for every node from top to down level by level in WSNs, which starts from the root node sink. The main idea of time-slot scheduling is that parent node decides to its child node schedule time-slot. For the node in near sink region, it is priority to assign the latest available time-slot to the largest degree child node of sink to save energy for this node. On the other hand, node in far sink region will allocate the first available time-slot to the child node with the biggest degree. There are two situations follows:

(a) If node *i* is a leaf node, which does not need to wait for all of sensing information from other nodes to aggregate, parent node will select the earliest available time-slot from A[] to it.
(b) If node *i* with the biggest degree is not a leaf node, parent node will select the latest available time-slot from$A$ [] to it.

No matter what method is adopted, after a round time-slot assignment, node*i*needs to send time-slot allocation information (F_i^t,N_i^p) to C_i^s, which needs to update$A$[]to ensure that nodes in the affected area do not arrange time-slot to avoid conflicts. As Algorithm 1 shows.

5. Experimental evaluation

In this section, we present the simulation results to evaluate UBA schedule scheme. We first introduce the simulation environment, focusing more on the network model we applied in our simulation experiments. We then present some comparisons with existing scheduling mechanism. Finally, we present the evaluation results for the impact of control parameters on the schedule performance. We use Omnet++ network simulator for simulation, and theoretical analysis to evaluate the performance of the proposed scheme.

5.1. Experimental parameters setting

We firstly evaluate the performance of our proposed scheme with two wireless sensor network topologies. The two aggregation trees are rooted in sink and have 28 nodes and 50 nodes respectively. We also consider the case of the growth of node number. Figs. 4 and 5 show the two randomly generated aggregation trees respectively. And a child-parent relationship has been established.

In these simulations, the two randomly generated aggregation trees are assumed that the energy of sink is infinite, other nodes have the same Initial energy 0.5 J in Table 1. Then the assumption of the energy only takes place in the case of

Algorithm 1
A hybrid Unicast joint Broadcast Aggregation (UBA) schedule algorithm.

```
Algorithm1: A hybrid Unicast joint Broadcast Aggregation (UBA) schedule algorithm
Input: A network G, the wireless sensor networks aggregation tree T rooted at the node sink (the node 1), and the sample cycle C;
Output: F_i^t, L_i and N_i^p for every node i (1<i<=n) in WSNs
1: Every node i initializes N_i^c and C_i^t based on the tree T;
2: allocating the space for array A_i [] whose size is q × max { N_i^c, C_i^t } and each element of the array is initialized to TRUE;
3: for C_1^t, according to node degree selecting node i;
      If node i is leaf node, then
         From A[] select the earliest available time-slot t to node i, then
            F_i^t <— t; N_i^p <— C; A_i [t] <— FALSE; C_i^t <— C_i^t -i;
            Send the message (F_i^t, N_i^p) to N_i^s;
            N_i^s set A[] = FALSE according to message (F_i^t, N_i^p);
      End if
      Else
         From A[] select the latest available time-slot t to i, then
            F_i^t <— t; N_i^p <— C; A_i [t] <— FALSE; C_i^t <— C_i^t -i;
            Send the message (F_i^t, N_i^p) to N_i^s and C_i^t;
            N_i^s and C_i^t set A[] = FALSE according to message (F_i^t, N_i^p);
      End else
   End for
   For traversing aggregation tree T's all nodes except for sink level by level;
      For select non leaf j according to the size of sub-tree's BFS
            If node j is not null, then
               Call TSDAC (N_j^c, F_j^t, N_j^p, A_j [], C_j^t).
      End for
  End for
  For every node i in WSNs
      If 0 < L_i < 3
         Data transmission manner adopts unicast
      End if
      Else
        Data transmission manner adopts broadcast
      End else
  End for
```

receiving or transmitting data packet, and is calculated by Eqs. (2) and (3). Except sink, other nodes' distance is from one node to its parent in the aggregation network.

5.2. Schedule time slot assignment

Exploiting proposed Algorithm 1, the results of schedule time slot assignment of the aggregation trees shown in Fig. 4 are presented in Table. 5.

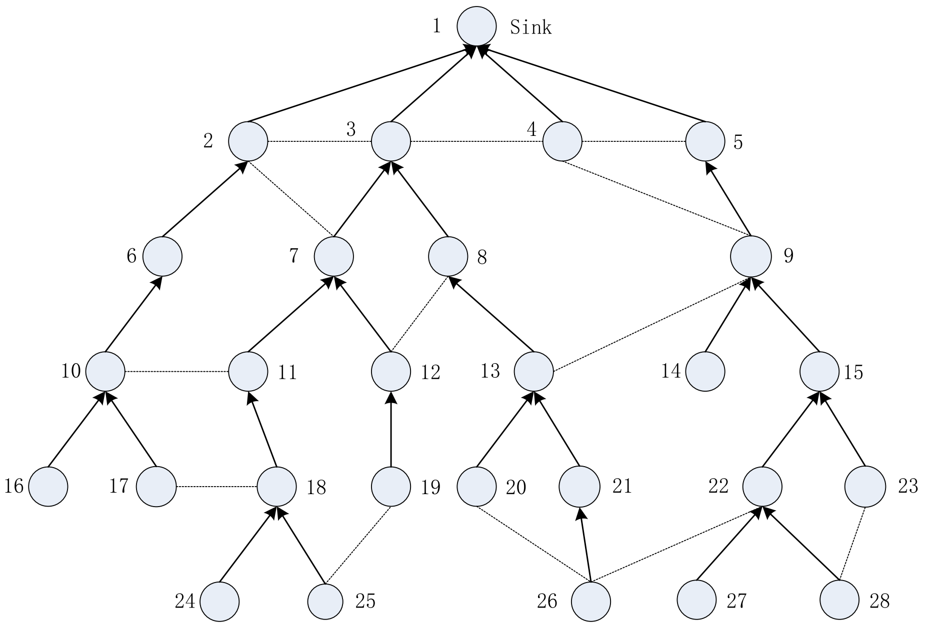

Fig. 4. A randomly generated aggregation tree with 28 nodes.

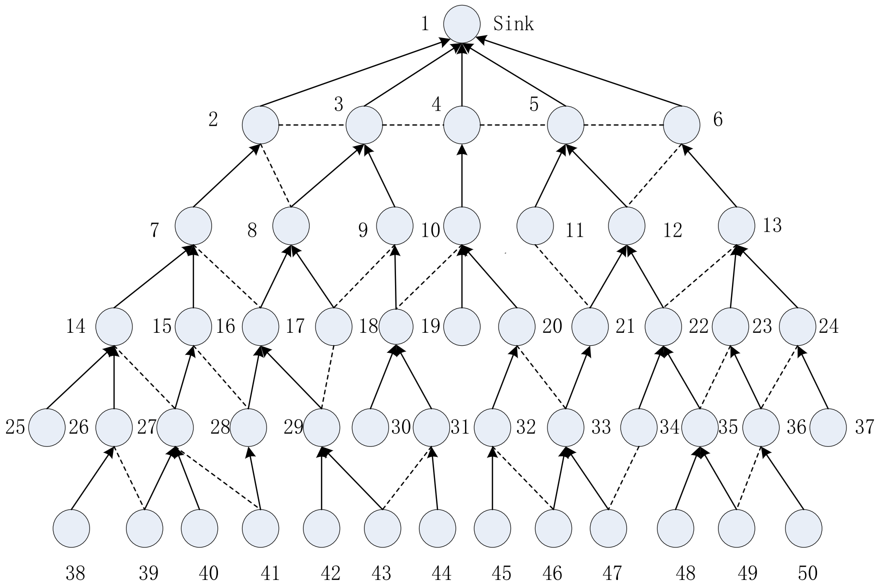

Fig. 5. A randomly generated aggregation tree with 50 nodes.

Table 5.
Node's schedule time slot.

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14
C = 4	×	3,4	4,4	1,4	2,4	1,4	2,8	6,8	3,4	2,4	1,8	3,8	4,4	1,4
C = 5	×	4,5	5,5	1,5	3,5	2,5	3,5	2,5	2,5	1,5	2,5	1,5	4,5	1,5
C = 6	×	5,6	6,6	1,6	4,6	3,6	4,6	3,6	3,6	2,6	3,6	2,6	4,6	1,6
ID	15	16	17	18	19	20	21	22	23	24	25	26	27	28
C = 4	2,4	3,4	1,4	3,4	1,4	1,4	3,4	3,4	1,4	2,4	4,4	4,4	1,4	2,4
C = 5	3,5	3,5	4,5	3,5	2,5	1,5	3,5	2,5	1,5	1,5	5,5	4,5	1,5	3,5
C = 6	2,6	1,6	4,6	1,6	1,6	1,6	3,6	3,6	1,6	2,6	3,6	4,6	1,6	2,6

Algorithm 2
Time-Slot Distribution Algorithm for Children TSDAC (N^c,F^t,N^p,A[],C^t).

```
While for node j, C_j^t, N_j^c > 0 and there is available time-slot t in the A[]
    If slot-time t = 1 and N_j^c > 1, then
        Select node k with the biggest degree from C_j^t, then
          F_k^t <— t; N_k^p <— N_j^p * N_j^c; C_j^t = C_j^t - k; Num = 1;
          Send the message (F_k^t, N_k^p) to C_k^n and N_k^s;
          C_k^n and N_k^s set A[] = FALSE according to message (F_k^t, N_k^p);
          For from C_j^t select node m, then
              F_m^t <— t + N_j^p *Num;  N_m^p <— N_j^p * N_j^c; C_j^t = C_j^t - m; Num++;
              Send the message (F_m^t, N_m^p) to C_m^n and N_m^s;
              C_m^n and N_m^s set A[] = FALSE according to message (F_m^t, N_m^p);
        End for
    End if
    Else
        Select node k with the biggest degree from C_j^t, then
        Case1: node k is leaf node, then
            From A[] select the earliest available time-slot k to i, then
            F_k^t <— t; N_j^p <— C; A_k[t] <— FALSE; C_k^t <— C_k^t - k;
            Send the message (F_k^t, N_j^p) to N_k^s;
            N_k^s set A[] = FALSE according to message (F_k^t, N_j^p);
        End case 1
        Case 2: node k is non-leaf node, then
            Boolean flag<—false;
            For t from F_j^t − 1 to 1
                While A_k[t] = TRUE then
                    flag <— true; F_k^t <— t; N_k^p <— N_j^p; C_j^t = C_j^t - k;
                    Send the message (F_k^t, N_k^p) to C_k^s and N_k^s;
                    C_k^s and N_k^s set A[] = FALSE according to message (F_k^t, N_k^p); Break;
                End while
            End for
            While flag! = true, then
                For t from F_j^t to A_j[].size
                    If A_j[t] = TRUE then
                        F_k^t <— t; N_k^p <— N_j^p; C_j^t = C_j^t - k;
                        Send the message (F_k^t, N_k^p) to C_k^s and N_k^s;
                        C_k^s and N_k^s set A[] = FALSE according to message(F_k^t, N_k^p); Break;
                    End if
                End for
            End while
        End case 2
    End else
```

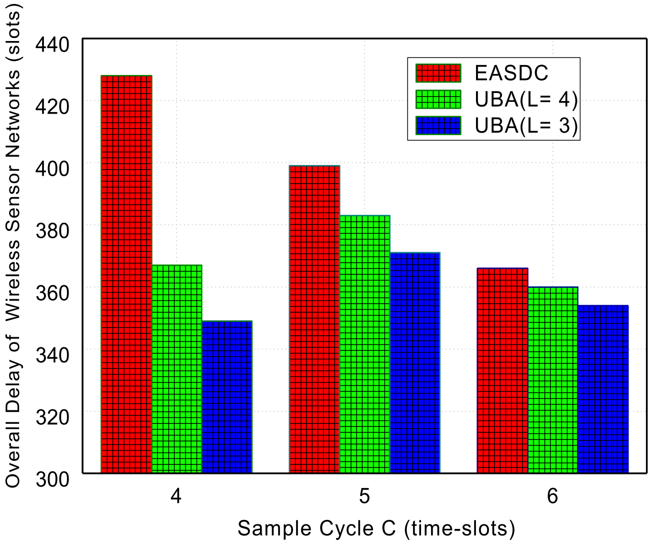

Fig. 6. Overall delay of wireless sensor networks.

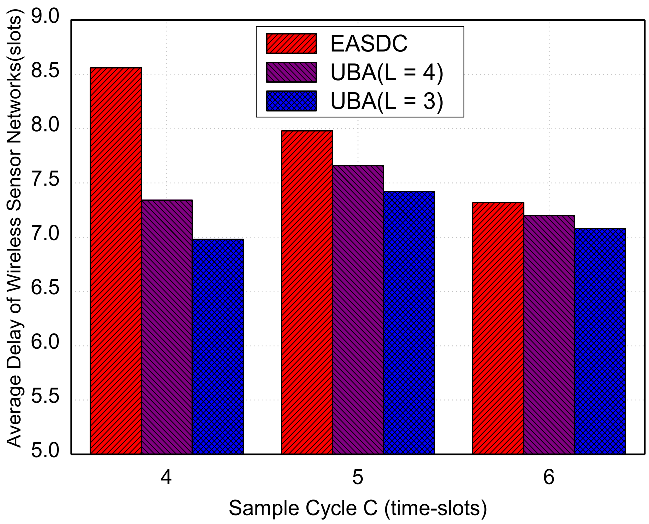

Fig. 7. Average delay of wireless sensor networks.

5.3. Evaluation on delay

In UBA scheduling scheme, the broadcast is adopted from the third level to the lower level. But EASDC uses a unicast method. In EASDC, each sensor node transmits sensing information by adopting unicast method based on interference free, and aggregates the sensing information to sink node level by level starting from the lowest level.

We first turn to show the overall efficiency for data transmission delay of UBA scheme. Figs. 6 and 7 show the overall network delay and average delay of Fig. 5 network with different scheduling sample cycles C and starting broadcast levels. In Figs. 6 and 7, L denotes starting broadcast level in the aggregation tree. In Fig. 6, when sample cycle C is constant, nodes in the far sink regional adopt broadcast and nodes in the near sink regional adopt unicast, the use of this scheduling strategies can reduce delay. This is because UBA scheme uses broadcast method to transmit sensing information to one-hop neighbor nodes, then one-hop neighbor nodes to sink node by multi-path routing. So UBA scheme can reduce more network delay than EASDC. Especially, when sample cycle C is smaller, the efficiency of reducing delay is more obvious in the real-time demanding network. Getting the results from experiment of Fig. 6, the network delay can be reduced by 14% to 18% when the sample cycle is fixed to 4, which illustrates the effectiveness of the proposed UBA scheme.

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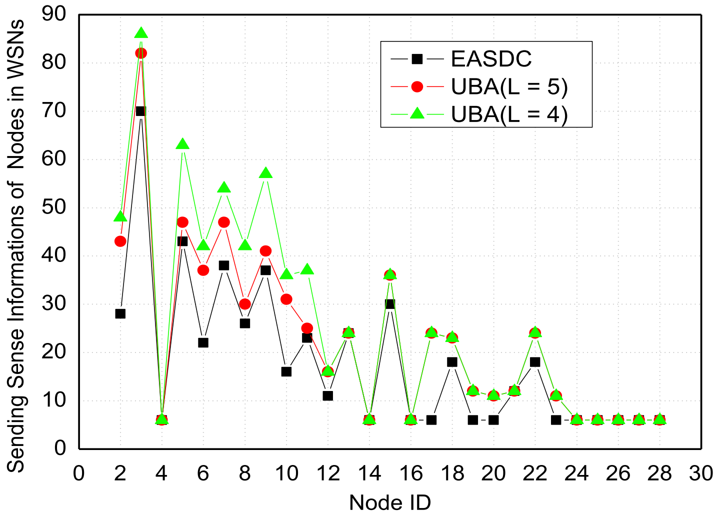

Fig. 8. Sending sense information of nodes in WSNs.

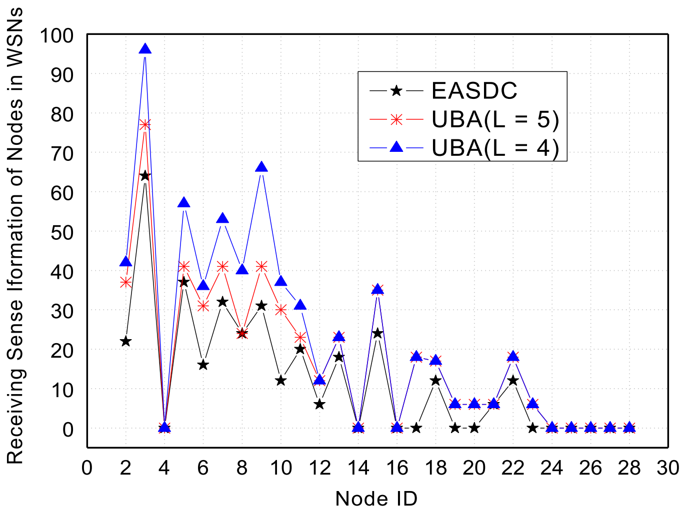

Fig. 9. Receiving sense information of nodes in WSNs.

5.4. The sensing information

For the network shown in Fig. 4, when simple cycle C is fixed to 5, Fig. 8 shows the sensing information of each node received within 30 time slots. Meanwhile, Fig. 9 shows that each node of network receives sensing information with different broadcast levels. From the experimental results showed in Figs. 8 and 9, it can be concluded that adopting UBA scheme can achieve a significant increase in the amount of sensing information received by a vast majority of nodes.

According to the network shown in Fig. 5, Fig. 10 provides the sensing information aggregated by sink when sample cycleCis respectively 4, 5, 6 and the length of time slot is 17. L denotes starting broadcast level in the aggregation tree. From Fig. 10 experiment results, it can be seen that when adopting UBA scheme, sink node can collect more sensing information. When the sample cycle is respectively 4, 5, 6, the improvement ration sensing information aggregated by sink is respectively 20.7%, 13.6%, 3.7%.

In Fig. 11, the sample cycle is fixed to 4, the experimental results shows the amount of sensing information in various time-slots. In this experiment, comparison with the Ref. [25] proposed EASDC scheme. From the experimental results, we can conclude that sensing information aggregated by sink which uses UBA scheme is significantly more than that of EASDC scheme. When the time-slot is 16, it can be found that the ratio of sensing information aggregated by sink is raised to 23.1% when using UBA scheme.

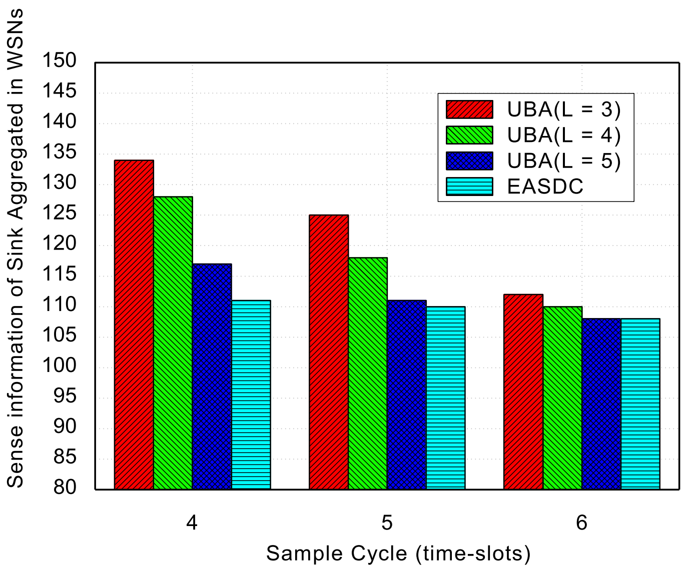

Fig. 10. Sensing Information of sink received.

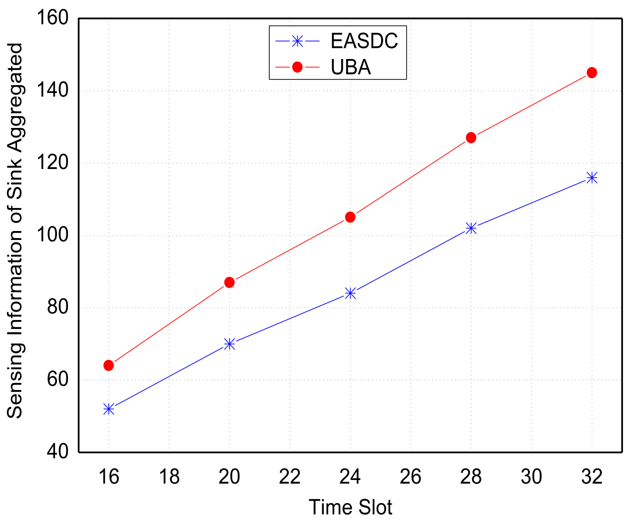

Fig. 11. Sensing information of sink aggregated.

5.5. Evaluation on energy consumption and lifetime

In WSNs through real-time data collection, since the nodes in the near sink region need to transmit data packet from its child nodes many times, which will consume this node much energy, but the nodes in the far sink region have residual energy. Therefore, UBA scheme adopts broadcast in the far sink region that will not shorten the network lifetime.

In Figs. 12 and 13, sample cycle C is fixed to 4 and the length of time-slot is 17. The experimental results show the sensing information aggregated by sink and the changing conditions of network delay. 0 in x axis indicates unicast method EASDC scheme; 1 indicates the last level broadcast of the aggregate tree when the UBA scheme is adopted; 2 indicates the last two levels broadcast of the aggregate tree; 3 indicates the last three levels broadcast of the aggregate tree. Figs. 12 and 13 shows, the more number of broadcast level in the far to sink region, the more sensing information will be aggregated by sink, while it also reduce the delay without shortening network lifetime.

5.6. Broadcast level optimization

The general principle of UBA scheme is to choose a right broadcast level to collect as much sensing information as possible and make network delay as small as possible without shortening network lifetime. We maintain the hierarchical position according to the distance from node to sink. Sink node level is defined as level 0, then the nodes needing one-

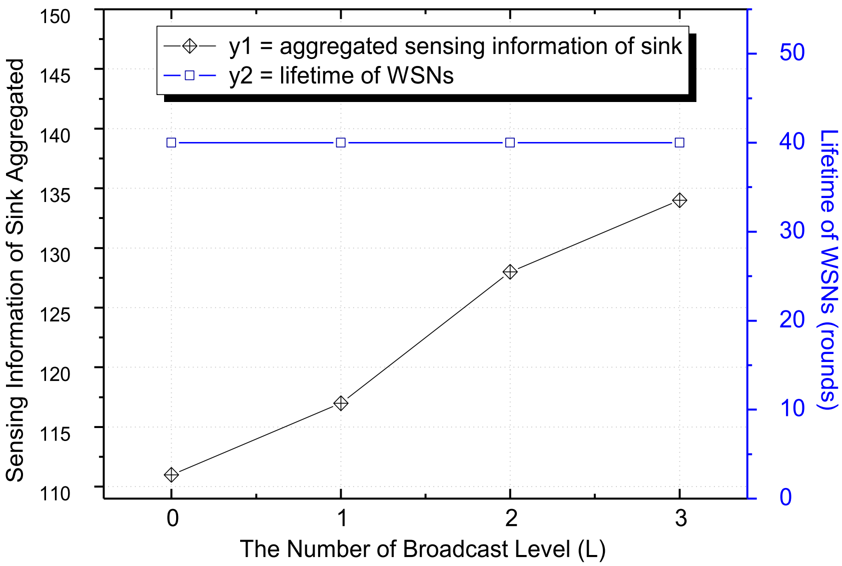

Fig. 12. Sensing information of sink aggregated and lifetime.

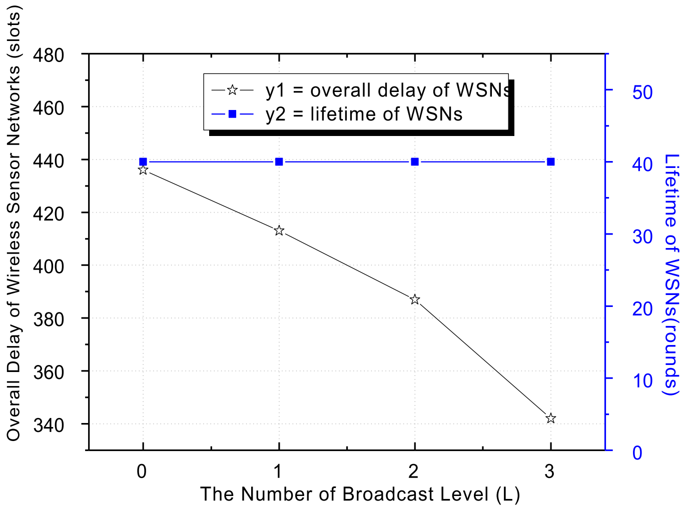

Fig. 13. Overall delay and lifetime of WSNs.

hop to sink is defined as level 1. Similarly, the number of hop *i* to sink is set as level *i*. Generally speaking, to make sure that the second level node can receive the sensing information as much as possible, the smallest broadcast level should begin broadcasting from level 3. If broadcast level starts from level 2, it will increase the amount of data packet and energy consumption of nodes in level 1, it means that network lifetime will be shortened. So it can not adopt broadcast from level 2. That's why it should broadcast from level 3 at least, meanwhile the nodes in level 2 can receive as much sensing information as possible. Once the nodes in level 2 receive the broadcast sensing information, a data packet mixed by the nodes and the sense information of their own will be transmitted to their parent node in level 1 without shortening the lifetime of nodes in level 1. From the minimum broadcast level to the child nodes level of aggregation tree, the nodes and their own sense information will be aggregated into a new data packet which will be transmitted to their parent nodes after the nodes at each level receiving the broadcast sense information, the main purpose is to reduce the energy consumed in the data transmission process.

In Fig. 14, network topology is shown in Fig. 5, scheduling time-slot is fixed to 17. The figure compares the sensing information aggregated by sink when starting broadcast level is different. We can find in Fig. 14 that the closer broadcast level is to sink, the more sensing information sink will collect. Fig. 15 shows the overall delay of the entire network in different broadcast levels. Similarly, the overall delay of network will be smaller if the broadcast level is closer to sink. Therefore, we can draw the conclusion that we did better choose a broadcast level which is nearest to sink under the same network lifetime.

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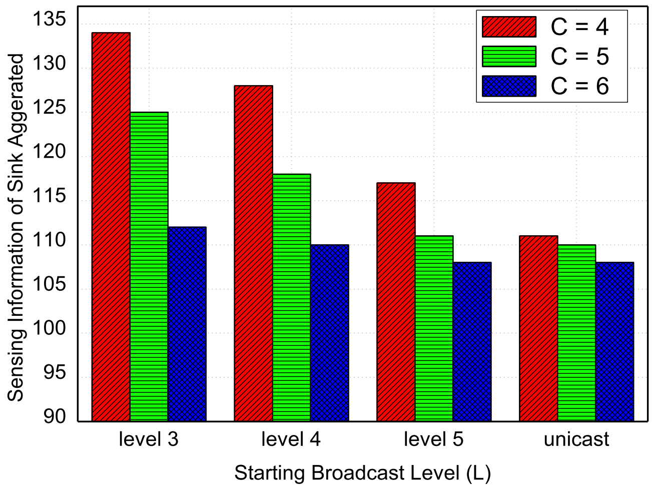

Fig. 14. Sensing information of sink aggregated.

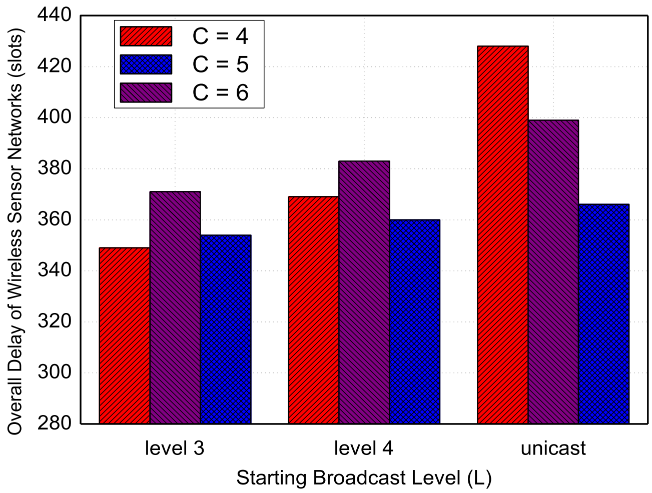

Fig. 15. Overall delay of wireless sensor networks.

5.7. The influence of network parameters on the performance

First, this paper will discuss the effects of network scale on UBA scheme. Network scale is the number of network level. In Fig. 16, the tree depth is respectively 6, 7, 8 and 9. The figures compare the sensing information of sink aggregated by using EASDC scheme and UBA scheme when the number of level varies. It can be seen that the sensing information aggregated by sink of our UBA scheme outperforms that of EASDC scheme significantly. Moreover, improvement ratio of sensing information will be larger with the increase of the number of level.

As Fig. 16 shows, the network scale is larger, sensing information aggregated by sink of UBA scheme will be more than that of EASDC scheme. When the network level is respectively 6 and 9, the improvement ratio of collecting sensing information of UBA scheme is respectively 6.3% and 24.64%, which is shown in Fig. 17. This is because the more level numbers are, the more levels sensing information collected by broadcasting. As a result, the more sensing information collected by sink, the less network delay.

Secondly, the effect of sample cycle on UBA scheme function is studied. In Fig. 18, network construct contains 50 nodes and the network is given in Fig. 5. The figure compares the sensing information aggregated by sink using UBA scheme and EASDC scheme when the sample cycle varies. It can be seen from the figures that our UBA scheme can gather more sensing information than EASDC scheme. The performance of UBA scheme is better than that of EASDC scheme in most cases. In EASDC scheme, if the sample cycle is too small, no matter how to allocate the time-slot for each node of network carefully, it can not ensure that every sensing information of nodes can be sent out within a sample cycle. However, UBA scheme can reduce the loss of the node sensing information.

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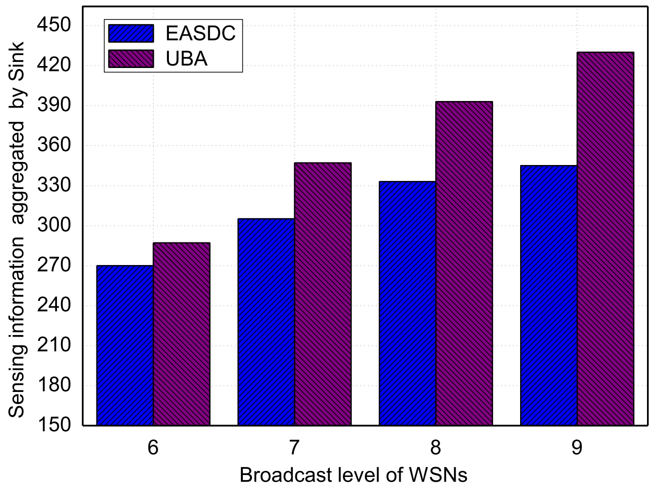

Fig. 16. Sensing information aggregated by sink.

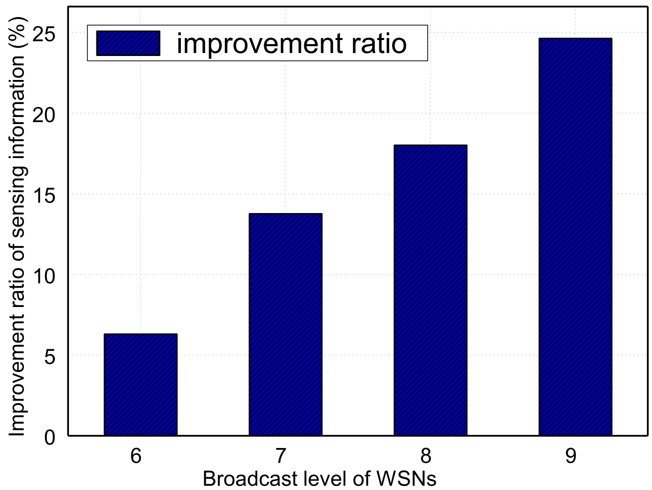

Fig. 17. Improvement ratio of sensing information.

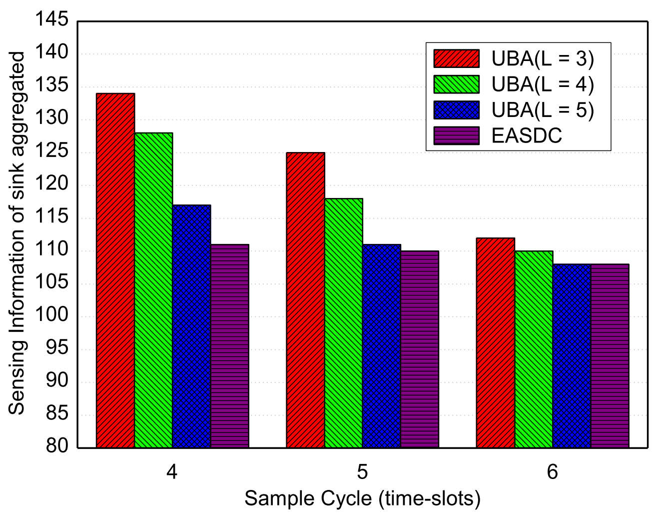

Fig. 18. Sensing information of sink aggregated.

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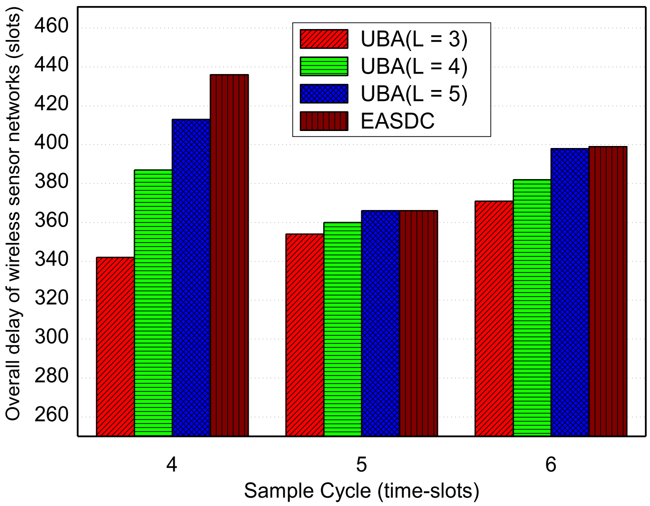

Fig. 19. Overall delay of the wireless sensor networks.

Likewise, Fig. 19 presents network delay experimental results in comparison with different sample cycles. With the sample cycles becoming larger, the overall delay gap gets smaller. And we can see from the experimental result that the smaller the sample cycle is, the more advantages UBA scheme has, vice versa. That is because when sample cycle is small, broadcast strategy has a better performance. All above illustrates that UBA scheme proposed in this paper is suitable for large-scale and real-time network.

6. Conclusion and future work

In this paper, a hybrid Unicast joint Broadcast Aggregation (UBA) Schedule scheme is proposed for maximizing aggregation information and minimizing network delay in data collection multi-hop wireless sensor networks. The two main mechanisms of UBA scheme are the adoption of a mixed scheduling mode and the use of residual energy of nodes, the former mechanism adopts broadcast strategy in the far sink region and unicast strategy in the near sink region, and the latter is making the best use of the residual energy of nodes in non-hotspots to implement broadcast strategy. What's more, Time-Slot Distribution Algorithm for Children (TSDAC) algorithm is also proposed, which can guide to assigning optimal time slots for children nodes and reduce network delay efficiently. Through simulation and detailed theoretical analyses of the proposed scheme, the evaluation results show that UBA scheme can improve sensing information by 25% and reduce delay by 14% - 18% under the same lifetime compared with EASDC and DAS scheme.

To maximize aggregation information and minimize delay is two pivot issues for in-network aggregation in lossy wireless sensor networks. Most existing in-network aggregation schedules designed for a fixed allocated time slot which the total aggregation information and delay can not be optimized at same time. For future work, we yearn to design a integrating unallocated time slot in-network aggregation schedule scheme that is capable of maximizing aggregation information and minimizing delay for lossy WSNs.

Acknowledgments

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